We Are Made of Starstuff

Kit A, Kit D

Science Focus: Exploring Nucleosynthesis

Lesson #	Lesson Title	Suggested Time
1	Are All Elements Created Equal?	50 minutes
2	In the Beginning: The Early Universe	50 minutes- part 1 50 minutes- part 2
3	From Stars to Atoms: Stellar Nucleosynthesis	50 minutes- part 1 50 minutes- part 2 50 minutes- part 3
4	Beyond Helium	50 minutes- part 1 50 minutes- part 2 50 minutes- part 3
5	A Breakthrough Discovery	50 minutes

We are Made of Starstuff- 9-12 (Physical Science)

Students take their understanding of the periodic table to a third dimension through the topic of nucleosynthesis (formation of the elements). They explore the nuclear processes of radioactive decay, fusion, and fission. Then, armed with that basic knowledge, delve into processes that formed the elements: Big Bang, stellar and explosive nucleosynthesis. These topics introduce physical and earth/space science standards that are often not covered in the traditional curriculum.

Physical Science Standards	Lesson
HS-PS1-8 Develop models to illustrate the changes in the composition of the nucleus of the atom and the energy released during the processes of fission, fusion, and radioactive decay.	2, 3, 4, 5
HS-PS2-4. Use mathematical representations of Newton's Law of Gravitation and Coulomb's Law to describe and predict the gravitational and electrostatic forces between objects.	2, 3, 4
HS-PS3-3. Design, build and refine a device that works within given constraints to convert one form of energy into another form of energy.	4
HS-PS3-5. Develop and use a model of two objects interacting through electric or magnetic fields to illustrate the forces between objects and the changes in energy of the objects due to the interaction.	4, 5
Earth/Space Science Standards	Lesson
HS-ESS1-1. Develop a model based on evidence to illustrate the life span of the Sun and the role of nuclear fusion in the Sun's core to release energy that eventually reaches Earth in the form of radiation.	3, 4
HS-ESS1-2. Construct an explanation of the Big Bang Theory based on astronomical evidence of light spectra, motion of distant galaxies and composition of matter in the universe.	1, 2
HS-ESS1-3. Communicate scientific ideas about the way stars, over their life cycle, produce elements.	4, 5
Engineering, Technology and Society Standards	Lesson
HS-ETS1-1. Analyze a major global challenge to specify qualitative and quantitative criteria and constraints for solutions that account for societal needs and wants.	1

We are Made of Starstuff

Materials List

- **Teacher-Provided**

Lesson	Materials Needed
1	_Pre-launch:_ *For each student:* • Periodic Charts (laminated) • Pre-assessment (Print Master) _Launch (1-1):_ *For each pair of students:* • Precious Metals Cards (laminated) _Explore (1-2) & Summarize (1-3):_ *For each pair of students:* • Precious Metals Cards (laminated) • Solar System Abundances Data Graph (laminated) _Assess (1-4):_ • *(Optional) Index Card (Assessment Exit Card if not using notebooks)* _Optional Extension:_ *For each group of students:* • *Lesson 1 Task Card (laminated)* • *Colored Pencils* • *Ruler* ➢ Computers ➢ Large Paper/ Poster Board
2	_Launch (2-1):_ *For each pair of students:* • Big Bang Graphic (laminated) _Explore (2-2, 2-3) & Summarize (2-4)_ *For the Classroom:* • Element Cards (laminated) • Ping-Pong Ball • Temperature Signs (2 – laminated) _Explore (2-5)_ *For each pair of students:* • Activity 2-5 Task Card *For each pair:* • Compare/contrast cards ➢ Computers _Summarize & Assess (2-6)_ • *Lesson 2 Assessment Card* ➢ *Computers* ➢ *Poster Paper*
3	_Launch (3-1):_ No materials needed _Explore (3-2):_ *For the classroom:* • Cloud Chamber (set up ahead of class) ➢ Ice Bath

	➢ Isopropyl Alcohol/Ethanol, >70%
	• Digital Geiger Counter
	• Pottery Samples
	• Cs/Ba isogenerator
	• Eluting Solution
	• Beaker
	• Non-latex Gloves
	• Snack Size Baggies
	• Chem-Wipes
	For each small group (3 students):
	• Geiger Counter Handout (Print Master)
	• Analog Geiger Counter
	• Activity 3-2 Task Card
	• Sample of Radioactive Material
	➢ Computer, Graphing Calculator, Graph Paper
	➢ Stopwatch/Timer App
	Summarize (3-3):
	No materials needed
	Explore (3-4) & Summarize (3-5)
	For each small group (4 students):
	• Two Nucleosynthesis Game Boxes
	• Game Rules Chart
	• Chart of Nuclides (laminated)
	Explore (3-6):
	For each small group (4 students):
	• Activity 3-6 Task Card
	• Geiger Counter
	• Box containing:
	    ○ Beta Source, 2 Unknown Sources
	    ○ Set of Degraders
	    ○ Ruler
	    ○ Protractor
	    ○ Clay
	    ○ Binder Clips
	Summarize (3-7):
	For each student:
	• Lesson 3 Assessment Card
	• Evidence Cards
	• Reasoning Template (laminated)

4	*Launch (4-1):* No materials needed *Explore (4-2):* *For each pair of students:* • Activity 4-2 Task Card • Colored Pencils ➢ Computers ➢ Poster Paper

	Summarize (4-3): *For each student:* • Periodic Table Template (Print Master) • Colored Pencils *Explore (4-4) & Summarize (4-5)* *For the classroom:* ➢ Large Sheet of Paper/Whiteboard ➢ Colored Markers *For each pair of students:* • Nucleosynthesis Game Kits • Chart of Nuclides • Activity 4-4 Task Card • 11x17 Chart of Nuclides • Colored Pencils *Explore (4-6):* *For each small group (3 students):* • Activity 4-6 Task Card • Authorization to Proceed (ATP) Card • Set of Magnets and Steel Balls • Set of Accelerator Tracks • Tape • Measuring Tape • Plastic Cup *For each student:* ➢ Safety Glasses
5	*Launch (5-1) & Explore (5-2)* *For each pair of students:* • Precious Metal Cards • Abundance Curve (laminated) • 11x17 Chart of Nuclides • Colored Pencils • Research on Star from Activity 4-2 *Summarize (5-3):* *For each student:* • Periodic Table • Colored Pencils • Lesson 5 Assessment Card

Note to Teachers:

This unit is a second revision of a curriculum unit of the same name written and piloted by the Education and Outreach Department at the Sanford Underground Research Facility in 2015-2016. It is designed to replace two weeks of a high school course curriculum with a study of nuclear science and the origin of the elements in the cosmos and connect to Sanford Lab science through the CASPAR (Compact Accelerator System for Performing Astrophysical Research) facility. All lessons are tied to NGSS physical and earth/space science standards, scientific and engineering practices, and crosscutting concepts. The revisions for 2018 reorder the lessons to integrate student sensemaking of nuclear processes into the storyline of the origin of the elements, rather than have them as a separate set of activities. It also introduces a new scientific breakthrough in this field that came in 2017 – GW170817. GW170817 was the first direct observation of two colliding neutron stars, observed on August 17, 2017, and announced in October 2017. This observation was made first at the Laser Interferometer Gravitational Observatory (LIGO) which was followed with gamma rays, visible light, and finally data throughout the electromagnetic spectrum. This observation marked the birth of the new field of multimessage astronomy and provided substantial evidence to the question of the origin of the heavy elements.

<u>Teacher Primer</u>
Because parts of this material may not be familiar to all teachers, there is a teacher primer on the flash drive with background material for each topic.

<u>Pre-Requisites</u>
The unit has been field-tested in chemistry (several levels) and astronomy courses at schools across the region. The current version assumes that students have studied the periodic table and know the basic components of matter (atoms and their constituents).

<u>Resources</u>
The unit comes with a materials kit that will be loaned to teachers in the state of South Dakota free of charge. Included in the kit is most of what a teacher needs to implement the unit. A notebook with the lessons and a unit flash drive are also included. The unit flash drive contains a Print Master file, keys to all handouts, PowerPoint presentations and other media such as videos.

<u>Science Notebooks</u>
Interactive science notebooks are strongly encouraged but not required for this unit. If students already use notebooks in science class, continue to use the same ones. The next page gives some guidance if the use of notebooks is new to you. Most lessons include laminated Task Cards for each activity and assessment and students are expected to record everything in a notebook.

<u>Assessments</u>
A pre- and post-assessment are included with the unit. These were used in the original field testing of the unit and are currently optional, should you, the teacher, choose to use them. A set of laminated periodic tables are included to use with these assessments.

In addition, each lesson has a formative assessment. Assessment cards are included with rubrics. These assessments are based on Claim-Evidence-Reasoning (CER) framework. We have attempted to make these three-dimensional and the scope varies by lesson – some are individual and some group; some require research and other are exit cards. The Lesson 5 Assessment can be used as the unit assessment if desired.

<u>Phenomenon-based Learning</u>

The Sanford Underground Research Facility Education and Outreach Department has adopted the vision of Ambitious Science Teaching (www.ambitiousscienceteaching.com) as the framework of all our curriculum units. Students spend the course of the unit coming to an understanding of a complex and puzzling natural phenomenon. In this unit, the phenomenon is the graph of abundances of the elements in the solar system. Students will be returning to that data throughout the unit.

* For the standards addressed in this unit, the South Dakota science standards are identical to the Next Generation Science Standards.

A Teacher's Guide to the Interactive Notebook

For this unit it is intended that students utilize an interactive notebook. If you already have a science journal, or notebook, that students maintain during the class please continue to use that format. If you do not have a journal or notebook for your classroom, use an Interactive notebook for the duration of this unit.

The interactive notebook should be kept in a spiral notebook or composition notebook.

The front side of the first piece of paper in the interactive notebook should be designated as a table of contents. The table of contents will be created as the pages of the notebook are created. Following the table of contents, all pages should be numbered, and the dates recorded.

The next front side page should be the title page. For this unit students should create a page that reads 'We are Made of Starstuff'. Students are free to decorate this page any way they chose.

Beginning with the backside of the second sheet of paper the students begin to make entries into their interactive notebook. Some examples of entries could include:

- Notes taken while reading articles or textbook or watching a video (Cornell Notes is a great template to use)
- Lab results and observations
- Vocabulary terms and definitions
- Venn Diagrams
- Student sketches/modules
- Mind-maps (concept maps)
- Questions that the student is pondering about the topic

At the end of the unit students can write a summary of their understanding of the unit. If you would like to have students write a summary, have them select two items that represent their best work. Students should give the dates of their entries and then explain why they chose these two items, what they learned from these two items, and how these items reflect scientific thinking or skills. Students must use evidence to defend their choices and should not provide emotional responses such as “that is my best drawing” or “that activity was a lot of fun”. The reflection should be written on the last page of the interactive notebook for that unit.

We encourage your students to take their notebooks home to share with their parents or adults living in the home with them. The adults should look through the notebook and read the reflection with the student.

Lesson 1, *Are all elements created equal?*

ACTIVITY 1-1. How Precious are Precious Metals?

Questions	What we Figure out	New Questions
Why are some elements worth more than others?	The worth of an element is due not only to its uses in society but to its abundance on earth. Supplies are limited.	Why are the supplies of some elements limited? Are there less precious metals available than other elements?

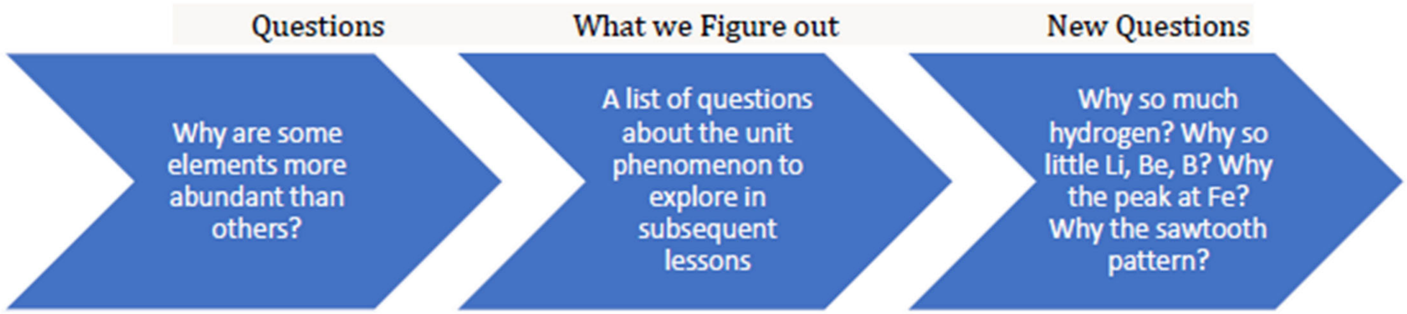
- **ACTIVITY** – Students will analyze economic data on five elements important to society and analyze their value to society and everyday life. They will examine predictions of when these elements will run out and consider possible solutions to this global problem.

ACTIVITY 1-2. What's It Worth?

Questions	What we Figure out	New Questions
Why are the supplies of some elements limited? Are there less precious metals available than other elements?	The correlation between solar system abundances and worth is weak; the correlation is stronger for crustal data.	Why are some elements more abundant than others? Could technology enable us to mine limited elements from space?

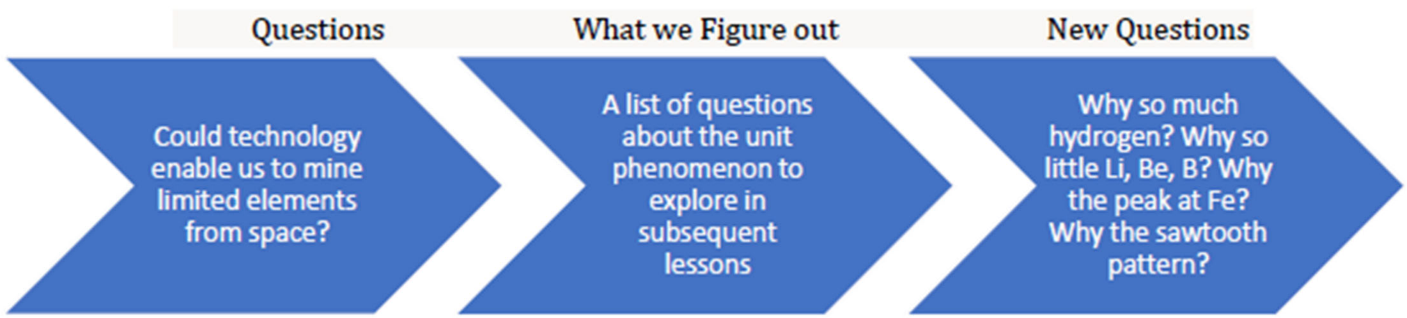
ACTIVITY – Students will be introduced to the anchoring phenomenon for the unit – data on the abundance of the elements in the solar system. They will re-examine the precious metals and look for correlations with abundance in the solar system and in the Earth's crust.

ACTIVITY 1-3. Exploring the Phenomenon



- **ACTIVITY** – Students attempt to make sense of the abundance of the elements in the solar system and develop questions in explore in future lessons.

ACTIVITY 1-4 (Formative Assessment). Space Mining, Inc.



ACTIVITY – Students propose a solution to the limited supply of one of the precious metals utilizing mining of asteroids.

Lesson 1	Are All Elements Created Equal?
Overview Standard(s) & Objectives	*This lesson should require one normal class period or part of a block period. The structure and flow of the lesson is given at the beginning of the Background Material section. DCIs, SEPs and CCCs for each activity are color-coded.* **Standards:** HS-ESS1-2: Construct an explanation of the Big Bang Theory based on astronomical evidence of light spectra, motion of distant galaxies and composition of matter in the universe. HS-ETS1-1. Analyze a major global challenge to specify qualitative and quantitative criteria and constraints for solutions that account for societal needs and wants. **Disciplinary Core Ideas:** • ESS1.A The Universe and Its Stars • ETS1.B Defining and Delimiting Engineering Problems **Science and Engineering Practices:** • Asking Questions and Defining Problems • Analyzing and Interpreting Data • Constructing Explanations and Designing Solutions **Crosscutting Concepts:** • Energy and Matter • Patterns • Influence of Science, Engineering and Technology on Society and the Natural World **Lesson Phenomenon:** abundance of elements in solar system (poster) **Lesson Level Learning Goals:** • Students will analyze economic data on five elements important to society and analyze their value to society and everyday life. They will examine predictions of when these elements will run out and consider possible solutions to this global problem. • Students attempt to make sense of the abundance of the elements in the solar system and develop questions in explore in future lessons. • Students propose a solution to the limited supply of one of the precious metals utilizing mining of asteroids. • Students will be introduced to the anchoring phenomenon for the unit – data on the abundance of the elements in the solar system. They will re-examine the precious metals and look for correlations with abundance in the solar system and in the Earth's crust.
Background Information and Reference Material	**Structure of Lesson:** 1. (PRE-LAUNCH) This unit starts with a pre-assessment which could be done the day before to save time. Students should be given a laminated periodic table along with the written assessment. They are not expected to know the content at this point, but the results should guide the teacher as to potential areas of misconception, lack of prior knowledge, etc. 2. (LAUNCH) Activity 1-1, *How Precious are Precious Metals?* is designed to

get students thinking about how certain elements which are important to society and their own lives are 'endangered' and could run out in their lifetime, a societal problem that needs a solution. Students work in pairs to examine the economic value and uses of five precious metals, and industry reports on the future supply.

3. (EXPLORE) In Activity 1-2, *What's It Worth?,* students are introduced to the unit anchoring phenomenon, data on the abundance of the elements in the solar system (laminated graph), and additional data on the abundance of the elements in the Earth's crust (in PowerPoint). They calculate correlations between abundances and 'worth' as defined by commodities prices for the precious metals. They make sense of the data and strength of the correlations in classroom discussions about the complexity of the societal problem.
4. (SUMMARIZE) In Activity 1-3, *Exploring the Phenomenon,* students examine the graph of abundances in more detail, looking for patterns and asking questions to explore in later lessons.
5. (FORMATIVE ASSESSMENT) In Activity 1-4, *Space Mining, LLC,* students have an opportunity to offer a solution for the global societal problem addressed in this lesson. They will be asked to make a case for mining a precious metal of their choice on a nearby asteroid.

(TEACHER TIP: The assessment activity 1-4 can be done in class, as an exit card or assigned as homework. Activity 1-3 and 1-4 could be interchanged if desired or if it fits better with the flow of the discussion following Activity 1-2.)

Content information for teachers: See the unit primer for Lesson 1

Examples of student work:

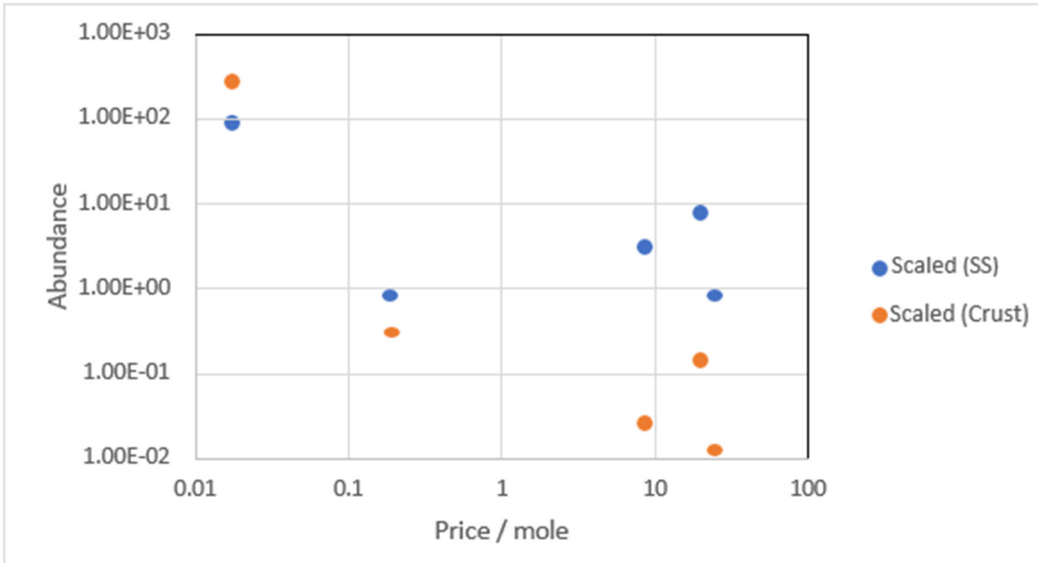
Activity 1-2, What's It Worth- EXPLORE

- Answers to questions in Slide 8 (class exercise)

Element	*Relative Abundance*	*Ratio to Silicon*	*Atomic Mass*	*Mass Abundance*	*Ratio to Silicon*
H	*$5x10^{10}$*	*50,000*	*1*	*$5x10^{10}$*	*1,800*
Si	*$1x10^{6}$*	*1.0*	*28*	*$28x10^{10}$*	*1.0*
U	*0.01*	*10^{-8}*	*238*	*2.38*	*$8.5x10^{-8}$*

There are 5 x 10^{12} more hydrogen atoms that uranium atoms in the solar system.

- Answers to student exercise, abundance of their precious metals (reading off the plot won't be this accurate)
  - Cu – 85.7
  - Pd – 2.86
  - Ag – 0.857
  - Pt – 7.14
  - Au – 0.857
- Figure 1.1 gives an example of correlation graphs students might derive as part of this activity. The plot uses data from solar system abundances as well as data from abundances in the Earth's crust (Slide 9 of

	PowerPoint). Both sets of data show a weak correlation with abundance, reflecting the importance of worldwide demand to determining prices. ***Figure 1.1 – An example of a correlation plot made using Excel. Price/ounce has been converted to price/mole.*** 
Materials	*Pre-launch:* *For each student:* • Periodic Charts (laminated) • Pre-assessment (Print Master) *Launch (1-1):* *For each pair of students:* • Precious Metals Cards (laminated) *Explore (1-2) & Summarize (1-3):* *For each pair of students:* • Precious Metals Cards (laminated) • Solar System Abundances Data Graph (laminated) *Assess (1-4):* • *(Optional) Index Card (Assessment Exit Card if not using notebooks)* *Optional Extension:* *For each group of students:* • *Lesson 1 Task Card (laminated)* • *Colored Pencils* • *Ruler* ➢ Computers ➢ Large Paper/Poster Board
Prior Knowledge	Students should have a basic understanding of the structure of an atom, the difference between elements, and the organization of the periodic table. Depending

	on where they are in chemistry studies at the time this unit is introduced, they may have mental models that the nucleus of the atom always remains unchanged. This misconception will be addressed in the unit. Students will need a basic understanding of the logarithmic scale for this and other lessons in this unit. For comparison of linear vs. log scales, once could view this video, also located on the flash drive.
Pre-assessment	1.) (Slide 2) As students enter the room and get ready, have the periodic rap video playing, also located on the flash drive. *(Teacher Tip: All video and audio files for the unit are linked from the Power Point files, or available on the flash drive. If you are using Keynote in your classroom to display PPT files, the direct links may not work).* 2.) (Slide 3) Explain to students that they are going to be starting a unit that examines the elements of the periodic table in greater detail; pass out periodic charts and the pre-assessment. Emphasize to the students that they should make their best guess on the pre-assessment if they don't know the answers. They will be exploring the topic in detail in the next several class periods. Allow 10 minutes for the pre-assessment. 3.) Pick up the pre-assessments but have students keep their periodic charts for the next activities. 4.) **Optional: (slide 4)** Review the organization of the periodic table if students are unfamiliar with it.
Launch (10 minutes)	
Engagement	Activity 1-1. How Precious are Precious Metals? 1.) (Slide 5) Have students work with a partner and hand each pair a set of laminated precious metal cards. Ask them to brainstorm with their partner and write down three reasons why the prices of the five 'precious metals' are so different. Then have them write down three reasons one or more of these elements are important in their lives. *2.)* In a class discussion, have groups first comment on the importance of these five elements. How would it affect their lives if they didn't exist? Then have the groups share some of their reasons for the price differential and write them on the board. Why are they called precious metals? *3.)* (Slide 6) Show the slide of the ACS *Periodic Table's Endangered Elements.* Does this inform the previous discussion or raise additional questions? Have students add to or revise their reasons for the price differentials. *(Teacher Tip: Most groups should have considered that some of the elements are rarer than others and its effect on the price. If not, you will need to lead them to that possibility before continuing).*
Explore (15 minutes)	
Exploration	Activity 1-2. What's it worth? 1.) (Slide 7) Give each group a laminated graph of the abundances of the elements in the solar system. Discuss the fact that the y-axis is logarithmic. This would be a

	good point to review linear versus log scales with this video if the class needs it. Point out that the graph represents relative abundances and values are scaled randomly to the element Silicon at 1 million. 2.) (Slide 8) Have them pick out as a class the most and least abundant elements in the solar system and work out the examples on the board on how they compare to silicon. *(Hydrogen – Most Abundant = $5x10^{10}$ =50,000 x more abundant than silicon; Uranium – Least Abundant = 10^{-2}=10^{8}x less abundant than silicon)*. Work out as a class how many more atoms of hydrogen are in the solar system than uranium atoms ($5x10^{12}$). What about if you convert to mass? What would the ratio be? (~$2x10^{10}$). 3.) Have the pairs use the data to determine he relative abundance of the five precious metals on their cards. Is there a correlation between the price of the element and the abundance? Why or why not? *(Teacher Tip: There is a correlation but not strong. By this point some students should have thought about whether abundances on Earth are the same as those in the solar system. If not, lead them there by asking them about hydrogen and helium on Earth. Is it 98% of the elemental abundance?).* 4.) (Slide 9) Show the graph of the abundances of the elements in the Earth's crust and work through with the class: does this present a better correlation with the spot price? Why are the abundances on Earth so different than the abundances in the solar system as a whole? 5.) (Slide 10) To finish the discussion of the precious metals, show the timetables for running out of certain elements. What are some ways society could mitigate the potential effects of running out of important elements?
Questions	• Are all elements created equal? What makes some elements more valuable than others? • For the precious metals used as an example here, how would it affect our lives if they didn't exist on Earth? • Why are the abundances on Earth so different than the abundances in the solar system as a whole? • What are some ways society could mitigate the potential effects of running out of important elements?
Summarize (20 minutes)	
Communicate	*(Teacher Tip: Activity 1.3 & 1.4 can be interchanged if you wish to do the assessment in class. Both address questions students should have at the end of the Exploration. The assessment can also be assigned as homework or used as an exit card).* Activity 1-3. Exploring the Phenomenon 1.) Post the large version of *Abundance of the Elements in the Solar System* at the front of the room and inform students that for the next several lessons they will be exploring this data. Have them work with a partner and write down somethings they notice about the data. What patterns do they see? In a class discussion make a record of the patterns the students have noticed. Do they have any explanations for the patterns?

	2.) What questions do students have about the data that cold be answered by further investigation? Record everyone's questions. Do they have any ideas for investigations that could help answer the questions? Some questions students are likely to come up with are: • Why is hydrogen (and helium) so much more abundant than anything else? • Why is Li, Be, B so low compared to the neighboring elements? • Why is Fe higher than its neighbors? • Why are there bumps in the abundances above Fe? • Why is there a zig-zag pattern? *(Teacher Tip: The unit is set up to explore these question from the lowest mass elements up to the highest mass elements. Try to steer the students towards exploring it in that order. Keep the list of questions in the front of the room with the abundance poster during the unit. Each day students should add new questions.)* Activity 1-4. Space Mining, Inc. (ASSESSMENT) 1.) (Slide 11) To close out the lesson, show the students this video about Asteroid Cruithne, a near-earth asteroid. 2.) Pass out the Lesson 1 Assessment Card. Students can write a paragraph in their notebook or turn in a paragraph as an exit card.
Terminology and Concepts to Solidify	Abundance - a measure of the occurrence of the element relative to all other elements in each environment. Abundance is measured in one of three ways: by the mass-fraction (the same as weight fraction); by the mole-fraction (fraction of atoms by numerical count, or sometimes fraction of molecules in gases); or by the volume-fraction (for mixed gases).
Connection to Big Ideas (Phenomena)	The data on abundances is the big idea for the unit. The class will be revisiting it as they explore the formation of the elements at various locations and times in the universe.
Follow Up/Practice	Students might want to explore more about asteroid mining. A link to a video about the company Planetary Resources, Inc. is listed on the Lesson 1 Assessment card to get them started. See optional extension.
Optional Extension	Have students organize into larger groups (optimal 3-4) and collect a Task Card for a project to develop a model of a periodic table that will reflect elemental abundances. These can be presented orally or displayed in class.
Assessment	Activity 1-4. See lesson 1 Assessment Card for rubric.

NAME______________________________

'We are Made of Starstuff'

UNIT PRE-ASSESSMENT

Referring to the periodic table of the elements, give your best guess to the following questions:

1. Are the abundances (amount) of all the elements the same?
    a. On earth?
    b. Throughout the solar system?
    c. Beyond the solar system?
    d. Why or why not?
2. What is the most abundant element on earth?
3. What is the most abundant element in the Sun?
4. Do all elements occur naturally?
5. Why are there so many elements in the periodic table? Where did they come from?

RUBRIC FOR PRE & POST ASSESSMENT

'We are Made of Starstuff'

Name:__________________ **Score______/12**

	3 pts.	2 pts.	1 pts.	Score	Comments
Use of terminology	Most terms are used appropriately to show meaning	Some of the terms are used appropriately to show meaning	Few terms are used and/or are used incorrectly		
Nuclear Processes	Evidence of nuclear processes in the cosmos are included in a way that shows an understanding of the types and range of properties	Evidence of nuclear processes are mentioned but no details given	No evidence or incorrect evidence of nuclear processes in the cosmos		
Live Cycle of stars	The life cycle of our sun and other stars are included in a way that shows and understanding of the processes taking place	The life cycle of our sun and/or other stars are mentioned but no details given	No discussion or incorrect discussion of the life cycle of our sun and other stars		
Nuclear Astrophysics Studies	Experimental studies of nuclear astrophysics are included in a way that show understanding of work happening in the field	Experimental studies of nuclear astrophysics are mentioned but no details given	No discussion or incorrect discussion of Experimental studies of nuclear astrophysics to give evidence for our understanding		

Lesson 2, *In the Beginning: The Early Universe*

ACTIVITY 2-1. The Big Bang Theory

Questions	What we Figure out	New Questions
Why is there so much hydrogen?	After the initial Big Bang event, energy transformed into particle pairs which annihilated back to pure energy. As the universe started cooling, particles survived, synthesizing nuclei, and finally atoms.	Can this theory explain why there is so much hydrogen in the universe?

ACTIVITY – Students explore the Big Bang theory (lesson phenomenon) and generate questions about it and what it has to do with the formation of elements. They also make sense of the term nucleosynthesis, which will be used throughout the unit.

ACTIVITY 2-2. Modeling Big Bang Nucleosynthesis, Part 1

Questions	What we Figure out	New Questions
Can this theory explain why there is so much hydrogen in the universe?	The formation of hydrogen and helium can be described by the Big Bang Nucleosynthesis (BBN) model within the Big Bang Theory.	Does our simple BBN model explain the H/He ratio in the Big Bang Theory?

ACTIVITY – Within the Big Bang Theory, students will explore the transition from pure energy to the first nuclei (Big Bang Nucleosynthesis) in the first 3+ minutes of the universe. They will explore the role of neutron decay in the model.

ACTIVITY 2-3. Modeling Big Bang Nucleosynthesis, Part 2

Questions	What we Figure out	New Questions
Does our simple BBN model explain the H/He ratio in the Big Bang Theory?	Due to the number of neutrons available, He production in BBN is limited to 24%.	What about more massive elements (Li, Be, B)?

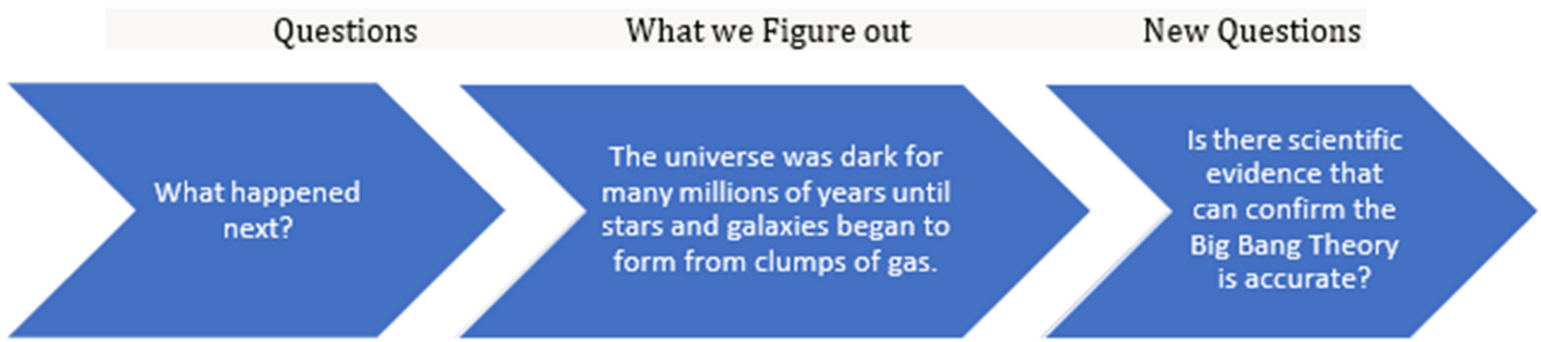
ACTIVITY – Using the game to develop their model, students will explore what parameters could change the ratio of H/He formed during BBN.

ACTIVITY 2-4. Energy and Matter

Questions	What we Figure out	New Questions
What about more massive elements (Li, Be, B)?	Mass-energy conservation, including the binding energy of a nucleus, limits production of heavier elements.	What happened next?

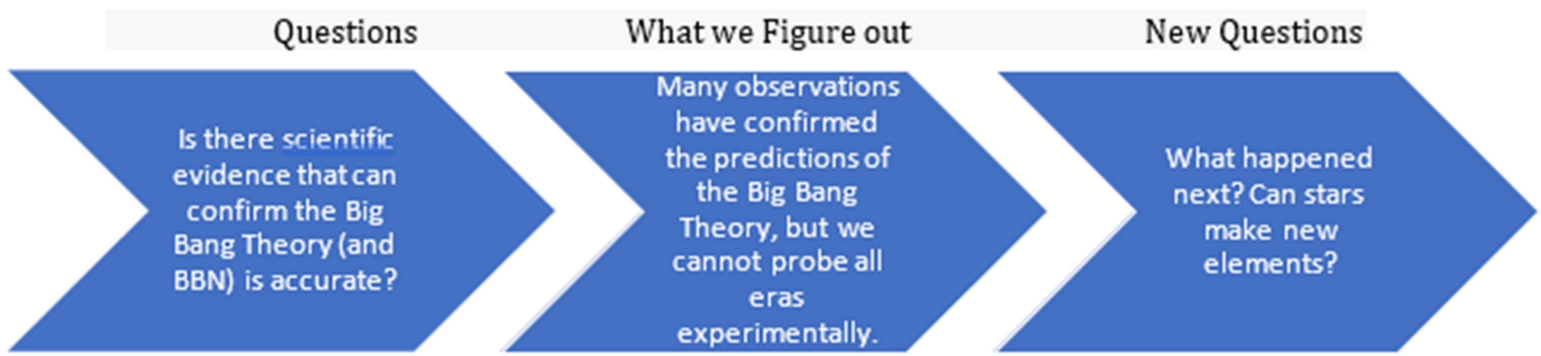
ACTIVITY – Students investigate the energetics of the fusion reactions that could lead to heavier elements in the Big Bang and construct explanations as to why most of the universe was comprised of hydrogen and helium at this time.

ACTIVITY 2-5. From nuclei to atoms to stars



ACTIVITY – Using mathematical representations of gravitational and electromagnetic interactions, students explore models for the formation of the first atoms and stars, 100 million to a billion years after the Big Bang.

ACTIVITY 2-6. Connecting to evidence



ACTIVITY – Students research evidence for the BBN model and communicate using claims, evidence and reasoning. (Lesson Assessment)

Lesson 2	In the Beginning: The Early Universe?
Overview Standard(s) & Objectives	*This lesson is designed for two 50-minute class periods or one block period. The assessment for the lesson is a research piece which can be done outside of class or could take an additional class period. The structure and flow of the lesson is given at the beginning of the Background Material section. DCIs, SEPs and CCCs for each activity are color-coded.* **Performance Expectations:** HS-PS1-8: Develop models to illustrate the changes in the composition of the nucleus of the atom and the energy released during the processes of fission, fusion, and radioactive decay. HS-PS2-4. Use mathematical representations of Newton's Laws of Gravitation and Coulomb's Laws to describe and predict the gravitational and electrostatic forces between objects. HS-ESS1-2: Construct an explanation of the Big Bang Theory based on astronomical evidence of light spectra, motion of distant galaxies, and composition of matter in the universe. **Disciplinary Core Ideas:** • PS1.C Nuclear Processes • PS2.B Types of Interactions • ESS1.A The Universe and Its Stars **Scientific and Engineering Practices:** • Developing and Using Models • Using mathematical representations and computational thinking • Constructing Explanations and Designing Solutions **Crosscutting Concepts:** • Energy and Matter • Patterns **Lesson Phenomenon:** • The Big Bang Theory poster **Lesson Objectives:** I. Students explore the Big Bang theory (lesson phenomenon) and generate questions about it and what it has to do with the formation of elements. They also make sense of the term nucleosynthesis, which will be used throughout the unit. II. Within the Big Bang Theory, students will explore the transition from pure energy to the first nuclei (Big Bang Nucleosynthesis) in the first 3+ minutes of the universe. They will explore the role of neutron decay in the model. III. Students will investigate what parameters could change the ratio of H/He predicted by the BBN model. IV. Students investigate the energetics of the fusion reactions that could lead to A>4 in BBN and draw conclusions as to why most of the universe was comprised of hydrogen and helium at this time. V. Using mathematical representations of gravitational and electromagnetic interactions, students explore models for the formation of the first atoms and stars

	100 million to a billion years after the Big Bang. VI. Students research evidence for the BBN model and communicate using claims, evidence, and reasoning scaffolding.
Background Information and Reference Material	**Structure of Lesson:** 6. (LAUNCH) In Activity 2-1, *The Big Bang Theory,* students are introduced to the Big Bang Theory as the most widely accepted theory for the evolution of the universe. The poster representation of the theory is the phenomenon for the lesson and will be tied back to the anchoring phenomenon (data of solar system abundances) throughout the lesson. Students will make observations and ask questions about the Big Bang Theory based on the poster and explore the first microsecond of the universe. They will discuss key concepts (mass-energy equivalence (binding energy); conservation laws) that will be used in modeling activities later. 7. (EXPLORE A&B) Activities 2-2 and 2-3, In *Modeling Big Bang Nucleosynthesis, Parts 1&2,* students model the fusion reactions that create nuclei with more than one nucleon (neutron or proton), incorporating the role of temperature and energy in the early universe. They then plan their own investigation as a class to explore parameters within the model that could affect the number of elements made. They compare their results with the predictions of Big Bang Nucleosynthesis theories. *(Teacher Tip: For schools with a 50-55 minute class period, the end of Activity 2-3 is a natural stopping point for Day 1 of this lesson.)* 8. (SUMMARIZE B) In Activity 2-4, *Energy and Matter,* students are introduced to the crosscutting concept of binding energy and use conservation laws to construct explanations for why nuclei heavier than helium are seldom created in BBN. These major crosscutting concepts around the topics of energy and matter are introduced here and will be returned to throughout the unit. 9. (EXPLORE C) In Activity 2-5, *From Nuclei to Atoms to Stars,* students use mathematical representations of Coulomb's law and Newton's Law of Gravitation to develop simple models to describe and predict the evolution of the universe from hydrogen and helium nuclei to atoms and finally to stars. 10. (SUMMARIZE C) In Activity 2-6, *Connecting to Evidence,* students work in groups to research and communicate key evidence that lead most scientists to accept the Big Bang Theory as the most likely explanation for how matter and energy evolved from the early universe to the structures we have today. The product of the research constitutes the assessment for this lesson. **Content information for teachers:** See the unit primer for Lesson 2. **Examples of student work**: *Summary of information on back of cards:*

1) *10 billion degrees – p and n move freely and do not interact*
2) *1 billion degrees (100 sec) – deuteron (d) forms from p+p or p+n; triton (3H) forms from d + n*
3) *< 1 billion degrees (200 sec) – the following reactions can occur*
    1. *3He: from p+d;*
    2. *4He: from 3He+n or 3H+p or 3He + d*
    3. *7Be: from 3He + 4He*
    4. *7Li: from 7Be + electron*

The reactions included in the modeling activity are given in Table 2.1.

Table 2.1. BBN Reactions

100 seconds (10^9 K)	200 seconds ($<10^9$ K)
p + p → 2H + e+ + v	p + 2H → 3He
p + n → 2H	3He + n → 4He
n + 2H → 3H	2H + 3He → 4He + p
	2H + 3He→ 4He + n + e+
	3H + p → 4He
	3He + 3He → 4He + 2p
	3He + 4He → 7Be
	7Be + e- → 7Li
	7Li + p → 4He + 4He

Activity 2-4, Energy and Matter

SUMMARIZE

The table the students put on the board should look like Table 2.1. Students will discuss the role of deuteron formation in nucleosynthesis and what would happen of deuterons could form much earlier and much later. But why did deuterons form at 100 seconds, and not 10 seconds or 1000 seconds?

References:

- The *Kinesthetic Big Bang* activity was adapted from a NASA booklet, *What is your Cosmic Connection to the Elements,* which is included on the unit media, or can be found at https://www.nasa.gov/pdf/190387main_Cosmic_Elements.pdf.
- The information about the Big Bang eras is taken from Sky and Telescope online blogs at http://www.skyandtelescope.com/astronomy-resources/how-did-the-universe-begin-happened-big-bang/
- The Attribute table is taken from the Universe Adventure website, at http://universeadventure.org/index.html. Additional information is available here about the various eras of the Big Bang.

Materials

For all activities:

- Lesson 2 PowerPoint

Launch (Activity 2-1)

For each pair of students:

- Big Bang graphic (laminated)

Explore (Activities 2-2 and 2-3) and Summarize (Activity 2-4) For

classroom:

	• Set of Element Cards: ○ Proton (^1H) ○ Neutron (n) ○ Deuteron (D = ^2H) ○ Triton (T = ^3H) ○ Helium-3 Nucleus (^3He) ○ Helium-4 Nucleus (^4He) ○ Beryllium-7 Nucleus (^7Be) ○ Lithium-7 Nucleus (^7Li) ○ 1 ping-pong ball • Laminated temperature signs: ○ 1 billion K (or 1,000,000,000 KELVIN or 10^9 KELVIN) ○ 10 billion K (or 10,000,000,000 KELVIN or 10^{10} KELVIN) ***Explore (Activity 2-5)*** ***For each pair of students:*** • Activity 2-5 task card • ^Computer with access to *Gravity Simulator* software (download to give more flexibility to students) ***Summarize and Assess (Activity 2-6)*** ***For each group of 3-4 students:*** • Lesson 2 Assessment card (one of three kinds) • ^Access to computer • ^Poster paper (optional)
Prior Knowledge	• From middle school standards, students should have a basic understanding that the concept of energy cuts across all science disciplines and energy is conserved in a system and atoms are conserved in chemical reactions. These conservation laws will extend to the nuclear and particle regime in this and following lessons.
Launch (15 minutes	
Engagement and Communication of Student Expectations	**Activity 2-1. The Big Bang Theory** 1) As students come in have the Big Bang Theory television theme song playing. Have the question of the day highlighted on the list of questions the students had. 2) (Slide 2) Write the question of the day on the board or highlight it in the list (*Why is the solar system mostly hydrogen?*) Remind students that starting today we are exploring the question about why the solar system is mostly hydrogen and we will start at the beginning by exploring the most widely accepted theory for the evolution of the universe, the Big Bang Theory (BBT). Over the next few days, we will also be exploring the evidence that has led scientists to accept BBT as the most likely scenario for the beginning of the universe. 3) (Slide 3) Pass out the Big Bang posters to each pair of students. Give them a few minutes to study the poster with their partner. A more detailed version of the chart is in the PowerPoint; students may wish to refer to it. Have them write observations and questions they have in their notebooks. 4) Starting with the earliest times in the Big Bang, have students report out on things

that they notice on the poster and questions they have. Record their questions on the board.

5) Do students see the ingredients of a hydrogen atom on the poster? (If necessary, review atomic structure and the definition of an isotope (Slide 4)). Have each pair of students work together and write down the time and temperature when each ingredient (electron, proton) of a hydrogen atom appears, and when the atom itself appears.

6) Students should have observed that while electrons are made early in time, protons and neutrons are not made until 1 microsecond after the initial event. Also, they should notice that protons and neutrons are formed from other particles. Solicit ideas as to what is happening and why.

7) (Slide 5) Then put-up Slide 5, which compares leptons and baryons and depicts neutrons and protons as each being made up of three quarks. Three fundamental particles make up an atom, up and down quarks, and electrons. Heavier cousins to these particles decay down to these fundamental particles. Solicit student ideas and understanding of what antimatter and what role it plays. Do students see particles in the Big Bang Theory poster that could possibly be antimatter?*(Teacher Tip: As far as scientists know the only difference between a particle and its antimatter partner is the electric charge. In the poster, there are equal numbers of electrons and positrons, a positive electron, in the early universe).*

8) (Slide 6) Among student ideas related to antimatter, some students have probably heard from popular culture that when matter and antimatter meet, it annihilates to pure energy. This is reflected in Einstein's famous equation, $E = mc^2$, called mass-energy equivalence. In the earliest epochs of the Big Bang, when the universe was very dense and very hot, particle/antiparticle pairs could pop into existence from energy, and immediately annihilate back to energy. There should have been equal amounts of particles and antiparticles created and they should have all immediately annihilated.

9) (Slide 7) The video should play automatically on this slide but can be found on the unit flash drive or here. Something happened to cause a slight imbalance of antimatter. The video addresses what scientists know had to have happened. They still do not know what caused the imbalance. This is one of the big physics questions that scientists are still trying to answer: where did all the antimatter go (why do we exist at all)?

10) Have student pairs revisit the Big Bang poster and the observations they made about the period approximately one microsecond (10^{-6} sec) after the Big Bang. What is left? *Protons, neutrons, electrons.* Where are the quarks that were left? What happened to the electrons? Can they draw any conclusions about the make-up of protons and neutrons? *Each is made from three quarks.*

11) (Slide 8) In this period, the universe cooled enough for the strong nuclear force to take over.

12) (Slide 9) One other crosscutting concept that students will need to consider while modeling the Big Bang Theory at these scales are conservation laws. In a class discussion, find out what conservation laws students are familiar with in other contexts? From middle school standards, they should be familiar with energy

conservation. Since at these scales energy and mass are equivalent, then the total mass-energy of the system must be considered. Electric charge is also conserved. Scientists discovered that other quantities are conserved only at the microscopic level, including lepton # and baryon #).

13) (Slide 10) Down quarks are more massive than up quarks (5 versus 2 MeV/c^2), so neutrons (udd) are more massive than protons (uud). By energy conservation, a neutron could decay into a proton and emit energy. Have each pair of students.

14) discuss and propose what other particles might be emitted if a neutron decayed to a proton, that could conserve charge, lepton number and baryon number. Share out in a class discussion. The second part of the PowerPoint slide shows that if a neutron decays into a proton + electron + anti-neutrino, all conservation laws are satisfied. This happens for a 'free' neutron (not inside a neutron). Statistically, a neutron will survive about 10 minutes before it decays.

Explore (15 minutes)

Activity 2-2. Modeling Big Bang Nucleosynthesis, Part 1

1.) (Slide 11) Introduce the vocabulary term, nucleosynthesis. In a class discussion, have students parse out what it means by breaking it down. In the next few activities, students will make sense of Big Bang Nucleosynthesis (BBN) – formation of nuclei during the Big Bang – to begin to answer some of the questions they have about the origin of the elements.

2.) (Slide 12) Introduce the next activity by having students look back at the poster and estimate when Big Bang Nucleosynthesis (BBN) began and ended. Solicit ideas as to why it is possible for complex nuclei to be made at this time? What do they think is the most likely thing to happen first? Why? (*They might think it is equally likely that p+p, n+p, n+n fuse, or if they are familiar with Coulomb's Law, they might think it is more likely for n+p or n+n to fuse.*)

3.) We learned earlier that free neutrons decay into protons (Slide 7) with an average lifetime of 10.3 minutes. Could this have an impact on what happens next? Can they speculate as to what it will be? *(They should figure out that the proton / neutron ratio changes with time and there will be more protons available than neutrons.)*

(Teacher Tip: More advanced students could do the math to get to the curves in Slide 10 but will have to be introduced to the concept of exponential decay. This exercise is included as an optional extension.)

4.) (Slide 13) By the time the universe has cooled down sufficiently for nucleosynthesis of heavier nuclei to begin, there is only one neutron left for every seven protons. The neutrons will continue to decay to protons until the universe has cooled down enough that a neutron and proton can stick together to make a deuteron nucleus (p+n).

5.) Pass out the proton and neutron cards; for every eight students, seven should get proton cards and one a neutron card. Have students look at the information on the back and discuss it as a class. Do they want to refine their estimate on the time when protons and neutrons began to combine to make nuclei? They should record their new thinking.

6.) Move into an open area for the modeling activity sequence. *(Teacher Tips: For the BBN Modeling activity, students will be moving around. The teacher should emphasize the need to be quiet to hear the directions. If possible, move to a large classroom, outside, hallway, or gym. Distribute the game cards. If you have a a large class, assign 1-2 students to help exchange cards during fusion events as the game progresses.)*

A. To begin, students arrange themselves in a tight central group representing the matter that emerges in the first second, a soup of elementary particles. Students in the model represent parts of forces that will explode apart to become protons (p's or normal H nuclei) and neutrons (n's). The teacher will handle the temperature cards and have student helpers to pass out heavier nuclei cards. Students have cards with names or formulas: p or n, Students hide all cards, since there are no elements before the Big Bang. If indoors, turn out the lights, representing the absence of electromagnetic energy before the Big Bang.

B. When the lights are turned on, the teacher or a student calls "Big Bang" and holds up the temperature sign with **10 BILLION DEGREES K**. Students hold up either the **PROTON** card or **NEUTRON**. Students start moving out from the dense center.

C. Some students should encounter (that is, safely bump) other students. The "particles" should not stick together.

D. Allowing time for the students to move and expand out a short way (which may be as short as 15 seconds in real time), the teacher gives the cue call of "100 seconds." The teacher pulls away the 10 BILLION K and sticks up **1 BILLION K**. Students hold their signs and continue to move outward. When two **PROTONS** meet, the two students decide if they want to bounce away or stick by locking arms to form a Deuteron nucleus. Then these students exchange their PROTON cards for a **DEUTERON (^{2}H)** card. Pairs representing Deuteron continue moving outward to encounter other **PROTONS**. Pairs representing Deuteron cannot stick to other single or couples of students until the next time cue is given (at step 6). The reaction is: p + p D + positron + neutrino.

E. A **PROTON** and **NEUTRON** may also decide to stick together to form **DEUTERON**. Those students can exchange their card for a **DEUTERON** card. This reaction is p + n D.

F. If a **DEUTERON** bumps into a **NEUTRON** and they join, **HYDROGEN 3** is formed. The three students should h lock arm) and exchange their cards for a 3 H. The reaction is: D + n → 3H

G. After seeing that students have started forming **DEUTERONS** and some **3H**, the teacher gives the cue call of "200 seconds." The **DEUTERON** couples do not have to join to other single or couples of students when they bump. However, now students can join if they wish. For a **DEUTERON** sticking to a free **PROTON**, the three students should all link arms, and turn in their cards, for a **HELIUM-3** (3He) card. This reaction is: D + p → 3He

	H. If two 3-Hes meet, only four of the six students should link, and trade their cards for a **HELIUM-4** (4He) card; the other two students should pick up a **PROTON** cards and go off on their own. This reaction is 3 He + 3 He → 4 He + p + p. I. Other possible reactions to produce 4 He are: 3 He + D → 4 He + p; 3 He + D → 4 He + n + positron; 3 He + n → 4 He 8. J. The teacher directs one of the remaining **HELIUM-3** (3 He) join with a HELIUM 4 (4 He). The teacher gives them the **BERYLLIUM-7** (7 Be) card, the **LITHIUM-7** (7 Li) card and a ping-pong ball representing an electron (e-). First this group should hold up the **BERYLLIUM-7** (7 Be) card and the ping-pong ball (e-). They then touch the **BERYLLIUM-7** (7 Be) to the electron, forming LITHIUM 7 (7 Li). They should then hide the **BERYLLIUM—7** (7 Be) card and the ping-pong ball, and hold up the **LITHIUM-7** (7 Li) card. This reaction is 3 He + 4 He → 7 Be, followed by 7 Be + e - → 7 Li *K.* The teacher gives the cue call of "End". Students freeze in position with their cards held up so that all can see what has occurred. Someone should record the number of different particles formed in your classroom BBN on the board. *(TEACHER TIP: Because students may want to stick more often than what correctly models the early universe, most likely, the outcome will be wrong. This will be addressed in the next investigation.)*
Questions for Student Exploration	• How does 'freezing' the motion at the end of the activity represent what's happening in the Big Bang Theory? • How are the numbers of particles and atoms we have formed different from what is predicted by BBN? • Why can't the groups keep combining like they did in this activity to form all the elements heavier than hydrogen, helium, and lithium?
Summary (5 minuts)	
Communicate	(Slide 14) Facilitate a class discussion to describe what was happening in their modeling activity. Why did nucleosynthesis end? What limited the formation of elements heavier than helium? As a class, record the results of the modeling activity in Row 1 of the table on Slide 11 and discuss reasons that the modeling in the game gives different results than the theory. What variables might lead to the discrepancies? Ask the students to think back. How did they decide whether to fuse with another nucleus or not? Did they choose one way more often than the other? As a class, can they come up with an investigation to determine whether this variable is important to the final abundances? Were there other variables that might affect the results?
Exploration (15 minutes)	
Facilitate	**Activity 2-3. Modeling Big Bang Nucleosynthesis, Part 2** 1) (Slide 11) Reset the game and run it one or more times under the conditions the class decided for their investigation. Record ratios in the table on Slide 14. *(Teacher Tip: One Example of a more rigorous challenge is given below, but the students should be*

	strongly encouraged to come to consensus on their own investigation and set it up). a. Reset the cards to the original proton/neutron ratio and run the model again. This time, when the teacher calls out 100 seconds and holds up the 1 billion K sign, students should count how often they meet another nucleon. They should only fuse every fifth time. Run the game this way until the teacher calls 200 seconds and freeze-out. Everyone hold up their cards and record the distribution of particles. Is it different? b. Repeat the game one more time. This time, nucleons should only fuse every 10^{th} time they meet. Record the distribution again. Is it different? Why should it matter how often the nucleons are allowed to fuse? Did students notice something different about the game in the three cases they ran? Have the students keep their cards at the end. 2) Were students able to find a set of parameters that gave the H/He ratio from the Big Bang theory? Did the parameter(s) they investigated change the results significantly? If not, can they suggest another scenario and try again? Is there a reason they can see that restrain the results to the ration predicted by the theory? 3) (Slide 12) How do these numbers compare with the abundance of hydrogen and helium in the solar system? Can students suggest reasons why they might be different? *(Teacher Tip: At first glance, students will probably use the abundance numbers directly from the chart and calculate 92% H / 7% He. However, one must consider that each 4He nucleus contains 4 nucleons. Taking that into account, the numbers are 76%/24%, just as the Big Bang Theory predicts.)*
Summary (15 minutes)	
Communicate	**Activity 2-4. Energy and Matter** 1) (Slide 15) Why was there so little Li, Be or heavier nuclei made in the Big Bang? Using reactions listed on the back of the game cards, make a table on the board for the reactions occurring at 100 seconds and 200 seconds (the two temperature regimes). Starting with the proton cards, have students write the reactions on the board. What do they notice about the two columns? Why do students think there so many more possible reactions as the universe cooled down? Is there one isotope that must form first before anything else can? *(2H - Deuterons)* 2) Working in pairs, have students discuss and speculate on two scenarios: 1. Deuteron began forming at 10 seconds after the Big Bang instead of 100 seconds as the game cards state. 2. Deuteron did not begin forming until 1000 seconds after the Big Bang. How might Big Bang Nucleosynthesis have proceeded in these two cases? Would the universe be different? Have groups share out what they think would be different in these two scenarios. *(There would be many more neutrons in the first case and close to zero in the second case. In the latter case, atoms as we know them would not exist)* 3) (Slide 16) Why is 100 seconds the magical time for when deuteron formed? The nuclear binding energy is defined as the mass of the constituent protons and neutrons minus the mass of the nucleus. The higher the binding energy, the more stable is the nucleus.

4) (Slide 17) Working in pairs, students should do the exercise of calculating the binding energy for a deuteron and for a 4-helium nucleus.

5) (Slide 18) The binding energy of all the light elements are given here. What is the least stable (d)? The most stable (4He)? These numbers have two major effects on the BBN theory. What else do students notice about this list? (*No A=5)*

6) (Slide 19) Since there are no mass 5 nuclei for proton fusion to proceed through, how were heavier things made. Look at the reactions that can jump over A=5 to make Li-6 or Be-7. Do they happen very often in the BBN model?

7) (Slide 20&21) Why are some nuclei more stable than others? Scientists puzzled about this for decades until they understood that there is nuclear shell structure, like the electron shells of an atom.

8) (Slide 22) Summarize BBN in the Big Bang Theory. If time permits, have each pair of students create a timeline of the first 3 minutes and 45 seconds of the Big Bang

9) in their notebooks, computers, or on larger pieces of paper. Students with access to computers can use the JinaWeb BBN movie/game to test their understanding of the BBN model.

Exploration (25 minutes)

Activity 2-5. From Nuclei to Atoms to Stars

1) (Slide 23) Ask students to remind you where they left off in the previous activity. At the end of the first few minutes of the Big Bang, the universe was 75% hydrogen nuclei, 25% helium nuclei, some free electrons, and very little else. Compare that with the abundance graph we have been using. Does the Big Bang tell the whole story about the formation of the elements?

2) (Slide 24) Facilitate a class discussion of when atoms can form. What would it take to form a neutral atom from a hydrogen or helium nucleus? Have students give their opinions, then introduce the formula for the electromagnetic interaction. Can students calculate the strength of interaction between an electron and a proton in a hydrogen atom? (Work through the formulas as a class or have them do them in their notebooks.)

3) (Slide 25) When BBN took place, the universe still had too much energy (0.1 MeV) for an electron to stick. It took another 380,000 years for it to cool down enough so that atoms could form.

4) (Slide 26) At the point light was released, photons could escape the early universe and the universe was no longer opaque. Those original photons are present today in the 'cosmic microwave background', another piece of evidence for the Big Bang Theory.

5) How did we get from atoms to the first stars? Now the universe is filled with isolated neutral atoms; the electromagnetic force between atoms is negligible. Photons are not emitted so the universe is dark. What happens next? What other fundamental interaction could become important? *Gravity*.

6) (Slide 27) Facilitate a class discussion of whether or not students think gravity could make stars from atoms during this period? Remind students of the equation for the

	Law of Universal Gravitation and have them note similarities/differences with Coulomb's Law. As a class, have them fill in the table on the slide. 7) Have the students work in pairs on computers and distribute Task Card 2-5 which introduces the gravity simulator (http://www.testtubegames.com/gravity.html). Using PART A of the task card, students will set up their model of the universe with the H/He ratio at the end of the Big Bang. Can they get a random or uniform field of hydrogen and helium atoms to fall together into stars? *(TEACHER TIP: Students might need reminding that the 75%/25% H/He ratio was by mass.)* 8) (Slide 28) After students try to make stars out of their hydrogen/helium universe, have students make sense of why or why not it is working? What did they try and what happened? Based on the gravitation equation, why do they think stars aren't forming? Using PART B of the Task Card, have them introduce a new particle to their model universe - a heavy mystery particle. What happens then? What happens as they vary the mass of the mystery particle (leaving the mass 'census' at 63%)? Can they get mass to collapse into bigger objects? 9) Play the video in the PowerPoint which shows a supercomputer generated simulation, based on gravitational equations for the formation of the Milky Way galaxy. The video is also available here. (*TEACHER TIP: This video was in a format that could not be downloaded for the flash drive and is only available on YouTube.)*
	Summary (10 minutes + homework)
Communicate	**Activity 2-6. Connecting to Evidence** 1) (Slide 27) What evidence is there today – 13.7 billion years later - for BBN in the first 3 minutes of the universe? Discuss as a class what kind of evidence they think scientists could find to show that the timeline they have constructed is accurate. Break into groups of 3-4 students; each group will research one of three kinds of evidence for BBN (***Lesson 2 Assessment Card):*** 1. Light spectra 2. Motion of distant galaxies 3. Composition of matter *(Teacher Tip: There are resources on the assessment cards to get students started. They should present their results (in poster format or oral presentation) in the form of Claim, Evidence, Reasoning.)*
Terminology and Concepts to Solidify	Antimatter - **Antimatter** is composed of antiparticles. Each particle of matter has a corresponding antiparticle of antimatter. The antiparticle of an electron is known as a positron, and the antiparticle of the proton is called an antiproton (made up of antiquarks). Antimatter has the same mass as its matter partner, but opposite charge. Baryon – A **Baryon** is any of a family of subatomic particles composed of three quarks or three antiquarks. Big Bang Nucleosynthesis – Within the Big Bang theory, **Big Bang Nucleosynthesis** (BBN) the process by which the first nuclei were formed between 100 seconds and three minutes after the singularity that began the Big Bang. Big Bang Theory – The **Big Bang Theory** is a generally accepted theory for the

beginning of the universe, a transition from conditions of unimaginable density and temperature to conditions of lower density and temperature.

Binding Energy - The **binding energy** of a nucleus is the energy that holds a nucleus together and is equal to the mass of the nucleus minus the total mass of the individual protons and neutrons that make up the nucleus.

Conservation Laws - In physics, a **conservation law** states that a particular measurable property of an isolated physical system does not change as the system evolves over time. In classical physics, laws of this type govern energy, momentum, angular momentum, mass, and electric charge. In particle physics, other conservation laws apply to properties of subatomic particles that are invariant during interactions.

Cosmology – **Cosmology** is a branch of physics which studies the history, structure, and fate of the universe.

Coulomb's Law - **Coulomb's Law** is a law of physics that describes the interaction between electrically charged objects. This law states that the electrostatic force between two objects is proportional to the product of the charge of each of the objects and inversely proportional to the square of the distance between these two objects.

Dark Ages – The **dark ages** occurred in Big Bang cosmology after recombination. The universe was transparent and had cooled enough to allow light to travel long distances, but there were no light-producing structures such as stars and galaxies.

Dark Matter - Roughly 80 percent of the mass of the universe is made up of material that scientists cannot directly observe. Known as **dark matter**, this bizarre ingredient does not emit light or energy.

Free Neutron Decay – A **free neutron** (outside a nucleus) lives approximately 14.5 minutes, decaying to a proton, an electron, and an antineutrino. A down quark inside the neutron has decayed into an up quark in the process.

Fundamental (Elementary) Particles - In particle physics, an **elementary particle** or **fundamental particle** is a particle whose substructure is unknown; thus, it is unknown whether it is composed of other particles. In the Standard Model, there are two families of fundamental particles: quarks and leptons (which include the electron).

Isotope - **Isotopes** are forms of the same element that contain equal numbers of protons but different numbers of neutrons in their nuclei, and hence differ in relative atomic mass but not in chemical properties. Isotopes can be stable or radioactive.

Lepton – **Leptons** are a family of fundamental particles within the standard model of particle physics. Leptons have half-integer spin (spin $\frac{1}{2}$) and does not undergo strong interactions. Leptons can be charged (electron, muon, tau) or neutral (neutrinos).

Magic numbers - When all the protons or neutrons in a nucleus are in filled ***shells***, the number of protons or neutrons is called a "magic number." Some of the magic numbers are 2, 8, 20, 28, 50, 82, and 126.

Mass-Energy Equivalence – **Mass-Energy Equivalence** is the physical principle that a measured quantity of energy is equivalent to a measured quantity of mass.
The equivalence is expressed by Einstein's equation $E = mc^2$, where E represents energy, m the equivalent mass, and c the speed of light.

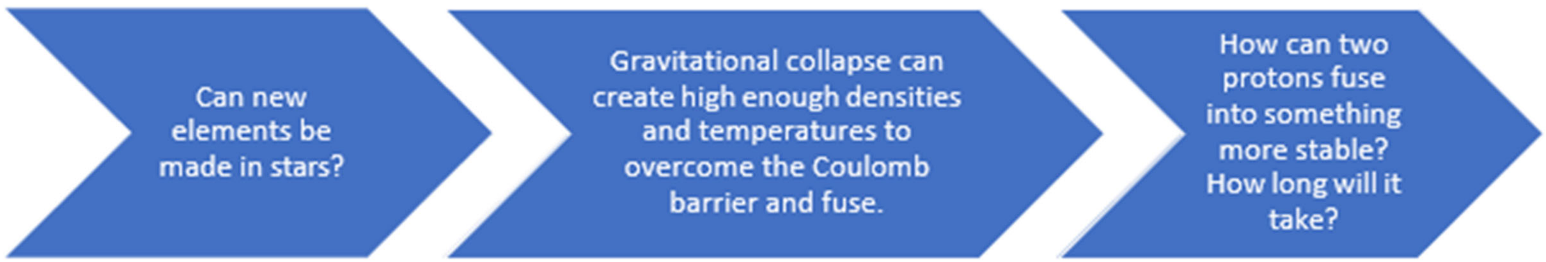
	Newton's Law of Universal Gravitation - **Newton's law of universal gravitation** states that a particle attracts every other particle in the universe with a force which is directly proportional to the product of their masses and inversely proportional to the square of the distance between their centers. Nuclear Mass – The mass of an atomic nucleus, which is usually measured in atomic mass units. It is less than the sum of the masses of its constituent protons and neutrons by the binding energy divided by the square of the speed of light. Nuclear Shell Model - A model of the atomic nucleus which uses the Pauli exclusion principle to describe the structure of the nucleus in terms of energy levels. Nucleosynthesis - **Nucleosynthesis** is the process that creates new atomic nuclei from pre-existing nucleons, primarily protons and neutrons. Pair Annihilation - **Pair annihilation** is an inverse process to pair production, in which a particle and its antiparticle collide and annihilate each other, the total energy of the two particles appearing as electromagnetic radiation. Pair Production - **Pair production** is a phenomenon of nature where energy is converted to mass. Energy is converted to a particle and its antiparticle partner. Quark – **Quarks** are a family of fundamental particles within the standard model of particle physics. Quarks combine to form composite particles called hadrons, the most stable of which are protons and neutrons, the components of atomic nuclei. There are six quarks (up, down, strange, charm, top and bottom). Recombination - In cosmology, **recombination** refers to the epoch at which charged electrons and protons first became bound to form electrically neutral hydrogen atoms. Reionization – In the Big Bang Theory, **reionization** ended the Dark Ages. This was a phase change that occurred once objects started to condense in the early universe that was energetic enough to re-ionize neutral hydrogen. The Standard Model - The **standard model** is the name given in the 1970s to a theory of fundamental particles and how they interact. It incorporated all that was known about subatomic particles at the time and predicted the existence of additional particles as well. Strong Nuclear Force - The **Strong Nuclear Force** (also referred to as the **strong force**) is one of the four basic forces in nature (the others being gravity, the electromagnetic force, and the weak nuclear force). As its name implies, it is the strongest of the four. However, it also has the shortest range, meaning that particles must be extremely close to feel it. The strong force is responsible for holding the quarks together to make protons and neutrons and for holding the nucleus together. In the Standard Model, the strong force is 'mediated', or carried, by a particle called a gluon. Weak Nuclear Force - In particle physics, the **weak interaction** (the **weak** **force** or **weak** nuclear **force**) is the mechanism of interaction between sub-atomic particles that causes radioactive decay, such as the decay of a neutron into a proton.
Connection to Big Ideas (Phenomena)	The formation of atoms and nucleosynthesis requires extreme amounts of energy to allow subatomic particles to interact at the nuclear level. These conditions existed at the beginning of the universe after the Big Bang and since then in the evolution of stars.

Follow Up/Practice	**See assessment.**
Assessment	Group research and communication in the form of a poster or oral presentation. Rubric is on the Lesson 2 assessment card.

Lesson 3, *From Stars to Atoms: Stellar Nucleosynthesis*

ACTIVITY 3-1. A Star is Born (LAUNCH)

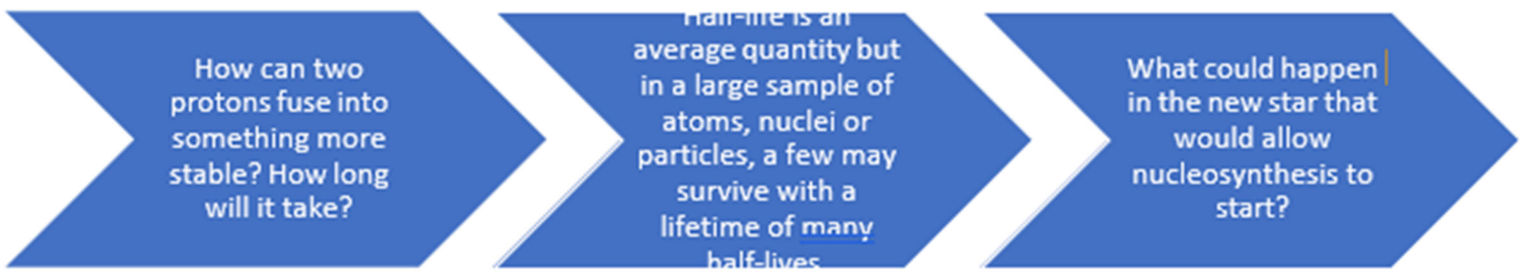
Questions — What we Figure out — New Questions



ACTIVITY – Using the understanding they gained in Lesson 2 about energy and matter, students compare the conditions matter is subjected to during protostar and star formation (lesson phenomenon) with the conditions during Big Bang Nucleosynthesis.

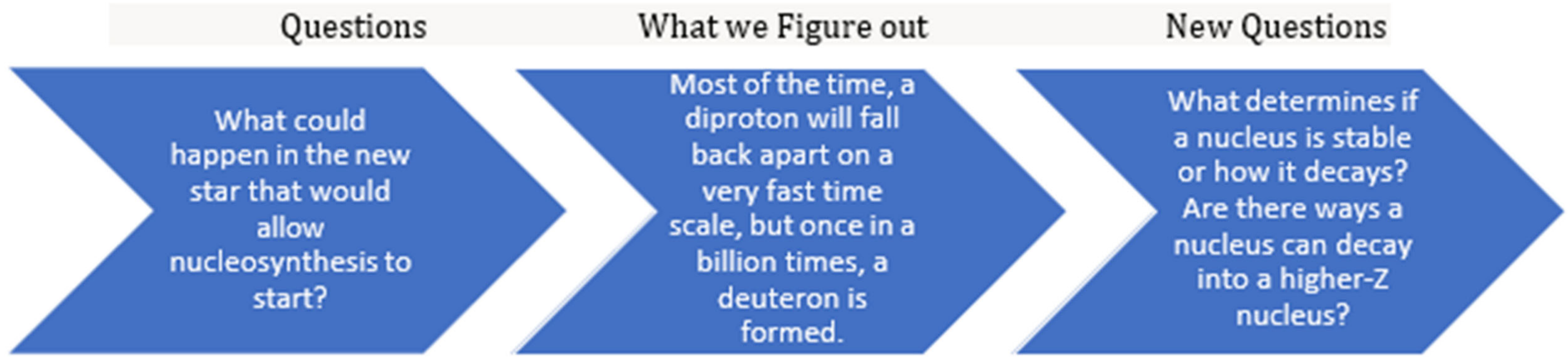
ACTIVITY 3-2. Radioactivity: Lifetime versus half-life (EXPLORE 3a)

Questions — What we Figure out — New Questions



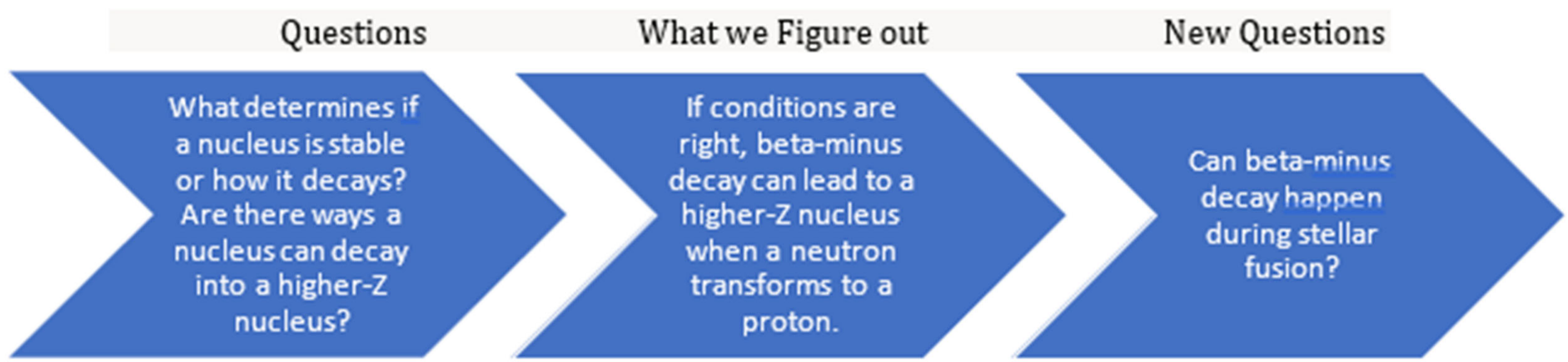
ACTIVITY – Students measure the half-life of a radioactive isotope, plot the data, and use mathematical representations to draw conclusions as to the statistical nature of half-life and the implications for production of new elements.

ACTIVITY 3-3. One in a Billion (SUMMARIZE 3a)



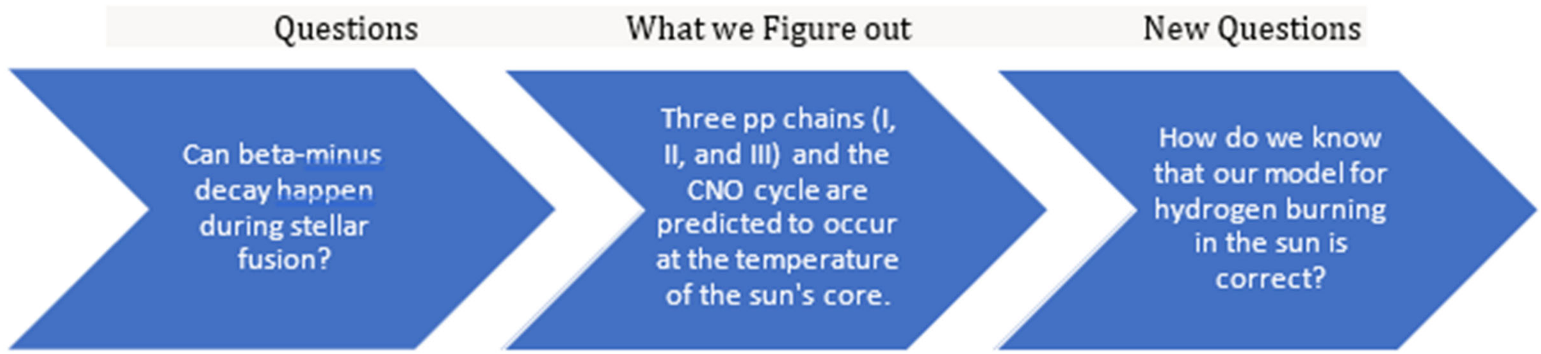
ACTIVITY – In the context of the statistical nature of half-life and the weak nuclear force, students make sense of rare processes that can make neutrons in the sun, a necessary ingredient for nucleosynthesis.

ACTIVITY 3-4. The Nucleosynthesis Game (EXPLORE 3b)



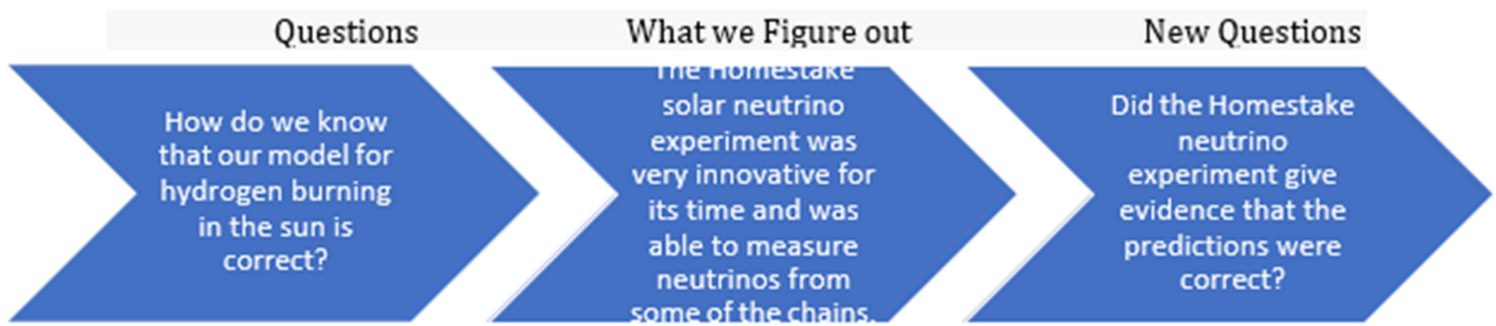
ACTIVITY – Students use the stellar nucleosynthesis game for sensemaking of the chart of the nuclides and the relative stability of nuclei.

ACTIVITY 3-5. Hydrogen burning stars: energy from the sun (SUMMARIZE 3b)



ACTIVITY – Students synthesize their understanding of nuclear fusion and decay into sensemaking of the nuclear reactions taking place in our sun and propose additional reactions that fit the model.

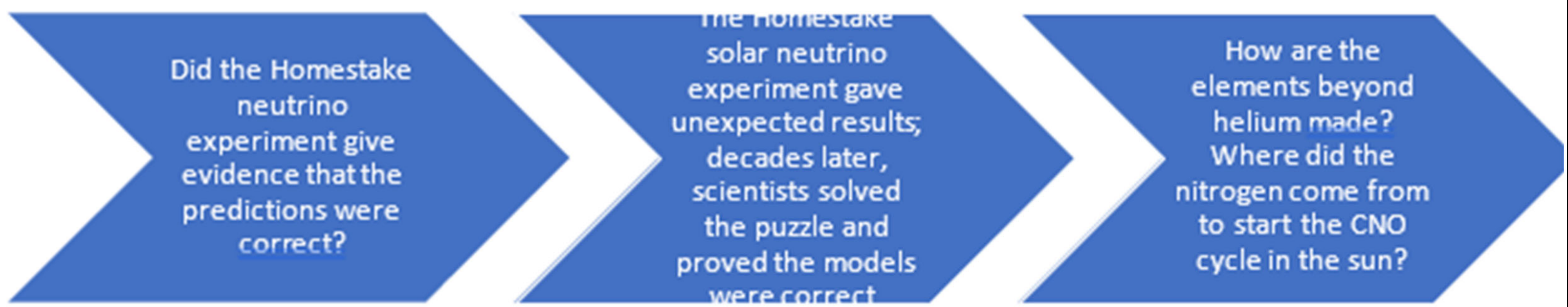
ACTIVITY 3-6. Connecting to evidence – Solar neutrinos (EXPLORE 3c)



ACTIVITY – Students will examine the Homestake solar neutrino experiment and the evidence that it provided for understanding nucleosynthesis in the sun. As part of their sensemaking of the experimental set up, they will plan and investigate on the properties of nuclear beta decay.

ACTIVITY 3-7. The Solar Neutrino Problem (SUMMARIZE 3c)

Questions | What we Figure out | New Questions



ACTIVITY – Students will examine the results from the Homestake solar neutrino experiment and will construct explanations based on Claims-Evidence-Reasoning for why the experiment did not give the results expected by scientists. (Lesson Assessment)

Lesson 3	From Stars to Atoms – Stellar Nucleosynthesis
Overview Standard(s) & Objectives	*This lesson is designed for three 50-minute class periods or two block periods. The structure and flow of the lesson is given at the beginning of the Background Material section. DCIs, SEPs and CCCs for each activity are color-coded.* **Performance Expectations:** HS-PS1-8: Develop models to illustrate the changes in the composition of the nucleus of the atom and the energy released during the processes of fission, fusion, and radioactive decay. HS-PS2-4: Use mathematical representations of Newton's Law of Gravitation and Coulomb's Law to describe and predict the gravitational and electrostatic forces between objects. HS-ESS1-1: Develop a model based on evidence to illustrate the life span of the sun and the role of nuclear fusion in the sun's core to release energy that eventually reaches Earth in the form of radiation. **Disciplinary Core Ideas:** • PS1.C Nuclear Processes • PS2.B Types of Interactions • PS3.D Energy in Chemical Processes and Everyday Life • ESS1.A The Universe and Its Stars **SEPs:** • Developing and using models • Using mathematical representations and computational thinking • Planning and carrying out investigations. **CCCs:** • Energy and Matter • Patterns • Scale, proportion, and quantity **Lesson Phenomenon:** Video of protostar formation and star formation. **Lesson Level Learning Goals:** I. Using the understanding they gained in Lesson 2 about energy and matter, students compare the conditions that matter is subjected to during protostar and star formation (lesson phenomenon) with the conditions during Big Bang Nucleosynthesis. II. Students measure the half-life of a radioactive isotope, plot the data, and use mathematical representations to draw conclusions as to the statistical nature of half-life and the implications for production of new elements. III. In the context of the statistical nature of half-life and the weak nuclear force, students make sense of rare processes that can make neutrons in the sun, a necessary ingredient for nucleosynthesis. IV. Students use the stellar nucleosynthesis game for sensemaking of the chart of the nuclides and the relative stability of nuclei.

	V. Students synthesize their understanding of nuclear fusion and decay into sensemaking of the nuclear reactions taking place in our sun and propose additional reactions that fit the model. VI. Students will learn about the Homestake solar neutrino experiment and the evidence that it provided for understanding nucleosynthesis in the sun. As part of their sensemaking of the experimental set up, they will plan and investigate on the properties of nuclear beta decay. VII. Students will examine the results from the Homestake solar neutrino experiment and will construct explanations based on Claims-Evidence-Reasoning for why the experiment did not give the results expected by scientists. (Lesson Assessment).
Background Information and Reference Material	**Structure of Lesson:** 1. (LAUNCH) Activity 3-1, *A Star is Born* starts with a video of protostar formation, the phenomenon for the lesson. Student return to some of the concepts of Lesson 2, developing questions about the transformation of gravitational potential energy to kinetic energy and the fusion process. They compare and contrast a rudimentary model for this process with that for the BBN process. 2. (EXPLORE) In Activity 3-2, *Nuclear Processes I,* students begin to make sense of competition between different nuclear processes important to nucleosynthesis - the concepts of lifetime and half-life – by collecting half-life data, then analyzing and interpreting the results. 3. (SUMMARIZE) In Activity 3-3, *One in a Billion,* students explore the implications of the statistical nature of half-life as they model the fusion of two protons into a diproton, with one in a billion diprotons undergoing nuclear beta decay to a deuteron, an essential ingredient of nucleosynthesis. *(Teacher Tip: For schools with a 50-55 minute class period, the end of Activity 3-3 is a natural stopping point for Day 1 of this lesson. If there is a little extra time, students can use it to figure out the game (Activity 3-4) ahead of actually playing it the next day.)* 4. (EXPLORE) In Activity 3-4, *The Nucleosynthesis Game*, students utilize magnetic marbles to build nuclei, to help make sense of models of the nuclear fusion processes that build up heavier elements in stars, and the competition between fusion and nuclear decay processes. In this game they are introduced to the Chart of the Nuclides. 5. (SUMMARIZE) In Activity 3-5, *Hydrogen-burning Stars,* students model the pp and CNO processes in hydrogen burning stars, and using energy-mass arguments, propose reactions for making nuclei beyond helium. *(Teacher Tip: for a S schools with a 50-55 minute class period, the end of Activity 3-5 is a natural stopping point for Day 2 of this lesson.)* 6. (EXPLORE) In Activity 3-6, *Connecting to Evidence: Solar Neutrinos,* students use the Homestake Solar Neutrino experiment as a case study for why and how technology enabled large detectors located underground to indirectly measure the presence of solar neutrinos as evidence of nucleosynthesis

	processes in the core of the sun. To make sense of the detection schemes they plan and conduct an investigation of the properties of nuclear beta decay. 7. (SUMMARIZE) In Activity 3-7, *The Solar Neutrino Problem,* students use Claim-Evidence-Reasoning scaffolding to examine two competing claims for the unexpected results of the Homestake Solar Neutrino Experiment. Was the experiment wrong, was the theory wrong, or is there another explanation? Student reasoning based on evidence will be used as the assessment for this lesson. **Content information for teachers:** See the unit primer for Lesson 3.
Materials	***For all activities***: ● Lesson 3 PowerPoint ● ALARA Poster ***Launch (Activity 3-1)*** *no materials needed* ***Explore (Activity 3-2)*** **For the classroom:** ● Cloud chamber (set up ahead of class) ● ^Ice bath (teacher provided) ● ^Isopropyl alcohol or ethanol, >70% (teacher provided) ● Geiger counter (digital) ● Pottery samples (two colors) ● Cs/Ba isogenerator ● Eluting solution ● Bealer ● Non-latex gloves ● Snack size baggies ● chem-wipes **For each small group (3 students optimal):** ● Geiger Counter Handout (Print Master) ● Geiger Counter (analog) ● Activity 3-2 Task Card ● Sample of radioactive material in a sealed baggie (see instructions for generating these from Cs/Ba generator) ● ^Computer with access to EXCEL, a graphing calculator or graph paper ● ^Stopwatch, room clock with second hand or Timer App on computer or tablet ***SUMMARIZE (Activity 3-3)*** *no materials needed* ***EXPLORE (Activity 3-4) and Summarize (Activity 3-5)*** **For each small group (4 student minimum and optimal)**: ● Two nucleosynthesis game boxes (10 each of four color-coded marbles, magnet, dice) ● Game rules chart and Chart of the Nuclides (laminated) ● Activity 3-5 Task Card (per pair of students)

<table>
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EXPLORE (Activity 3-6)
For each small group (3-4 students)

Activity 3-6 Task Card
Geiger counter
Box containing

Beta source and two unknown sources
A set of degraders of varying material and thickness
A ruler and protractor
Clay (for holding sources & degraders)
Binder clips (for holding sources & degraders)

Ruler

SUMMARIZE (Activity 3-7)
For each student

Lesson 3 Assessment card
Set of evidence cards
Reasoning Template (Print Master)

</td></tr>
<tr><td>Prior Knowledge</td><td>This lesson builds on concepts that were introduced in Lesson 2: nuclear fusion reactions, conservation laws, binding energy, electromagnetic and gravitational interactions.</td></tr>
<tr><td colspan="2">Launch (10 minutes)</td></tr>
<tr><td>Engagement and Communication of Student Expectations</td><td>
Activity 3-1. A Star is Born
(Teacher Note: Before class starts, set up the cloud chamber according to the directions in the Materials set up. You will need to provide ice, an ice chest, a source of water and a drain. If cooling is started just before class, it should be operating well by time the students get to it.)
1) (Slide 2) Play the video protostar formation in the Orion Nebula (on the lesson PowerPoint (or at https://www.youtube.com/watch?v=jzkCFMkX-tM). Protostars are the last step before the star begins to shine. Ask students to brainstorm with a neighbor what is happening in the video as the atoms are pulled together by gravity. What will happen on the atomic level? Does the energy of the atoms change? If so, how is that manifested?
2) In a larger class discussion have groups suggest what they think will happen as the particles undergo gravitational collapse. Write the ideas on the board. The gravitational potential energy converts to kinetic energy of the atoms. That causes the temperature of the system to rise. At high energy, the electrons will be stripped off, leaving a plasma of nuclei and free electrons.
3) (Slide 3&4) As gravitational collapse increases, gravitational potential energy is converted to kinetic energy and the temperature continues to rise in the core of the protostar. The hydrogen and helium nuclei have higher and higher kinetic energy. At approximately 10 million K, the Coulomb barrier can be overcome for two protons. What happens next? Brainstorm as a class.
4) (Slide 5) Have students work with a partner to work out the components of the system in the core of the protostar. For every 100 atoms, how many are hydrogen? How much helium? How many total protons are there in the system? Neutrons?
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	Electrons? Have students propose how heavier elements could be made in this system. Binding energies are given in the PowerPoint as reference. 5) (Slide 6) Discuss as a class. Students should conclude that there is a major difference between this system and the BBN processes they studied earlier because there are not enough neutrons in the system, and those that are there are tied up in helium nucleus. So can two protons fuse to make something heavier?
Explore (35 mintues)	
Procedure	**Activity 3-2. Radioactivity: Lifetime versus Half-life** 1. (Slide 7) Demonstrate how early scientists realized that certain materials emitted invisible particles by using the cloud chamber. Have students rotate in groups to the front of the room to observe the tracks in the chamber and draw what they see in their journal. Scientists like Henri Becquerel and Marie and Pierre Curie used film as the detector and the first observation happened accidentally. An understanding of radioactivity will help provide evidence for the formation of elements in stars. *TEACHER TIP: If the cloud chamber is unavailable, a video demonstration is available on the flash drive media or here.* 2. Demonstrate the use of a Geiger counter set with the audio turned on with two pieces of pottery, one radioactive and the other not. Move the Geiger counter further away and closer and let them hear the difference. What is happening? Solicit student comments to facilitate a class discussion that may reveal some misconceptions about radiation. Without correcting these, make a note of them to refer to in the summary of the lesson. 3. Organize class into groups of 3 (optimum). Distribute a Geiger counter and Geiger Counter Handout (from Print Master) to each group. Point out the labeled diagram in the handout, in particular the active window. Suggest that students leave the audio off unless they are counting clicks. 4. Each group will complete the handout on the use of Geiger counters, determining background radiation levels in the room as an exercise in the use of the meters, their sensitivities, and limitations. *(Teacher Tip: Because the background counting rate is very low, students will need to count light flashes or clicks in a minute period to fill in the table on their handout. Reading the scale will not work for backgrounds.)* 5) Once everyone has finished the handout, stop and check in. What is the average background each group has calculated? Is it different in different parts of the room? Why might that be? *(Teacher Tip: Use the student results to check that each group is using the meter properly. It's possible that students will find actual differences in background radiation levels in different parts of the room due to building materials or other material stored in the room.)* 6) Slide 7-9) Refer back to Slide 7. Once the early scientists discovered this mysterious result, we now call radioactivity, how could they learn more about it? What kind of measurements might they make? Solicit ideas, then switch to Slide

8. These are tracks from an early bubble chamber, like a cloud chamber. By putting the chamber inside a magnet, scientists were able to get quantitative as well as qualitative data. Using Slide 9, review the conservation laws (discussed in Lesson 2) as they apply to nuclear processes.

7) (Slide 10) Review with the class the basic ALARA principles listed on the safety poster. Tell them that to keep exposure to radiation 'as low as reasonably achievable' scientists use time (keep it short), distance (keep it distant) and shielding to minimize their exposure. They will be following these principles for all laboratories.

BASIC RADIATION PRECAUTIONS:

- Never use radioactive material around food or beverages.
- To minimize exposure when handling a radioactive source, keep it at an arm's length when possible.
- Wash your hands after working with radioactive sources.
- Pick up solid sealed sources holding their sides. Be careful to not pierce the plastic with a fingernail.
- Place solid sealed sources face down (label side up), and at a distance from live organisms when not in immediate use.
- Do not put any sources in your pockets.
- Handle sources with respect.

8) (Slide 11) Introduce the concept of half-life, then pass out a Lesson 3-2 task card to each group. Before beginning the investigation, facilitate a class discussion on the safe use of the Cs/Ba isotope generator (isogenerator), and a short explanation of how an isogenerator works. Remind students that in addition to the general ALARA principles there are special precautions to be made for this laboratory because the sample is in the form of a liquid (unsealed):
   - Do not have food and drink in work areas.
   - Do not ingest any of the liquid.
   - Leave the sample bag sealed, but if there is a spill, wear gloves while you wipe it up with a paper towel. Put everything (including the gloves) in a plastic bag and dispose of it in the trash.
   - If any liquid solution splashes onto clothes, use a damp cloth to wipe off as much as possible. The remaining radioactivity in the solution will decay rapidly, producing minimal radiation exposure.
   - Wash hands after handling.
9) Each group will spend 3-5 minutes planning their investigation, assigning tasks, preparing data table, etc. Suggest that measurements be taken every 20-30 seconds. Once students are set up and ready to begin, they should send someone from their group to retrieve a sample.
10) For safety reasons, the teacher should either prepare the samples themselves or closely supervise students, as they prepare them. To minimize spillage, all samples should be prepared together once students

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are ready. A few drops of the sample is enough for each group. After eluting the sample, seal the bag so that nothing can spill. Whomever is handling the solution should wear gloves, but once the bags are sealed it is not necessary.
11) Students will graph the counts versus time. They will then estimate the half-life from their graph. Students with advanced math skills (trigonometry) might use semi-log paper or prepare a log plot using EXCEL or Logger Pro. They could fit a curve to extract the half-life.
12) Students should include an error measurement on their graph. Can they estimate the error in their derived half-life due to the errors?

(Teacher Tip: If you are doing this lab with several class periods on the same day, you may have to be careful to not put too much liquid in each baggie early in the day so that there is still activity left in the generator for later classes. A couple of drops is enough to do the measurement.)

13) (Slide 12) Once the data is measured and graphed, ask each group to discuss the thought questions on the task card and answer in their journals. Share out with the full class. The slide shows the mathematical representation of the half-life equation.
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<tr><td>Questions for Student Exploration</td><td>
1) Why is it important to re-measure the room background before starting when it was done in a previous laboratory?
2) Is it important when you start measuring?
3) How important is the time interval you measure if you were doing it again, would you choose a different interval?
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<tr><td colspan="2">Summary (10 minutes)</td></tr>
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Activity 3-3. One in a Billion
1) (Slide 13) An example of a nucleus that decays by two different paths is shown. This isotope has very important medical applications. The Mo-99 is made in reactors in the form of an isogenerator (cow) which is milked by the hospital. The process is much like the one used to prepare the Barium sample in our experiment. More information is available on the back of the task card.

2) (Slide 14) Remind students that before the class digressed to make sense of half-lives, they were examined what was happening in the core of a protostar as gravitational collapse proceeded, and protons had enough energy to overcome the Coulomb barrier. When that happens, a diproton forms. The half-life for the diproton to fall back apart into two protons is very short and 999,999,999 times out of a billion, it falls back apart into two protons. (Click again) However, because half-life is a statistical process, once in a billion times, the diproton will hold together long enough for another process to take place.

3) (Slide 15) The process by which a proton transforms to a neutron is called beta-plus decay. Have each group of students check that the conservation laws apply to this decay by answering the questions on the slide, speculating if necessary
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Questions for Student Exploration	• Why is it so important that beta-decay can take place in the core of the protostar?
Exploration (30 minutes)	
Student Exploration	Activity 3-4. The Nucleosynthesis Game 1) Reorganize into groups of four or five at a table. Each pair of students will get a game box and each table will get a laminated rule sheet. Each group will divide into two teams and play against each other. 2) (Slide 16) Before students open their boxes, use the PowerPoint slide to walk through beta-plus decay (p→n) and the complementary process beta-minus decay (n→p). In both cases, the total number of protons + neutrons (nucleons) stay constant. That means the product nucleus will be on a diagonal in a matrix of neutron number versus proton number. 3) (Slide 17) Using the PowerPoint while students follow along with the Nucleosynthesis Rule Sheet, walk through some examples of what will happen if the students roll a 4 (nuclear decay). If their nucleus is white, it is stable and will not decay. Point out that beta-decay occurs for many isotopes. Most of the time, the nucleus will decay towards a more stable configuration, or towards the path of stability. 4) Have each group figure out how to set up the game to control their marbles if they roll a 6 (nuclear collision), and how they will then divide the marbles that remain on the magnets. Any marbles that fly off (are emitted) go back in their box. *(TEACHER TIPS:* • *If the nucleus undergoes nuclear beta decay, students will receive either a neutrino or antineutrino. These should be kept and counted at the end, but do not stick to the nucleus, since they have no charge.* • *During nuclear collision, students will roll their nuclei towards each other. Any neutrons or protons that shoot off go back into the game box. If the nuclei stick together. They should be broken in the middle and each team keeps the new nucleus closest to them.)* 5) *Students may need help with the decay chart the first couple of times they roll a four. If their nucleus is stable (white), nothing happens. If they have a nucleus not on the chart (e.g., Be-4) it is because it does not exist, and they should take off protons or neutrons until they get to something listed.*
Summary (25 minutes)	
Communicate	Activity 3-5. Hydrogen-burning Stars: Energy from the Sun 1) After calling the game, the teacher will poll each team to determine their final nucleus. Class bragging rights will go to the team with the biggest, most stable nucleus (aiming for C-12, O-16 or Ne-20). 2) Have each team add up the number of neutrinos and antineutrinos they have collected. That will determine the number of beta-decays that happened. Facilitate students to create a table on the whiteboard and record each groups' values and the average. On average, are the numbers of beta-plus and beta-minus decays approximately equal? Would this result be expected to happen in the center of stars?

Why or why not?

3) Pass out a Lesson 3-5 task card to each pair. Utilizing the game kit, have students' model in their notebooks the pp-I chain shown on the front of the card step by step, noting places where energy and neutrinos are released, and answering the questions on the card. If a pair finishes early, or if time permits, have them also work through either the pp-II or pp-III chain on the back of the sheet, answering the additional questions.

4) (Slide 18) As a class, discuss the pp-I process. Were both neutrinos and anti-neutrinos created? Why or why not? Did every step release energy? How could we calculate the energy released at each step? Work through the first step as a class. Masses are listed on the slide. With their partner, students should work through the rest of the pp-I chain, calculating the total energy released when four protons fuse to make a 4-He nucleus.

5) (Slide 18) Can other nuclei besides 4He be made in hydrogen burning stars? Have students work with their partners to propose some reactions that might work to make nuclei with higher Z. (Remind them to consider binding energy in their discussion. students might want to use the game pieces and chart of the nuclides to try to figure out possible reactions.

6) (Slide 18) In a class discussion, groups should suggest what reactions they think might happen and write them on the board. Then as a class, discuss some of the proposed reactions. Keep Slide 18 up during the discussion to refer to the binding energy table and fusion temperature table. Come to a class consensus as to which reactions may be most likely to happen.

7) (Slide 19) The pp chain students worked through in detail is the most likely reaction to happen in the sun (83.3% of the time). It is called the proton fusion chain branch 1 (pp I). Slide 17 shows two other paths that happen in the sun. A 3He nuclei stays around the core of the sun approximately 400 years, so it has the possibility of encountering a 4He nucleus and fusing to make 7-Be. From there, two other paths can take place. Both end in two 4He nuclei.

8) (Slide 20) An additional path to 4He can take place if there are significant populations of nitrogen in the core of the sun. This is a 'catalytic' chain because the heavier nuclei are preserved. Walk through the steps of this chain starting at the top (p+12C) and working around the circle in a clockwise direction.

(Teacher tip: If time permits, have students write in their journals the nuclear reactions for each step of one or more of the pp-II, pp-III or CNO chains, paying attention to conservation of lepton number, baryon number and charge.)

9) (Slide 19&20) Is there evidence that these three pp chains and the CNO cycle actually take place in the core of the sun? In a class discussion brainstorm what scientific data could be collected to prove or disprove the model for nucleosynthesis in the sun? Remind students that the density and temperature in the core of the sun is high. Can particles escape? Radiation? What kind?

10) (Slide 21) Could analyzing the light from the sun give evidence for which processes are taking place in the center? The problem is that the sun is very dense, and the photons of light undergo a lot of scattering before they escape. In fact, it takes approximately 10,000 years for a photon to reach the surface. Most of the spectral

	lines seen in a solar spectrum are coming from the chromosphere, so making claims about what is happening in the core from light spectra is problematic. 11) (Slide 22) What particle is made in during hydrogen fusion that has no charge so can move through matter with little interaction? *Neutrinos* If we can measure neutrinos from the sun (very hard) then maybe we could understand which processes are actually taking place and make conclusions about the temperature in the center of the sun. 12) (Slide 23) Show the short (2:28) video about the Ray Davis experiment at the former Homestake Gold Mine, the current home of the Sanford Underground Research Facility. The next activity will examine this landmark experiment in greater detail. *(Teacher tip: The video can be shown at the beginning of the following class period if preferred.)*
Exploration (45 minutes)	
Student Exploration	Activity 3-6. Connecting to evidence – Solar Neutrinos 1) (Slide 24) How can one detect a neutrino when it mostly goes right through everything without interacting? It can only be done indirectly. Refer to the bubble chamber photo on the slide while the class discusses what is meant by indirect detection. What are some clues that a neutrino caused the tracks seen? 2) Neutrino interactions are measured in a unit called a SNU (Solar Neutrino Unit) which is the neutrino flux that will give 10^{-36} interactions per target atom per second. That means if you had one atom, it would take 10^{36} seconds before a neutrino interacted. How long would one have to wait? *3×10^{28} years* What is the age of the universe? *4×10^{9} years* Brainstorm ways to get around this infinitesimally small number. 3) (Slide 25) Either together as a class, with a partner, or individually in their journals, students should work through the calculation of how many atoms of ^{37}Cl are in 100,000 gallons of C_2Cl_4. They need to consider the natural abundance of ^{37}Cl (approximately 25%). Density values are given on the slide. Does having a large detector solve the neutrino detection problems? Why couldn't Davis detect neutrinos with the ^{35}Cl? 4) (Slide 26) Davis proposed to extract the argon from the tank of liquid and look for radioactivity offline. This takes time. Look up as a class what the properties of the ^{35}Ar product from neutrino capture? *^{35}Ar has a decay of seconds so even though it happens, Davis couldn't detect it with his technique.* 5) (Slide 27) Theoretician John Bahcall predicted that 62 billion neutrinos per cm^2 6) reach the earth from the sun. However, most of those are lower energy proton neutrinos from the 83.3% pp-I process. Ray Davis calculated that his detector would produce 4-11 radioactive ^{37}Ar atoms per day from the higher energy ^{8}B neutrinos produced in pp-III. Those atoms beta decay back to ^{37}Cl with a half-life of 35 days. How could those few atoms be detected among the ~10^{30} atoms of C_2Cl_4? Brainstorm some possibilities as a class. 7) (Slide 28&29) When building such a large detector, interactions of charged particles can cause major background. Ray Davis proposed to use a mile of rock to stop cosmic ray showers in the atmosphere that would make his detection impossible. As a class or individually in a journal, plot the cosmic ray interactions as a function of depth that he published in his seminal 1964 paper proposing the

experiment.

8) Does going underground get rid of all the background that might interfere with detecting neutrinos? In order to narrow down the possibilities and determine the best way to measure the ^{37}Ar, we will look more carefully at the properties of radioactive decay. Organize the class into groups of 3-4 students and pass out Activity Task Card 3-6. Groups will explore the properties of beta decay and other radioactive decays leading to background as input into the design of the Solar Neutrino Experiment. Each group should pick up a Geiger counter, ruler, container of degrader materials, a protractor, a baggie of binder clips and clay, and a set of three radioactive sources (a ^{90}Sr beta source plus two unknown background sources.

9) Students should first explore the behavior of the sources qualitatively using the materials at their disposal. (***Task A on card)***

10) After a few minutes, stop and have each group report in. Ask them what parameters they explored and list them on the board. Variables (parameters) that groups will hopefully mention are distance from Geiger counter, angle, density, or thickness of degraders. Make a table on the board following the sample table on the back of their task card and fill it in as a class; an example could end up looking like:

Parameter	Range of counts
Angle	0-45 degrees
Distance in air	0 – 10 cm
Degrader Type	Stops in Al, Brass, plastic
Degrader Thickness (pick one type as an example)	0 – 0.015

(Teacher Tip: The purpose of this table is so that when students design their experiment, they choose a set up that will work. For example, if they decide to use degrader type as their variable, they need to know that they cannot fix the distance for their experiment at >10 cm but need to get closer.)

11) Each group will then discuss what information might help them in designing the Ray Davis experiment, decide which variable they want to explore quantitatively, then design the investigation and make a procedure and data table in their science notebooks. (***Task B on card)*** Conduct the investigation and analyze the data.

12) In a class discussion have groups report out on what they learned from their investigations. Based on what they learned do they think it will be easy to measure the beta decays coming from a few argon atoms a day? Would the beta particles escape the tank? Will there be issues with background radiation that might be coming from the rock or other locations in the area?

13) (Slide 30) Ray Davis was concerned about background radiation from the rock in the mine. To keep that radiation from getting into the tank, he filled the whole

	cave with water. Do you think this will be effective in stopping alpha, beta, and gamma decay? Why wouldn't the tank walls be sufficient?
Summary (10 minutes)	
Communicate	Activity 3-7. The Solar Neutrino Problem 1) (Slide 31) The early results came in from the experiment within a few months and were surprising. There were only 1/3 of the number of ^{37}Ar atoms as were predicted from the models. Most scientists thought that the experiment was just too hard, and Ray Davis was not getting all the argon out. He kept improving the system and testing the system – and collecting more data. He proved to many scientists that his data was accurate. What else could be wrong? 2) (Slide 32) Pass out a set of the solar neutrino problem card sort to each pair of students. With a partner, have students sort the cards by whether they support Claim 1 (the experiment gave credible results), Claim 2 (the model is credible, and something was wrong with the experimental data), neither or both. All the evidence comes from scientific literature. Does it strongly support one claim or the other? 3) Once each pair comes to consensus, pass out a Lesson 3 assessment card to each student. In their notebook or on a separate piece of paper, they should write a paragraph using evidence to support one of the four claims (<u>experiment</u> is credible, <u>model</u> is credible, <u>neither</u> are credible, <u>both</u> are credible). An evaluation rubric is on the back of the Assessment Card. When everyone is done, poll the class. Which claim did students believe was best supported by the evidence? 4) (Slide 33) After students have completed their paragraph, play the video interview with Nobel Prize winner Art McDonald, who explains how the 'Solar Neutrino Problem' was solved. Which claim turned out to be correct? *(Teacher Tip: The written assessment can be given as homework. In that case, wait until the beginning of Lesson 4 to play the video in Slide 33.)*
Terminology and Concepts to Solidify	<u>Activity</u> – **Activity** is a quantity related to radioactivity of an unstable isotope. The SI unit of activity is the Becquerel. <u>Alpha Decay</u> - **Alpha decay** is a form of radioactive in which a nucleus emits an alpha particle, or helium nucleus. The decay of a nucleus (Z,A) leaves a 'daughter' nucleus (Z-2, A-4). <u>Becquerel</u> – A **Becquerel (Bq)** is the SI derived unit of radioactivity. One becquerel is defined as the activity of a quantity of radioactive material in which one nucleus decays per second. <u>Beta decay (β)</u> – **Beta decay** is a form of radioactive decay caused by the weak nuclear force, in which a beta particle (electron or positron) and a neutrino or antineutrino is emitted from the nucleus of an atom. In β^+-decay, a proton in the nucleus transforms to a neutron; in β^--decay, a neutron in the nucleus transforms to a proton. <u>Bubble Chamber</u> - A **bubble chamber** is a simple, visual detector of radioactive particles. The chamber is a vessel filled with a superheated transparent liquid (most often liquid hydrogen) used to detect electrically charged particles moving through it. <u>Cloud chamber</u> **–** A **cloud chamber** is another visual detector of radioactive particles,

	that utilizes a supersaturated vapor instead of a liquid to detect electrically charged particles moving through it. Coulomb Barrier – The **Coulomb barrier** is the electric potential energy between two nuclei at the distance where the attractive strong interaction takes over. In order to overcome the barrier and undergo fusion, the two nuclei must have sufficient kinetic energy, or temperature. Quantum mechanics allows for some nuclei to fuse at lower temperatures by 'tunneling' through the barrier. Curie – A **Curie (Ci)** is a unit of radioactivity equal to 3.7×10^{10} disintegrations per second. Gamma Decay – **Gamma decay** happens when an excited nucleus relaxes into a lower energy state through the neutrons and/or protons falling into lower energy shells. A high energy photon called a gamma ray is emitted with an energy equal to the energy difference between the two shells. Each isotope has its own characteristic gamma ray decay pattern which can be used as a finger print of the isotope. Geiger (Geiger-Müller) Counter – The **Geiger counter** is an instrument for detecting ionizing radiation, consisting of a gas-filled tube in which electrical pulses are produced when a gas is ionized by radiation. Gravitational Potential Energy - **Gravitational potential energy** is energy an object possesses because of its position in a gravitational field. Half-life – The **half-life** for particle or nuclear decay is defined as the time in which half the (large number of) atoms of a particular radioactive nuclide disintegrate. The half- life is a characteristic property of each radioactive isotope. Protostar - A **protostar** is a contracting mass of gas in a late stage of star formation, just before nuclear fusion takes over. Radioactivity - **Radioactivity is** defined as the spontaneous emission of particles or electromagnetic radiation, or both at the same time, from the decay of certain atomic nuclei. Specific Activity – **Specific activity** is the activity per quantity of atoms of a particular radioactive substance. The SI unit is Becquerels/gram (Bq/g) Statistical Fluctuation – **Statistical fluctuations** are fluctuations in quantities derived from many identical random processes. They are fundamental and unavoidable. It can be proved that the relative fluctuations reduce as the square root of the number of identical processes.
Connection to Big Ideas (Phenomena)	At the end of nucleosynthesis in the Big Bang, the universe was predominantly hydrogen and helium. Could nucleosynthesis beyond helium happen in hydrogen burning stars the size of our sun? After studying models of hydrogen burning in the sun, the answer is no. We will have to look towards larger, hotter stars as sources of higher Z elements.
Follow Up/Practice	Nuclear Fission - Fission | Chain Reaction | Atomic Nuclei - PhET Interactive Simulations (colorado.edu) To learn about the process of fission, visit University of Colorado at Boulder PhFT simulations.
Optional Extension	Design and investigate to determine the effectiveness of water as a shield of background radiation surrounding the Davis tank. **Please do not put radioactive sources directly in the water (Fiestaware is okay.)**

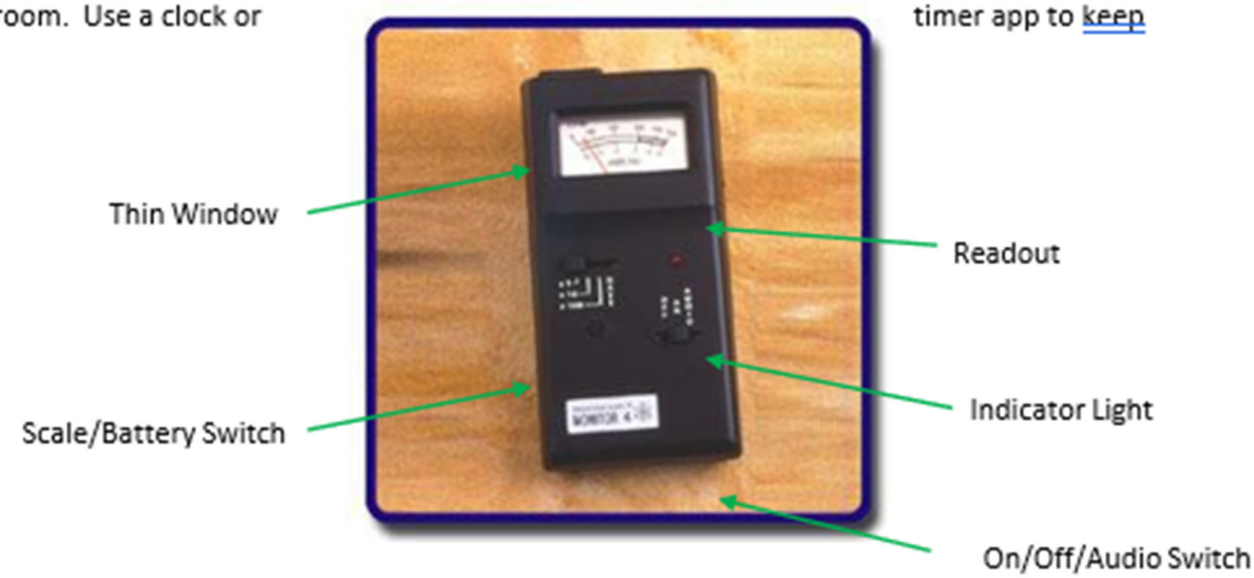
Assessment	The lesson assessment is an individual Claims-Evidence-Reasoning paragraph about the Solar Neutrino Problem. The rubric is included on the assessment card.

'WE ARE MADE OF STARSTUFF'

LESSON 3. FAMILIARIZING YOURSELVES WITH A GEIGER-MULLER (GM) COUNTER

NAMES ____

In this investigation, you will be working with a radiation monitor that contains a Geiger-Muller tube. You will explore how this monitor works by measuring the background radiation in your classroom. Use a clock or timer app to keep time.



The thin mica window at the front of the monitor window is fragile! Please do not let anything (especially a pointed object) touch the window.

1. Obtain a monitor for your team. Turn it on and check whether the battery is good by setting the Scale/Battery Switch to BATT. The needle should be within the region marked 'Battery'.

2. Set the Scale/Battery Switch to x1, which is the most sensitive scale. Use either the audio or indicator light to count how many counts you get in one-minute intervals. One team member should keep time, one count and one record the data in the data table.

ROOM BACKGROUND

Time (min)	CPM	Change in Counts (from previous value)
1		
2		
3		
4		
5		
6		
Average CPM		

3. What do you observe about the counts that are detected in the different time intervals?

4. Find another group and compare your results.
Are they all the same or not? Do their values show the same patterns as yours did? Are their average values similar to yours? Does it matter what part of the room you are in?

5. Why are your counts not zero?

6. Suppose you need to determine the background radiation because it is your job to report this in a classroom safety report. Would it be better to measure and report the number of counts in a 5 second interval, 30 second interval, 60 second interval or 120 second interval? Why? Explain your choice.

7. Can you get the same background information you calculated above by reading the scale indicator in counts per minute (cpm)? Why or why not?

Rules of the Nucleosynthesis Game:

- The goal of the game is to be the first team to form a carbon (^{12}C) nucleus in stellar nucleosynthesis. The magnetic sphere is the 'strong force' center. of your nucleus. Start with that.
- Each group plays against one other team and rolls the dice to see who goes first.
- Groups take turns rolling the dice and building their nucleus according to the following rules.

Marble Color codes:

Yellow	proton
Green	neutron
Red	neutrino
Blue	Anti-neutrinos

Dice Codes:

Number	Action
1	Add a proton to your nucleus
2	Add a neutron to your nucleus
3	Your choice: add a proton or neutron to your nucleus
4	Nuclear decay: follow decay path on Chart of the Nuclides* (see back). If your nucleus decays to another shaded box, follow that decay also. Your nucleus should ultimately end up in a stable configuration. Collect your neutrinos in the lid of your box since they do not stick to the nucleus in the strong interaction.
5	Lose your turn
6	Collision! Each team at your table rolls their nuclei at each other's. Any nucleons that break off go back in your game box. Any nucleons you capture from the other side are added to your nucleus. If the two nuclei stick together, separate. in middle and each team gets what sticks to their magnet.

Chart of the Nuclides:

10	Ne							Ne16	Ne17	Ne18	Ne19	Ne20	Ne21	Ne22	Ne23	Ne24	Ne25	Ne26
9	F						F14	F15	F16	F17	F18	F19	F20	F21	F22	F23	F24	F25
8	O					O12	O13	O14	O15	O16	O17	O18	O19	O20	O21	O22	O23	O24
7	N				N10	N11	N12	N13	N14	N15	N16	N17	N18	N19	N20	N21	N22	N23
6	C			C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20	C21	C22
5	B		B6	B7	B8	B9	B10	B11	B12	B13	B14	B15	B16	B17	B18	B19		
4	Be		Be5	Be6	Be7	Be8	Be9	Be10	Be11	Be12	Be13	Be14	Be 15	Be16				
3	Li	Li3	Li4	Li5	Li6	Li7	Li8	Li9	Li10	Li11	Li12							
2	He	He2	He3	He4 (α)	He5	He6	He7	He8	He9	He10								
1	H	H1 (p)	H2	H3	H4	H5	H6	H7										
0	n		n1															
↑#p/#n→		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16

Decay Codes:

1p	β⁺ + v	1n	α
2p	β- + anti-v	2n	? (Unknown)
β⁺p + v	β⁻n + anti-v		

SOLAR NEUTRINO CARD SORT

RESULTS OF EXPERIMENT (1970-1994): 2.56 ± 0.23 SNU (0.48 atoms/day)	RESULTS OF MODEL: 7.7 ± 1.3 SNU (1.5 atoms/day)
CLAIM: The experimentalists did everything they could to get rid of systematic errors in their experiment and the data was credible.	CLAIM: The theoreticians did everything they could to get rid of uncertainties in the input to their model calculations and the calculations were credible.
CLAIM: Both the experimentalists and theoreticians did enough to get rid of errors and uncertainties and both the data and models were credible. SOMETHING ELSE WAS GOING ON!	CLAIM: Neither the experimentalists and theoreticians did enough to get rid of errors and uncertainties. BETTER EXPEIMENTS AND MODELS ARE NEEDED!
The reaction rate was measured for. $^3He + ^3He \rightarrow ^4He + 2p$ and used as input to the solar model calculations.	In 1968, Bahcall and Shaviv calculated the uncertainty in the solar model by varying all the parameters for the nuclear reactions within what was then believed to be plausible limits.
The production rate for $^7Be + p \rightarrow ^8B$ was measured and used as input to the solar model calculations.	The detectors used at Brookhaven National lab for counting 37Ar were improved in 1970, reducing the background in the energy region of interest to 1 event per month.
Other paths from ^{37}Cl to ^{37}Ar (other than neutrino capture) were calculated and/or measured.	Flooding the chamber with water eliminated any possibility that 37Ar was made in the tank from fast neutrons from the surrounding rock wall.
The tank was carefully constructed and tested to make sure that air could not leak in because air contains 0.93% argon.	Adding a known amount of ^{36}Cl-labeled C_2Cl_4, which decays to 36Ar, Davis and collaborators showed that argon was removed from the tank with high efficiency.
40 'educators' provided vigorous agitation and thorough mixing of the helium purge gas with the liquid.	The theoretical capture rate of neutrinos on 37Cl is very sensitive to the rates of the two reactions: $^7Be + p \rightarrow ^8B$ and $^3He + ^4He \rightarrow ^7Be$
Before filling the tank, it was thoroughly cleaned, then selected areas were tested to make sure that the alpha emission rate from the inside walls was below acceptable limits.	There is no way (yet) to directly measure the temperature in the core of the sun.

ANSWER KEY (AUTHORS' OPINION BUT OTHER ANSWERS COULD BE SUPPORTED). Students will learn that both experiment and theory were finally proved correct, and that the discrepancy was explained by unknown properties of neutrinos (CLAIM 3).

The reaction rate was measured for. $^{3}He + {^{3}He} \rightarrow {^{4}He} + 2p$ and used as input to the solar model calculations.	In 1968, Bahcall and Shaviv calculated the uncertainty in the solar model by varying all the parameters for the nuclear reactions within what was then believed to be plausible limits.
The production rate for $^{7}Be + p \rightarrow {^{8}B}$ was measured and used as input to the solar model calculations.	The detectors used at Brookhaven National lab for counting ^{37}Ar were improved in 1970, reducing the background in the energy region of interest to 1 event per month.
Other paths from ^{37}Cl to ^{37}Ar (other than neutrino capture) were calculated and/or measured.	Flooding the chamber with water eliminated any possibility that ^{37}Ar was made in the tank from fast neutrons from the surrounding rock wall.
The tank was carefully constructed and tested to make sure that air could not leak in because air contains 0.93% argon.	Adding a known amount of ^{36}Cl-labeled C_2Cl_4, which decays to ^{36}Ar, Davis and collaborators showed that argon was removed from the tank with high efficiency.
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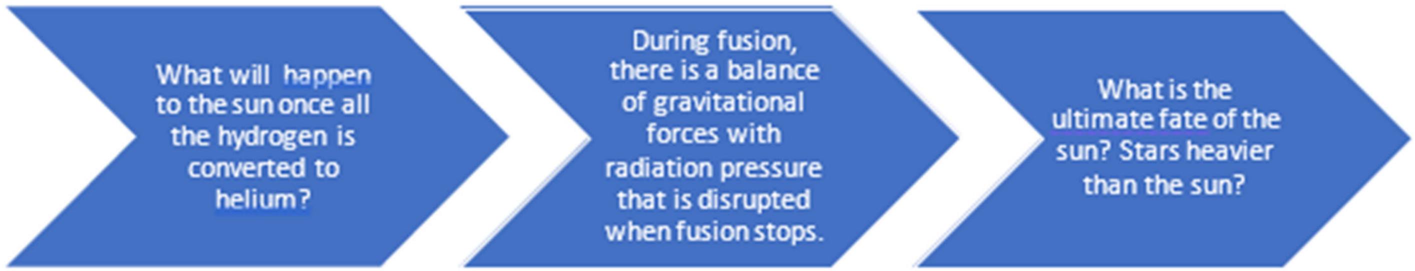
Before filling the tank, it was thoroughly cleaned, then selected areas were tested to make sure that the alpha emission rate from the inside walls was below acceptable limits.	There is no way (yet) to directly measure the temperature in the core of the sun.
SUPPORTS CLAIM 1 (Experiment was credible)	SUPPORTS CLAIM 2 (Theory was credible)
SUPPORTS CLAIM 3 (Both experiment and theory credible)	SUPPORTS CLAIM 4 (Neither experiment nor theory credible)

Lesson 4, *Beyond Helium*

ACTIVITY 4-1. When the Light Fades (LAUNCH)

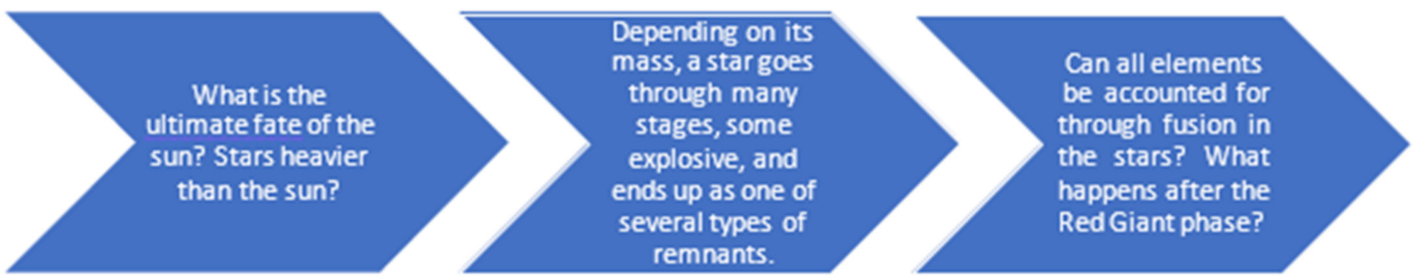
Questions | What we Figure out | New Questions



ACTIVITY – After recapping what they learned about the sun and stellar fusion in Lesson 3, students will use mathematical representations to predict whether helium can undergo fusion in the core of the sun once the hydrogen is exhausted.

ACTIVITY 4-2. Star in a Box (EXPLORE 4a)

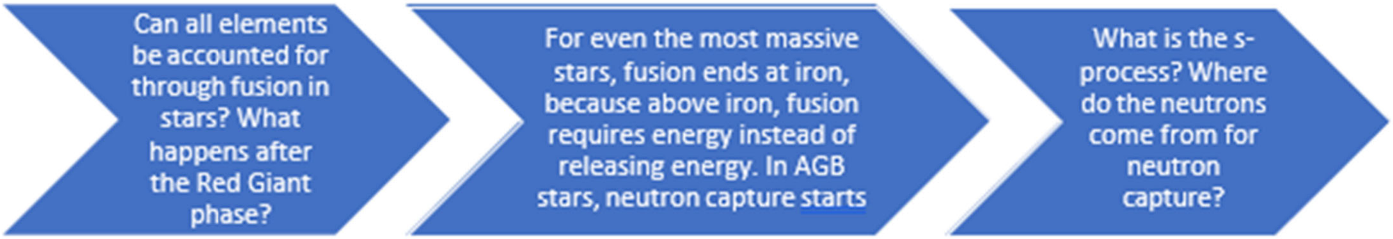
Questions | What We Figure out | New Questions



ACTIVITY – Students will utilize the *Star in a Box* simulation to diagram and compare the life cycle and properties of the sun and one other star of their choosing. They will research and communicate ideas for where and when nuclear fusion occurs in the evolution of stars away from the main sequence.

ACTIVITY 4-3. The end of Fusion (SUMMARIZE 4a)

Questions | What we Figure out | New Questions



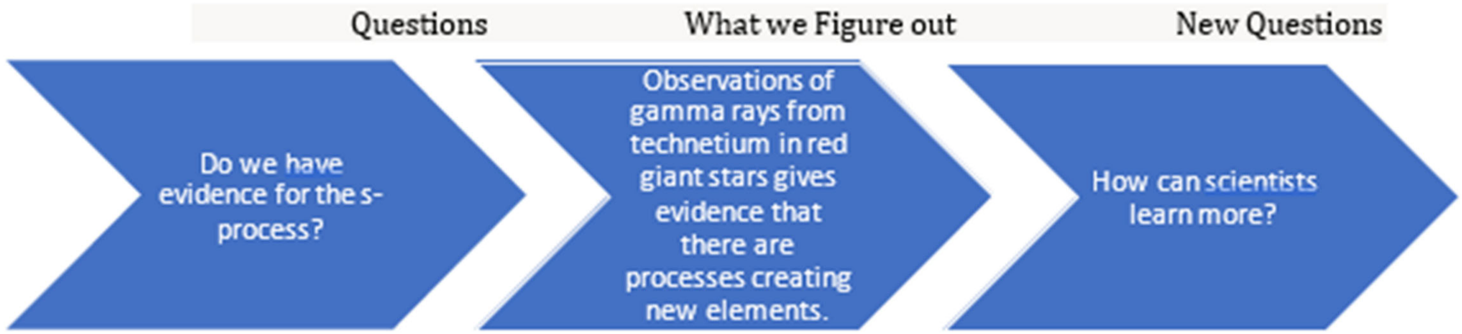
ACTIVITY – Students share out their discoveries from the last two activities, making connections back to the unit phenomenon.

ACTIVITY 4-4. The s-process (EXPLORE 4b)

Questions | What we Figure out | New Questions

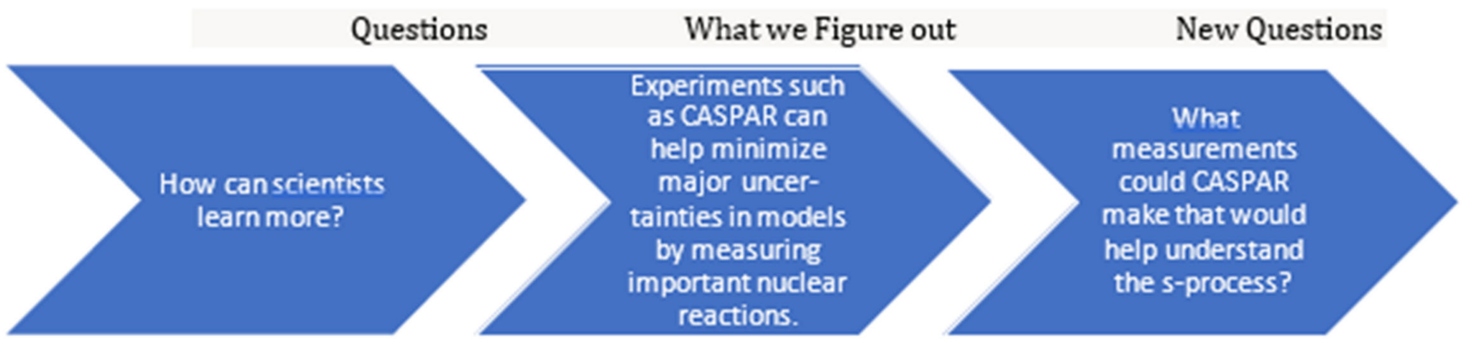
ACTIVITY – Students model the s-process (slow neutron capture) to explore whether it can account for all stable isotopes heavier than iron.

ACTIVITY 4-5. Connecting to Evidence: Revisiting Technetium (SUMMARIZE 4b)



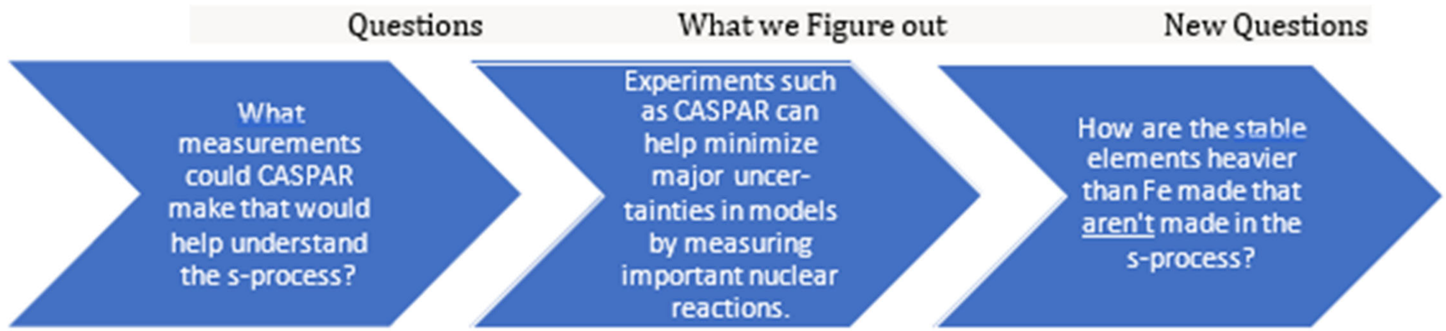
ACTIVITY – Students will examine evidence for the s-process happening in stars in the red giant (AGB) phase of their life.

ACTIVITY 4-6. Connecting to Sanford Lab: The CASPAR Experiment (EXPLORE 4c)



ACTIVITY – Students will explore earth-bound technology that is used to measure nuclear processes in order to develop and improve nucleosynthesis models.

ACTIVITY 4-7. Go Fund Me! (SUMMARIZE 4c)



ACTIVITY – Students will use evidence and reasoning to defend a nuclear reaction to be studied at CASPAR at Sanford Lab to improve s-process nucleosynthesis models. (Lesson Assessment)

Lesson 4	Beyond Helium
Overview Standard(s) & Objectives	*This lesson is designed for three 50-minute class periods or two block periods. The structure and flow of the lesson is given at the beginning of the Background Material section. DCIs, SEPs and CCCs for each activity are color-coded.* **Performance Expectations:** HS-PS1-8. Develop models to illustrate the change in the composition of the nucleus of the atom and the energy released during the processes of fission, fusion and radioactive decay. HS-PS2-4. Use mathematical representations of Newton's Law of Gravitation and Coulomb's Law to describe and predict the gravitational and electrostatic forces between objects. HS-PS3-3. Design, build and refine a device that works within given constraints to convert one form of energy into another form of energy. HS-PS3-5. Develop and use a model of two objects interacting through electric or magnetic fields to illustrate the forces between objects and the changes in energy of the objects due to the interaction. HS-ESS1-1. Develop a model based on evidence to illustrate the life span of the Sun and the role of nuclear fusion in the Sun's core to release energy that eventually reaches Earth in the form of radiation. HS-ESS1-3. Communicate scientific ideas about the way stars, over their life cycle, produce elements. **Disciplinary Core Ideas:** ● PS1.C Nuclear Processes ● ESS1.A The Universe and Its Stars **SEPs:** ● Developing and using models ● Using mathematical representations ● Constructing explanations and designing solutions ● Obtaining, evaluating, and communicating information **CCCs:** ● Energy and Matter ● Scale, proportion, and quantity ● Patterns **Lesson Phenomenon:** Video of the fate of the sun **Lesson Objectives:** ● After recapping what they learned about the sun and stellar fusion in Lesson 3, students will use mathematical representations to predict whether helium can start to fuse in the core of the sun once the hydrogen is exhausted. ● Students will utilize the Star-in-a-Box simulation to diagram and compare the life cycle and properties of the sun and one other star of their choosing. They will research and communicate ideas for where and when nuclear fusion occurs in the evolution of stars when they are off of the main sequence.

	• Students share out their discoveries from the last two activities, making connections back to the unit phenomenon. • Students will model the s-process (slow neutron capture) to explore whether it can account for all stable isotopes heavier that Fe. • Students will examine evidence for the s-process happening in stars in the red giant (AGB) phase of their life. • Students will explore earth-bound technology that is used to measure nuclear processes to develop and improve nucleosynthesis models. • Students will use evidence and reasoning to defend a nuclear reaction to be studied at the CASPAR experiment at Sanford Lab to improve s- process nucleosynthesis models.
Background Information	**Structure of Lesson:** 1. (LAUNCH) In Activity 4-1, *When the Light Fades*, the lesson is launched with a short video of the fate of the sun, the phenomenon for the lesson. Students recap what they learned about the sun and what questions they still have. They use their knowledge of the gravitational and electromagnetic interactions and energy transfer to propose an explanation for what will happen to the sun once hydrogen fusion in the core is exhausted. *2.* (EXPLORE) In Activity 4-2, *Star in a Box,* students explore stellar evolution models to determine the fate of the sun and one other star of their choosing. They then research and evaluate the dynamics of the evolution of their two stars from the main sequence to the red giant phase, including possible nuclear fusion and other reactions that can lead to nuclei more massive than helium, and communicate that information to their classmates in the form of a poster. *(Teacher Tip: For schools with a 50-55 minute class period, the group research and communication part of Activity 4-2 can carry over to Day 2 of this lesson (or be completed outside class)).* 3. (SUMMARIZE) In Activity 4-3, *The End of Fusion*, students revisit the concept of binding energy in order to make sense of why fusion reactions can only produce elements up to iron. *4.* (EXPLORE) In Activity 4-4, *The s-process in AGB Stars,* students model slow neutron capture (the s-process) in cool, luminous stars, determining the trends for which elements and isotopes can be created through the s-process. 5. (SUMMARIZE) In Activity 4-5, *Connecting to Evidence: Revisiting technetium)* Students examine data showing the presence of the element technetium in electromagnetic radiation from AGB stars, and draw conclusions whether those stars could be possible sites of the s-process. *(Teacher Tip: For schools with a 50–55-minute class period, this is a natural stopping place for Day 2 of this lesson. If the research activity was completed outside of class, then the next activity can be included in Day 2.)* 6. (EXPLORE) In Activity 4-6, *Connecting to Sanford Lab: The CASPAR*

	Experiment) students construct models to explore the science and engineering behind underground accelerators which are used to provide input to the models for stellar evolution. 7. (FORMATIVE ASSESSMENT) In Activity 4-7, *Go Fund Me!* students will use evidence and reasoning to communicate the importance to s-process models of the next nuclear reaction to be measured with CASPAR.
Materials	*Launch (4-1):* No materials needed *Explore (4-2):* *For each pair of students:* • Activity 4-2 Task Card • Colored Pencils ➢ Computers ➢ Poster Paper *Summarize (4-3):* *For each student:* • Periodic Table Template (Print Master) • Colored Pencils *Explore (4-4) & Summarize (4-5)* *For the classroom:* ➢ Large Sheet of Paper/Whiteboard ➢ Colored Markers *For each pair of students:* • Nucleosynthesis Game Kits • Chart of Nuclides • Activity 4-4 Task Card • 11x17 Chart of Nuclides • Colored Pencils *Explore (4-6):* *For each small group (3 students):* • Activity 4-6 Task Card • Authorization to Proceed (ATP) Card • Set of Magnets and Steel Balls • Set of Accelerator Tracks • Tape • Measuring Tape • Plastic Cup *For each student:* Safety Glasses
Prior Knowledge	This lesson expands on the concepts students explored with our own sun in Lesson 3 to all stars in the universe.
Engagement and Communication	**Activity 4-1. When the Light Fades**

of Student Expectations

1. Pass out the periodic table templates (one per student) and colored pencils (per pair of students). Give students a minute to get organized and decide on a color- coding scheme for the origin of each element. Use hydrogen as an example; it is made in the Big Bang. Anywhere else? Students should color in hydrogen with their choice of color for Big Bang nucleosynthesis. Helium is made in both BBN and stellar fusion, so that box should be split between two colors.

(TEACHER TIP: Students should be reminded to hang onto their periodic tables because they will be revisiting them several times during the next several activities.)

2) (Slide 2) Play the video of the evolution of the sun. In a class discussion, have students recap what they learned about the sun in the previous lesson, and what questions they still have. Write them on the board.

   Some questions they might think about are:

   - *Once hydrogen burning is complete, what will happen to the sun? Why? Will it cool down?*
     - *Are there other processes that could replace helium as a fuel?*
   - *We still have an open question of where the nitrogen came from to start the CNO process.*

3) (Slide 3) Remind students that hydrogen fusion ‘turning on’ stopped the gravitational collapse of the protostar and stabilized the young star. The fusion process caused an outward pressure (radiation pressure) to counteract the force of gravity.

4) Have students work with a partner and brainstorm what might happen when the hydrogen in the sun is exhausted. After a couple of minutes, facilitate a class discussion. What ideas do students have for what will happen next? What factors might be important to figure out what happens next?

5) (Slide 4) Introduce the ‘virial theorem’ which can be used to approximate the kinetic energy (temperature) change during the gravitational collapse of an ‘ensemble’ (group) of particles of identical particles such as protons. In studying this mathematical representation, what factors play a role in the collapse of particles? Can students calculate a maximum temperature for the center of the sun? What if a star with a mass of $10T_{\odot}$ collapsed? Would the temperature be higher or lower? By how much?

6) (Slide 4) Revisit the Coulomb barrier for fusion of two nuclei. How much harder is it to fuse two helium nuclei? If the temperature for hydrogen fusion to start is approximately 0.03 billion K, what is the estimated temperature for helium nuclei to fuse?

7) (Slide 5) Early astronomers classified stars by their brightness (luminosity) and their surface temperature. They found that most stars fell on a curve which they called the ‘main sequence’. Where they fall on the curve depends on their mass. The life cycle of a star also depends on its mass. We will explore what happens to a star the mass of the sun and a heavier star.

Break students into pairs for the Star in a Box activity and pass out an Activity 4-2 task card to each pair. Each group needs access to a computer and internet with the link at https://lcogt.net/education/starinabox/.

<table>
<tr><td>Exploration</td><td>

Activity 4-2. Star-in-a-box

1) Students will use the Star-in-a-Box model to explore the life cycle of a star of $M_{\odot}$ = 1 (equivalent to the sun) and one other star of their choosing from options given. There are three parts to the exploration:
   - PART A: Using questions on the task card, explore the life cycle of a $M_{\odot}$ = 1 star and their second chosen star.
   - PART B: They will create a Hertzsprung-Russell (H-R) diagram and draw the life cycle of the sun. Draw the second star on the same H-R diagram. From the observed luminosity and temperature of the star, students should be able to draw conclusions as to which stage it is at in its evolution.
   - PART C: For the sun, choose different three points during its evolution between the Main Sequence phase and the Red Giant phase and add substructure details, including size and, if nuclear fusion is taking place, show what and where.

(TEACHER TIP: Part C will require some research by students in or out of class. Before beginning Part C, take a break and do the next part to give them a starting point.)

2) (Slide 6) When most groups are done or nearly done with their H-R diagrams, take a short break and revisit the effect of binding energy on fusion. Students learned in Lesson 2 that because of its low binding energy, 8-Be, the product of two helium nuclei fusing, has a lifetime of only 8 x 10^{-17} seconds, making it a bottleneck for fusion. In order to get past this bottleneck, a third helium nuclei must be fused to make C-12 (triple-alpha fusion). This requires a temperature of greater than 100 million K in the core of the star. Was there a stage in the sun's evolution where temperatures were that high? What about their second star?

3) (Slide 7) PART C of this task will require some research either in or outside of class. Working with their partners, students will expand their basic H-R diagram of the evolution of the sun to include details of at least three stages that the star will pass through, during its evolution to and through the Red Giant stage (the end-of-life stages will be addressed in Lesson 5). Some research references are given in the PowerPoint. Include the size and substructure of the sun at each stage, and if nuclear fusion is taking place, show what and where. If time is available, students can also do the same research for their second star.

(Teachers Note: Poster size sheets of paper can be made available for this activity; students could also use a computer. Part C of this task could be assigned for out-of-class time.)

(Slide 8, OPTIONAL) A sample of the kind of diagram students might generate fo the sun is shown in the PowerPoint as an example.

</td></tr>
<tr><td>Questions for Student Exploration</td><td>Questions are listed on the Lesson 4-2 Task Card.</td></tr>
<tr><td colspan="2">Summarize</td></tr>
</table>

Communicate and Synthesize	**Activity 4-3. The End of Fusion**

1. (Slide 10) On the whiteboard or a large sheet of paper, draw and label axes for a class composite H-R diagram. Based on their research, each group should add at least one point along the path of a one solar mass star. The composite H-R diagram should look something like the diagram shown in the PowerPoint. Step through the fusion processes in the PowerPoint and have one student mark where those occur on the composite H-R diagram. When helium burning is exhausted and the star begins to cool again, it is on a path parallel to its original path. This is called the Asymptotic Giant Branch (AGB).
2. (Slide 8) Facilitate a discussion about which elements were made during fusion. All groups should have reached the same conclusions about the main elements made during the sun's time on the main sequence and its transition to a red giant (*He, C, O).* Students should take out their periodic table templates and color those in with their choice of colors for fusion reactions. Then have groups present the results of their research into other stars, starting with the lowest mass stars and working up. As new elements are made in the more massive stars, students can color those in.
3. What is the heaviest element made in the most massive stars? (*Fe or Ni).* Why can fusion not proceed to even higher Z elements? Have students suggest ideas.
4. (Slide 9) The answer to this puzzle again lies in the underlying property of nuclei-binding energy. The fusion of two silicon to make iron is the last set of fusion reactions which release energy. If you try to fuse two iron nuclei to make something heavier, it requires additional energy, so fusion cannot be sustained.

4. (Slide 9) The answer to this puzzle again lies in the underlying property of nuclei-binding energy.

Exploration

Communicate	**Activity 4-4. The S-Process**

1) (Slide 11) Refer to the substructure of the sun that students researched and added to the large H-R diagram. Make note of the layers that form as the sun expands. As the star goes through stages of hydrogen burning in the outer shell, and helium burning, first in the core, then in an inner shell around a carbon core, sometimes there will be a thermal pulse of energy, which serves to mix up the layers, sending carbon outwards and hydrogen inwards.
2) Form groups of 4 students and give each group two Activity 4-4 task cards, two of the nucleosynthesis game kits used in Lesson 3, along with one Chart of the Nuclides from Lesson 3. In **Part A**, students will start with carbon, oxygen, helium, and protons and brainstorm some reactions that might happen once there is thermal mixing in the star. Is it possible to form new elements? Will some of these elements beta decay to other elements?
3) Share out ideas as a class and list on the board. (*Some possibilities are 4He + 12C→16O; 4He + 16O →20Ne; 1H + 12C → 13N (beta decays to 13C); 13C + 4He →16O + n*)
4) Students are not likely to come up with reactions that emit neutrons, but they do

happen when nuclei are made with extra energy. Why is it easy for an excited nucleus to emit a neutron? *No charge so no Coulomb barrier*

5) (Slide 11) Both protons and neutrons can combine with a heavier nucleus to make a new isotope or element. We call this 'capture'. Scientists refer to the p-process and the s-process for proton capture and 'slow' neutron capture, respectively. Using the slide, review neutron capture, proton capture and beta-decay, and which elements are made in each case. Have the class decide which square on the table should be colored for each process.

6) (Slide 12) In most cases, proton capture happens with very low probability. Why? To get an estimate of how difficult it is, estimate the Coulomb barrier for a 56Fe nucleus to capture a proton, compared to two protons to fuse. To overcome the barrier, the protons must be at very high energy, higher than found in the center of stars. There are some nuclei that are thought to be made through proton capture, but it is still a mystery where in the cosmos they are made.

7) Because there is no Coulomb barrier, neutron capture is much more probable. In AGB stars, neutrons can be captured by heavier nuclei to make new elements. For **Part B** of Task Card 4-4, split each group into pairs and give each pair, a laminated *Chart of the Nuclides (11" x 17"),* an 11" x17" student handout and a set of colored pencils. The 'rules' for the s-process are on the card. Have students circle Fe-56 on their chart, then pick one color to mark the path of the s-process following the rules on the task card. The half-lives for beta-decay are given on the laminated chart of the nuclides for each unstable element.

(TEACHER TIP: Students will be using the handout again in Lesson 5, so groups should write their names on them and hang on to them when done with this activity. Students should work with the same partner in Lesson 5.)

(TEACHER TIP: The Chart of the Nuclides (both versions) is broken into several pieces to fit everything on two pages. Students will be able to follow the s-process through all five precious metals by jumping from piece to the next. A picture of a completed Chart is given on the unit flash drive for reference).

(TEACHER TIP: If the beta-decay half-life equals the neutron capture rate (10 years), students can choose which process to follow. This is a branch in the path, but students will find whichever branch they follow, they meet up again. Be Careful: There are three isotopes shown in the chart (Zn65, Ge71, Kr81) which undergo beta-plus decay. If your path runs through one of those isotopes, it changes direction at that point).

8) (Slide 13) Once the path up to gold has been marked, students can write 'S' in the stable isotopes created during the s-process. These are s-process nuclei. Can all stable isotopes in this region of the chart of the nuclides be made in the s-process. What do they notice about the s-process path.

9) On each student's periodic table template, they should pick a color to color the s-process elements. If not all the stable isotopes of an element can be accounted for by the s-process, they should only partially color it – the missing isotopes must be made some other way.

Summary

Student Exploration	Activity 4-5. Connecting to Evidence – Revisiting Technetium 1) In Lesson 3, students learned that Tc-99m is an important medical isotope with many applications. It is also unique in having no stable isotopes. So how can that give us evidence for the s-process? 2) In a class discussion, have students recall what they learned about Tc-99m and its use in medical applications. What isotope is made in reactors as a source of Tc? *Mo-99* *(TEACHER TIP: The back of the Activity 3-2 Task Card featured Tc-99m. You might want to pass it back out if students didn't read it or need review.)* 3) Have each pair of students study their s-process path. Does it go through Tc? Did everyone's path go through the same isotope(s) of Tc? Which isotope(s)? Go to this website as a class and look at the decay chain those isotopes. What is its half-life and how does it decay? 4) (Slide 14) If we saw evidence for Tc in the stars, what would that tell us? After a class discussion, show the data for Tc gamma rays in the Milky Way. Is this evidence for the s-process? This data gave very important early evidence that the models for the lifetime of the stars was correct. 5) (Slide 15) This slide shows a more contemporary measurement: a gamma ray map of the Milky Way galaxy for Fe-60, taken using the Integral Gamma Telescope. What is the half-life for Fe-60? Does this measurement give evidence for the s-process? 6) Are there any other elements lighter than gold that have no stable isotopes? Is there an isotope that is on the s-process path? Speculate on whether studying this element might give us additional information? *Promethium (Pm) has no stable isotopes. 147Pm is on the s-process path, but only has a half-life of 2.6 years so is unlikely to undergo the s-process.*
Exploration	
Communicate	**Activity 4-6. Connections to Sanford Lab: CASPAR** 1) Brainstorm ideas about how scientists could gain additional knowledge about nucleosynthesis at various sites in the cosmos, perhaps to answer the debate from the previous day. What questions need to be considered? *Some examples: "What types of elements come from what types of stars?" and "What are the conditions that exist in those stars to cause nucleosynthesis?" Could we reproduce those conditions in a lab? What tools would we need?* 2) (Slide 16) Play Steven Hawking video – 'The Birth of Stars' where he describes what it would take to make a star in a laboratory (on flash drive and linked from PowerPoint). Afterwards continue the discussion. Could we ever make a star in the laboratory? 3) (Slide 17) Break into small groups (3 students optimal) and introduce the magnetic accelerator activity by showing the video (on unit flash drive or at https://www.youtube.com/watch?v=UaQ8pcGMMsQ0. Use the video to facilitate class discussion on what is happening in the device. What are the sources of stored energy and how do they transfer to kinetic energy?

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4) Pass out Activity 4-6 Task Cards and materials for the Engineering Challenge. Once students have designed, tested, and refined their accelerator they will have an opportunity to see how their design compares to other teams by having a challenge to see which device transfers the most energy to a plastic cup. Guidelines are in the handout.

5) Emphasize to students that the magnets in their kits are very strong and very fragile. Students must get their design and procedure approved by the teacher before testing, and they must wear safety glasses while testing their device.

(TEACHER TIP: Before testing their device, groups must draw a diagram and write a procedure for ‘firing’. If it appears that they are proceeding with safety in mind, give them an “Authorization to Proceed’ card and let them begin testing. Have students brainstorm what parameters they could vary as they design their own magnetic acceleration device.)
</td></tr>
<tr><td colspan="2">Summarize</td></tr>
<tr><td>Communicate</td><td>
Activity 4-7. Go Fund Me! (Assessment)
1) (Slide 17-20) Finish the PowerPoint which introduces the Sanford Underground Research Facility, the CASPAR facility and the experiments the CASPAR collaboration are pursuing to better understand nucleosynthesis in the s-process.

2) (Slide 21) Pass out the Lesson 4 Assessment Card. The CASPAR collaboration plans to measure the reaction $^{22}Ne + {}^{4}He \rightarrow n + {}^{25}Mg$. The assessment describes the stellar environment in which this reaction is thought to occur. Students will justify (in their notebook or to submit as an exit card) why this reaction is an important experiment using the CASPAR facility and should be funded.

(TEACHER TIP: The assessment could be done as a homework assignment. At the end of Lesson 4, remind students that they will be revisiting some of the topics of this lesson in Lesson 5. They should have the following products with them: i) their research on the life cycle of the second star (Activity 4-2), ii) the s-process pathway (Activity 4-4) and iii) their periodic table.)
</td></tr>
<tr><td>Terminology and concepts to Solidify</td><td>
<u>Asymptotic giant branch star</u> – The Asymptotic Giant Branch (AGB) is a cool, luminous period of stellar evolution undertaken by all low- to intermediate-mass stars (0.6–10 solar masses) late in their lives.

<u>Black hole</u> – A Black Hole is a region of space having a gravitational field so intense that no matter or radiation can escape.

<u>Hertzsprung-Russell Diagram</u> – The Hertzsprung-Russell (H-R) diagram is a a two-dimensional graph, devised independently by Ejnar Hertzsprung (1873–1967) and Henry Norris Russell (1877–1957), in which the absolute magnitudes of stars are plotted against their spectral types. Stars are found to occupy only certain regions of such a diagram.

<u>Main sequence star</u> –Stars that in the hydrogen fusion stage are found in a certain region of the H-R Diagram and are referred to as Main Sequence stars.

<u>Nebula</u> – A nebula is an interstellar cloud of dust, hydrogen, helium and other ionized
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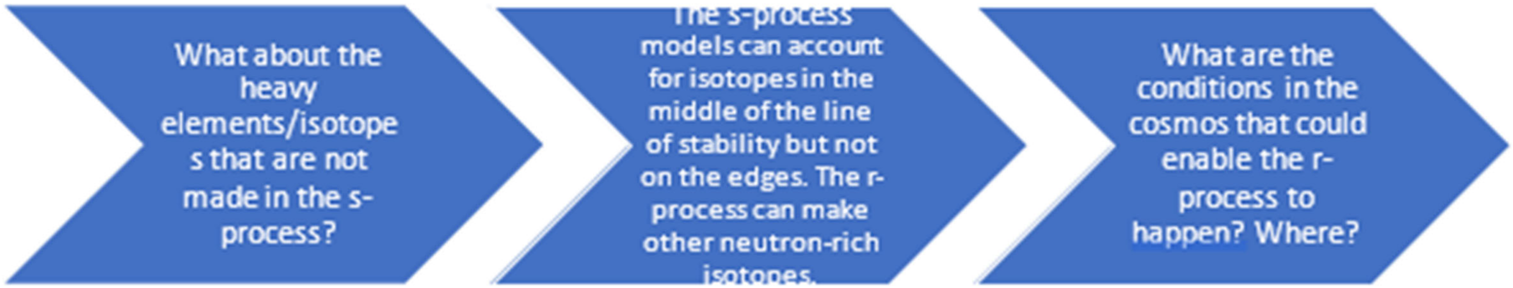
	gases; nebulae can come from a variety of sources – red giants, supernovae, etc. Neutron-rich – Isotopes of an element with more neutrons than the stable isotopes of that element are **neutron-rich**. Neutron-rich nuclei decay by beta-minus decay. Neutron star - a **neutron star** is a celestial object consisting of an extremely dense mass of neutrons, formed at the core of a supernova, where electrons and nuclei are compressed together so intensely by the force of gravity that protons and electrons merge together into neutrons. Particle accelerator – A **particle accelerator** is a device that uses electromagnetic fields to propel charged particles to high speeds and to contain them in well-defined beams. Planetary nebula – A **planetary nebula** is an expanding glowing shell of ionized gas ejected from old red giant stars late in their lives. p-process nucleosynthesis – **p-process nucleosynthesis** (slow proton-capture) occur in regions of the cosmos with free protons at low densities. Proton capture reactions are not very efficient because of the Coulomb barrier (electromagnetic repulsion). Initially the p-process was thought to happen during core-collapse supernovae but that has been disproven in models and alternative sites are not understood. Proton-rich – Isotopes of an element with fewer neutrons than the stable isotopes of that element are **proton-rich**. Proton-rich nuclei decay by beta-plus decay. Red giant **– Red giant stars** have exhausted the supply of hydrogen in their cores and switched to thermonuclear fusion of hydrogen in a shell surrounding the core. They have radii tens to hundreds of times larger than that of the Sun. However, their outer envelope is lower in temperature, giving them a reddish-orange hue. s-process nucleosynthesis – **s-process nucleosynthesis** (slow neutron capture) occurs in regions the cosmos with free neutrons being created at low densities, in which nuclei can capture a neutron approximately once every 10 years. Typical sites are during stellar fusion at the end of the He-burning or C-burning stage. Stellar nucleosynthesis – **Stellar nucleosynthesis** is the process by which elements are made within stars through various nuclear fusion reactions in the core and overlying mantle of stars.
Connection to Big Ideas (Phenomena)	Stellar nucleosynthesis can occur during several stages of a star's life, depending on the star's mass. Fusion in heavier stars than the sun leads to elements up to iron. Other elements near stability can be made in s-process nucleosynthesis. These processes cannot account for all the stable elements/isotopes in our solar system.
Follow Up/Practice	See assessment.
Optional Extension	The life cycle of stars is rich in content which can be explored further by interested students.
Assessment	See Lesson 4 Assessment card; rubric is on the reverse.

ACTIVITY 5-1. The Origin of Precious Metals (LAUNCH)

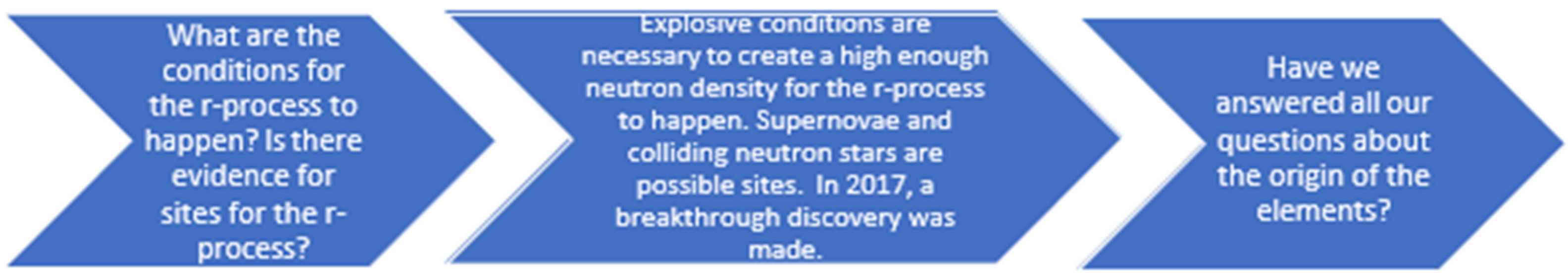
Questions | What we Figure out | New Questions



ACTIVITY – Students will begin synthesizing all they have learned by revisiting the precious metals from Lesson 1, and comparing neutron capture models that could lead to their formation.

ACTIVITY 5-2. Refining r-process models and sites (EXPLORE)

Questions | What We Figure out | New Questions



ACTIVITY – Students will examine details in data and models that depend on nuclear processes important to the r-process and compare two possible sites for the r-process, supernovae, and colliding neutron stars, arguing from evidence which is most likely. Then they will examine a new observation (2017) which has led scientists to conclude that most of the gold in the universe could come from colliding neutron stars.

ACTIVITY 5-3. 'We are Made of Starstuff' (SUMMARIZE)

Have we answered all our questions about the origin of the elements?

ACTIVITY – After revisiting the list of questions the class developed in Lesson 1, students will reflect on the famous quote on which this unit is based, 'We are Made of Starstuff', as a final assessment. (Unit assessment)

Lesson 5	A Breakthrough Discovery
Overview Standard(s) & Objectives	*This lesson is designed for one 50-minute class periods or one-half of a block period. The structure and flow of the lesson is given at the beginning of the Background Material section. DCIs, SEPs and CCCs for each activity are color-coded.* ***Building towards:*** **Performance Expectations:** HS-PS1-8. Develop models to illustrate the change in the composition of the nucleus of the atom and the energy released during the processes of fission, fusion and radioactive decay. HS-PS3-5. Develop and use a model of two objects interacting through electric or magnetic fields to illustrate the forces between objects and the changes in energy of the objects due to the interaction. HS-ESS1-3. Communicate scientific ideas about the way stars, over their life cycle, produce elements. **Disciplinary Core Ideas:** • PS1.C Nuclear Processes • ESS1.A The Universe and Its Stars **SEPs:** • Developing and using models • Using mathematical representations • Obtaining, evaluating, and communicating information **CCCs:** • Energy and Matter • Scale, proportion, and quantity • Patterns **Lesson Phenomenon:** Unit Phenomenon (graph of the abundance of the elements) **Lesson Objectives:** I. Students will begin synthesizing all they have learned by revisiting the precious metals from Lesson 1, comparing neutron capture models that could lead to their formation. II. Students will examine details in data and models that depend on nuclear processes important to the r-process, comparing two possible sites for the r-process, supernovae, and colliding neutron stars, arguing form evidence which is most likely. They will then examine a new observation (2017) which has led scientists to conclude that most of the gold in the universe could come from colliding neutron stars. III. After revisiting the list of questions, the class developed in Lesson 1, students will reflect on the famous quote on which this unit is based, 'We are Made of Starstuff'. This is the final assessment for the unit.

Background Information	**Structure of Lesson:** 1. (LAUNCH) In Activity 5-1, *The Origin of Precious Metals*, students recap what they learned about the s-process and draw conclusions as to how well s-process models can explain the abundances of the precious metals studied in Lesson 1. They then explore a similar model, the r-process, in which higher neutron fluxes result in more neutrons capture and a different path to the heavier elements. *2.* (EXPLORE) In Activity 5-2, *Refining r-process models and sites,* students explore stellar evolution models to determine the fate of the sun and one other star of their choosing. They then research and evaluate the dynamics of the evolution of their two stars from the main sequence to the red giant phase, including possible nuclear fusion and other reactions that can lead to nuclei more massive than helium, and communicate that information to their classmates in the form of a poster.
Materials	*Launch (5-1) & Explore (5-2)* *For each pair of students:* • Precious Metal Cards • Abundance Curve (laminated) • 11x17 Chart of Nuclides • Colored Pencils • Research on Star from Activity 4-2 *Summarize (5-3):* *For each student:* • Periodic Table • Colored Pencils • Lesson 5 Assessment Card
Prior Knowledge	This lesson brings together all the concepts students have been working on throughout the unit.
Engagement and Communication of Student Expectations	**Activity 5-1. The Origin of the Precious Metals** 1) Pass out the precious metal cards and laminated abundance chart from Lesson 1, and have students pull out the s-process graph they made in Lesson 4. Check out the five precious metals. Are they totally s-process elements, partially s-process elements, or not at all s-process elements? Have pairs look up the isotopic ratios and calculate in their notebooks what percentage of each element could come from the s-process. 2) (Slide 2) Step through the slide and facilitate a class discussion about the five precious metals. Which isotopes are s-process? Facilitate the class to discuss what they notice about the isotopes that are ‘missing’. *They are mostly either proton-rich or neutron-rich.* Could there be environments in the cosmos that could lead to those isotopes? For example, could there be environments that have many more neutrons or protons than in red giants/AGB stars? If there were, how might that change the process? *(Teacher Tip: Try to draw them to thinking about the rate of neutron capture in the s-process (once every 10 years). If the density of neutrons was greater, would that rate*

	change?) 3) (Slide 3) A model for what could happen is called the r-process (rapid-neutron capture) Using a different color of pencil, have students draw the r-process for a model where neutron densities are high enough that a neutron could be captured every 100 microseconds. Before starting, each pair should discuss a plan for dealing with isotopes with beta decay rates near to 100 microseconds. How will they handle branching? 4) When most students are finished, call time. Whatever explosive event that caused all the extra neutrons is over. Now the radioactive isotopes that were made will beta-decay to stability. With a third color of pencil, draw the beta-decay paths. Does the r-process account for some or all the isotopes missing from the s-process?
Exploration (20 minutes)	
Exploration	**Activity 5-2. R-process Sites: Explosive Nucleosynthesis** *1)* In a class discussion, have students examine the details of the abundance chart for elements heavier than iron. What features do they notice that would need to be explained by nucleosynthesis models for the heavier elements? *(Teacher Tip: You might suggest that students put a blank piece of paper over their laminated abundance graph and trace the average trend of the abundances above iron, ignoring the sawtooth patterns. They should notice two bumps, one around Z = 50 and one around Z=82.)* 2) (Slide 4) Nuclear shell structure is an important input for nucleosynthesis models. Early calculations showed that peaks in both the r-process and s-process occur around the closed shells at Z, N = 50, 82 and 126. In a class discussion, have students reason as to why the r-process peak is lower than the s-process peak in the calculations. (Note that the x-axis on the PowerPoint slide is Atomic Weight, not atomic number.). *Because the r-process peak is more neutron rich* *3)* (Slide 5) Current r-process models also show the effect of nuclear shell structure. More elements accumulate around the closed neutron shells because those nuclei are more stable. Play the r-process movie (on PowerPoint and unit flash drive) which is based on current models. Where could the r-process happen? That question puzzled scientists for decades. Scientists knew that it would take a very explosive environment to create a density of free neutrons large enough to make elements as massive as gold. 4) Scientists realized that any site for the r-process must be explosive, otherwise the neutron density would not be high enough. This is referred to as explosive nucleosynthesis. Working in the same pairs from Activity 4-2, have each pair pull out their research notes and H-R diagram for their second star (not the sun). Examining that star's life cycle, did the star ever go through a very explosive stage during its life? What stages might be explosive? After a short discussion, have groups share out in a class discussion. Did all groups find an explosive stage in their star's life cycle? Can they identify what is the property of a star that will determine whether it goes through an explosive stage? *A star must be more*

massive than the sun to go through an explosive supernova phase. After the supernova, the star ends up as a neutron star or black hole.

5) (Slide 6) For decades, supernovae were the leading candidate among scientists for the primary site of the r-process. Much effort has gone into modeling supernovae explosions. To better refine the models, astronomers observe the remnants of the supernova. Play the video on the PowerPoint as an example.
6) (Slide 7) What if we could observe a more recent supernova as it exploded? In 1987, a supernova explosion took place in one of our neighboring galaxies, the Large Magellenic Cloud. Scientists have been studying the nature and dynamics of the remnants for 30 years.
7) (Slide 8) SN1987a was notable because for the first time, underground detectors were in operation that saw an anomalous signal of low-energy neutrinos. After they compared notes and talked to astronomers, they realized that they were detecting neutrinos from the event, arriving at earth ahead of light. Now most neutrino experiments watch for these anomalies and are part of a worldwide network.

(TEACHER TIP: The next activity (#8) is optional if you have the time; this debate was the culminating event in the last revision of the unit. Copies of the articles, which are 10-15 years old, are included in the kit. The PowerPoint will examine prevailing theories as of 2018.)

8) Break the class into two groups and pass out copies of the two articles (in kit). Each group should spend a few minutes reading the article and writing down some points that favor that claim for the origin of gold. Then have a class debate.
9) (Slide 9&10) As astronomers collected more data and refined their models, it became more difficult to explain the abundances of the Z, N = 82 and 126 peaks through a supernova explosion. Scientists began to look for other sites for the r-process. To make the heaviest elements, models showed an environment with 75% neutrons was needed. But neutrinos interacted with neutrons during the supernova explosion, reducing their numbers to <55%. As early as 1999, scientists were looking at other possible sources of neutrons for the r-process.
10) (Slide 11&12). Many supernovae end life as a neutron star, which has very high neutron densities. More massive stars that undergo a supernova stage end life as a black hole. A neutron star is the size of a city, with densities so high that a teaspoon of material weighs a billion tons.
11) (Slide 13) Was it possible that a binary star system could end as two neutron stars, which could eventually collide? The prevailing theory was still supernovae because it was believed that they were much more abundant in the cosmos than binary star systems with two neutron stars.
12) (Slide 14) In October 2017, an announcement was made by scientists that on August 17, 2017, gravitational waves were detected from two colliding neutron stars. At the same time, the event was studied with telescopes across the electromagnetic spectrum. This momentous event changed the thinking that scientists had about the origin of gold and other heavy elements. Play the video which describes the discovery (linked from PowerPoint). The second video will give the ‘chirp’ signal in the gravity wave observatories as the two neutron stars finally merged.

	13) (Slide 15) The electromagnetic observations of the event showed two components, one signal from lighter elements and a longer duration, higher wavelength signal from heavier elements. 14) (Slide 16) When all the data was compiled, the picture emerging is that there were two jets - one emitted towards the beginning of the merger with a lower density of neutrons, and the second emitted during the actual merger with a higher density. Scientists think the first jet is a shock wave and is emitted along with a neutrino wind, similar to a supernova. The second one, with a higher neutron density, they call a tidal wave. 15) (Slide 17) The lower density could correspond to the 100 ms timescales we looked at earlier. What if there were 10x more neutrons and a nucleus encountered one every 1-10 ms? Returning to the neutron capture chart, and choosing another color of pencil, have students draw the path for a high neutron density r-process event. In a class discussion, discuss how this path could lead to heavier elements when it beta-decays. *(Teacher Tip: Students will quickly run off the left edge of the chart in this scenario. Think about what will happen when things way off the edge starts beta-decaying on the diagonal)* 16) (Slide 18) Studies of electromagnetic emissions in all wavelengths over several months gave scientists information about ejecta from both jets. They were able to measure the amount of mass ejected in each jet. 17) (Slide 19&20) This one discovery changed conclusions as to the origin of the heavy elements. These two slides are before and after the event. 18) (Slide 21) In order to really know for sure how all the elements are made, more data is needed, the masses and beta-decay half-lives for very neutron- rich elements. A new facility is coming on line in the near future to measure some of these important values.
Questions for Student Exploration	• Why is the Facility for Rare Ion Beams so much bigger than the CASPAR accelerator we examined in Lesson 4? • Is there one 'right' answer to the origin of heavy elements such as gold? Could there be multiple sites in the cosmos creating gold?
Summarize (10 minutes)	
Communicate and Synthesize	**Activity 5-3. 'We are Made of Starstuff'** 1) Have students pull out their periodic table templates and fill in the r-process elements. If they wish, they can distinguish between heavy r-process elements and light r-process elements. 2) Facilitate a class discussion about the various types of nucleosyntheses introduced in this unit. Are they necessary to make the precious metals that we rely on for our daily life. Is one step any more important than another? 3) Hand out the Lesson 6 Assessment Card (1 per student). Give them the remainder of the class period to work on their essay and finish at home.

Terminology and Concepts to Solidify	Ejecta – **Ejecta** is material ejected during an explosive event such as a supernova or colliding neutron stars. Explosive nucleosynthesis – **Explosive nucleosynthesis** occurs when a star, or some portion of the star, undergoes a thermonuclear runaway that results in an explosion. Supernovae are some of the most spectacular examples of this phenomenon. More common, however, are novae; these are thermonuclear runaways on the surface of a white dwarf star in a binary star system. Gravitational Wave Observatory – a facility that looks for ripples in space-time due to cataclysmic events happening in the universe, such as colliding black holes or neutron stars. The Laser Interferometry Gravitational-Wave Observatory (LIGO) is the **gravitational wave observatory** in the U.S., with sites at Hanford, WA and Livingston, LA. The VIRGO facility is in Italy. Multimessage Astronomy (MMA) – **Multimessage Astronomy** is a new field that combines data from multiple types of detectors to obtain information about events in the universe. Examples include GW170817, first detected in gravity waves, followed by gamma rays and other electromagnetic radiation. Another recent example is the detection of a very high energy neutrino in ICECube which was followed by gamma ray detection of a blazer from the same spot in the sky. r-process nucleosynthesis – Nucleosynthesis occurring in a region of high neutron densities, in which nuclei can capture a neutron approximately once every 0.1 second. Typical sites are core-collapse supernovae, colliding neutron stars and neutron stars colliding with a black hole. Scientists distinguish between the **heavy r-process**, which makes elements with A>130 and requires >75% neutron density, and **light r-process**, which makes elements with A<130 and requires 60-75% neutron density. rp-process nucleosynthesis – Nucleosynthesis occurring in a region of high proton densities, in which nuclei can rapidly capture protons before undergoing beta-decay. The **rp-process** is thought to end at tellurium because alpha decay begins to dominate. A possible site of the rp-process is an accreting binary system where one of the stars is a neutron star.
Connection to Big Ideas (Phenomena)	Explosive nucleosynthesis, such as the r-process, is necessary to explain the existence of the heavier elements. Before 2017, the predominant site for r-process nucleosynthesis was thought to be supernova explosions. However, models were failing to fit observational data. On August 17, 2017, a ripple in space-time was observed which was followed closely by a burst of gamma rays, and later by electromagnetic radiation at all wavelengths.
Follow Up/Practice	This is the end of the unit. Students are encouraged to research questions that they still have unanswered.
Optional Extension	The readings and debate are an option to be done after the breakthrough discovery is revealed. The readings are included in the kit.

Assessment	An essay on Carl Sagan's famous quote which provides the title of this unit is the final assessment for the unit. As an alternative, the post-assessment (duplicate of pre-assessment) can be given.

NAME______________________________

'We are Made of Starstuff'

UNIT POST-ASSESSMENT

Referring to the periodic table of the elements, answer the following questions to the best of your ability:

6. Are the abundances (amount) of all the elements the same?
   a. On earth?
   b. Throughout the solar system?
   c. Beyond the solar system?
   d. Why or why not?

7. What is the most abundant element on earth?
8. What is the most abundant element in the Sun?
9. Do all elements occur naturally?
10. Why are there so many elements in the periodic table? Where did they come from?

RUBRIC FOR PRE & POST ASSESSMENT
'We are Made of Starstuff'

Name:________________ **Score** _____ /12

	3 pts.	2 pts.	1 pt.	Score	Comments
Use of terminology	Most terms are used appropriately to show meaning	Some of the terms are used appropriately to show meaning	Few terms are used and/or are used incorrectly		
Nuclear Processes	Evidence of nuclear processes in the cosmos are included in a way that shows an understanding of the types and range of properties	Evidence of nuclear processes are mentioned but no details given	No evidence or incorrect evidence of nuclear processes in the cosmos		
Live Cycle of stars	The life cycle of our sun and other stars are included in a way that shows and understanding of the processes taking place	The life cycle of our sun and/or other stars are mentioned but no details given	No discussion or incorrect discussion of the life cycle of our sun and other stars		
Nuclear Astrophysic s Studies	Experimental studies of nuclear astrophysics are included in a way that show understanding of work happening in the field	Experimental studies of nuclear astrophysics are mentioned but no details given	No discussion or incorrect discussion of Experimental studies of nuclear astrophysics to give evidence for our understanding		

We Are Made of Starstuff

Kit B, Kit C

Science Focus: Exploring Nucleosynthesis

Lesson #	Lesson Title	Suggested Time
1	Are All Elements Created Equal?	50 minutes
2	In the Beginning: The Early Universe	50 minutes- part 1 50 minutes- part 2
3	From Stars to Atoms: Stellar Nucleosynthesis	50 minutes- part 1 50 minutes- part 2 50 minutes- part 3
4	Beyond Helium	50 minutes- part 1 50 minutes- part 2 50 minutes- part 3
5	A Breakthrough Discovery	50 minutes

We are Made of Starstuff- 9-12 (Physical Science)

Students take their understanding of the periodic table to a third dimension through the topic of nucleosynthesis (formation of the elements). They explore the nuclear processes of radioactive decay, fusion, and fission. Then, armed with that basic knowledge, delve into processes that formed the elements: Big Bang, stellar and explosive nucleosynthesis. These topics introduce physical and earth/space science standards that are often not covered in the traditional curriculum.

Physical Science Standards	Lesson

HS-PS1-8 Develop models to illustrate the changes in the composition of the nucleus of the atom and the energy released during the processes of fission, fusion, and radioactive decay.	2, 3, 4, 5
HS-PS2-4. Use mathematical representations of Newton's Law of Gravitation and Coulomb's Law to describe and predict the gravitational and electrostatic forces between objects.	2, 3, 4
HS-PS3-3. Design, build and refine a device that works within given constraints to convert one form of energy into another form of energy.	4
HS-PS3-5. Develop and use a model of two objects interacting through electric or magnetic fields to illustrate the forces between objects and the changes in energy of the objects due to the interaction.	4, 5
Earth/Space Science Standards	**Lesson**
HS-ESS1-1. Develop a model based on evidence to illustrate the life span of the Sun and the role of nuclear fusion in the Sun's core to release energy that eventually reaches Earth in the form of radiation.	3, 4
HS-ESS1-2. Construct an explanation of the Big Bang Theory based on astronomical evidence of light spectra, motion of distant galaxies and composition of matter in the universe.	1, 2
HS-ESS1-3. Communicate scientific ideas about the way stars, over their life cycle, produce elements.	4, 5
Engineering, Technology and Society Standards	**Lesson**
HS-ETS1-1. Analyze a major global challenge to specify qualitative and quantitative criteria and constraints for solutions that account for societal needs and wants.	1

We are Made of Starstuff

Materials List

➢ **Teacher-Provided**

Lesson	Materials Needed
1	*Pre-launch:* *For each student:* • Periodic Charts (laminated) • Pre-assessment (Print Master) *Launch (1-1):* *For each pair of students:* • Precious Metals Cards (laminated) *Explore (1-2) & Summarize (1-3):* *For each pair of students:* • Precious Metals Cards (laminated) • Solar System Abundances Data Graph (laminated) *Assess (1-4):* • *(Optional) Index Card (Assessment Exit Card if not using notebooks)* *Optional Extension:* *For each group of students:* • *Lesson 1 Task Card (laminated)* • *Colored Pencils* • *Ruler* ➢ Computers ➢ Large Paper/ Poster Board
2	*Launch (2-1):* *For each pair of students:* • Big Bang Graphic (laminated) *Explore (2-2, 2-3) & Summarize (2-4)* *For the Classroom:* • Element Cards (laminated) • Ping-Pong Ball • Temperature Signs (2 – laminated) *Explore (2-5)* *For each pair of students:* • Activity 2-5 Task Card *For each pair:* • Compare/contrast cards ➢ Computers *Summarize & Assess (2-6)* • *Lesson 2 Assessment Card* ➢ *Computers* ➢ *Poster Paper*
3	*Launch (3-1):* No materials needed *Explore (3-2):* *For the classroom:*

	• Cloud Chamber (set up ahead of class)
	➢ Ice Bath
	➢ Isopropyl Alcohol/Ethanol, >70%
	• Digital Geiger Counter
	• Pottery Samples
	• Cs/Ba isogenerator
	• Eluting Solution
	• Beaker
	• Non-latex Gloves
	• Snack Size Baggies
	• Chem-Wipes
	For each small group (3 students):
	• Vernier Go Direct Handout (Print Master)
	• Vernier Go Direct Radiation Monitor
	• Activity 3-2 Task Card
	• Sample of Radioactive Material
	➢ Computer, Graphing Calculator, Graph Paper
	➢ Vernier Graphical Analysis Software
	➢ Stopwatch/Timer App
	Summarize (3-3):
	No materials needed
	Explore (3-4) & Summarize (3-5)
	For each small group (4 students):
	• Two Nucleosynthesis Game Boxes
	• Game Rules Chart
	• Chart of Nuclides (laminated)
	Explore (3-6):
	For each small group (4 students):
	• Activity 3-6 Task Card
	• Geiger Counter
	• Box containing:
	    ○ Beta Source, 2 Unknown Sources
	    ○ Set of Degraders
	    ○ Ruler
	    ○ Protractor
	    ○ Clay
	    ○ Binder Clips
	Summarize (3-7):
	For each student:
	• Lesson 3 Assessment Card
	• Evidence Cards
	• Reasoning Template (laminated)

4	*Launch (4-1):* No materials needed *Explore (4-2):* *For each pair of students:* • Activity 4-2 Task Card

	• Colored Pencils ➢ Computers ➢ Poster Paper *Summarize (4-3):* *For each student:* • Periodic Table Template (Print Master) • Colored Pencils *Explore (4-4) & Summarize (4-5)* *For the classroom:* ➢ Large Sheet of Paper/Whiteboard ➢ Colored Markers *For each pair of students:* • Nucleosynthesis Game Kits • Chart of Nuclides • Activity 4-4 Task Card • 11x17 Chart of Nuclides • Colored Pencils *Explore (4-6):* *For each small group (3 students):* • Activity 4-6 Task Card • Authorization to Proceed (ATP) Card • Set of Magnets and Steel Balls • Set of Accelerator Tracks • Tape • Measuring Tape • Plastic Cup *For each student:* ➢ Safety Glasses
5	*Launch (5-1) & Explore (5-2)* *For each pair of students:* • Precious Metal Cards • Abundance Curve (laminated) • 11x17 Chart of Nuclides • Colored Pencils • Research on Star from Activity 4-2 *Summarize (5-3):* *For each student:* • Periodic Table • Colored Pencils • Lesson 5 Assessment Card

Note to Teachers:

This unit is a second revision of a curriculum unit of the same name written and piloted by the Education and Outreach Department at the Sanford Underground Research Facility in 2015-2016. It is designed to replace two weeks of a high school course curriculum with a study of nuclear science and the origin of the elements in the cosmos and connect to Sanford Lab science through the CASPAR (Compact Accelerator System for Performing Astrophysical Research) facility. All lessons are tied to NGSS physical and earth/space science standards, scientific and engineering practices, and crosscutting concepts. The revisions for 2018 reorder the lessons to integrate student sensemaking of nuclear processes into the storyline of the origin of the elements, rather than have them as a separate set of activities. It also introduces a new scientific breakthrough in this field that came in 2017 – GW170817. GW170817 was the first direct observation of two colliding neutron stars, observed on August 17, 2017, and announced in October 2017. This observation was made first at the Laser Interferometer Gravitational Observatory (LIGO) which was followed with gamma rays, visible light, and finally data throughout the electromagnetic spectrum. This observation marked the birth of the new field of multimessage astronomy and provided substantial evidence to the question of the origin of the heavy elements.

Teacher Primer

Because parts of this material may not be familiar to all teachers, there is a teacher primer on the flash drive with background material for each topic.

Pre-Requisites

The unit has been field-tested in chemistry (several levels) and astronomy courses at schools across the region. The current version assumes that students have studied the periodic table and know the basic components of matter (atoms and their constituents).

Resources

The unit comes with a materials kit that will be loaned to teachers in the state of South Dakota free of charge. Included in the kit is most of what a teacher needs to implement the unit. A notebook with the lessons and a unit flash drive are also included. The unit flash drive contains a Print Master file, keys to all handouts, PowerPoint presentations and other media such as videos.

Science Notebooks

Interactive science notebooks are strongly encouraged but not required for this unit. If students already use notebooks in science class, continue to use the same ones. The next page gives some guidance if the use of notebooks is new to you. Most lessons include laminated Task Cards for each activity and assessment and students are expected to record everything in a notebook.

Assessments

A pre- and post-assessment are included with the unit. These were used in the original field testing of the unit and are currently optional, should you, the teacher, choose to use them. A set of laminated periodic tables are included to use with these assessments.

In addition, each lesson has a formative assessment. Assessment cards are included with rubrics. These assessments are based on Claim-Evidence-Reasoning (CER) framework. We have attempted to make these three-dimensional and the scope varies by lesson – some are individual and some group; some require research and other are exit cards. The Lesson 5 Assessment can be used as the unit assessment if desired.

Phenomenon-based Learning

The Sanford Underground Research Facility Education and Outreach Department has adopted the vision of Ambitious Science Teaching (www.ambitiousscienceteaching.com) as the framework of all our curriculum units. Students spend the course of the unit coming to an understanding of a complex and puzzling natural phenomenon. In this unit, the phenomenon is the graph of abundances of the elements in the solar system. Students will be returning to that data throughout the unit.

* For the standards addressed in this unit, the South Dakota science standards are identical to the Next Generation Science Standards.

A Teacher's Guide to the Interactive Notebook

For this unit it is intended that students utilize an interactive notebook. If you already have a science journal, or notebook, that students maintain during the class please continue to use that format. If you do not have a journal or notebook for your classroom, use an Interactive notebook for the duration of this unit.

The interactive notebook should be kept in a spiral notebook or composition notebook.

The front side of the first piece of paper in the interactive notebook should be designated as a table of contents. The table of contents will be created as the pages of the notebook are created. Following the table of contents, all pages should be numbered, and the dates recorded.

The next front side page should be the title page. For this unit students should create a page that reads 'We are Made of Starstuff'. Students are free to decorate this page any way they chose.

Beginning with the backside of the second sheet of paper the students begin to make entries into their interactive notebook. Some examples of entries could include:

- Notes taken while reading articles or textbook or watching a video (Cornell Notes is a great template to use)
- Lab results and observations
- Vocabulary terms and definitions
- Venn Diagrams
- Student sketches/modules
- Mind-maps (concept maps)
- Questions that the student is pondering about the topic

At the end of the unit students can write a summary of their understanding of the unit. If you would like to have students write a summary, have them select two items that represent their best work. Students should give the dates of their entries and then explain why they chose these two items, what they learned from these two items, and how these items reflect scientific thinking or skills. Students must use evidence to defend their choices and should not provide emotional responses such as "that is my best drawing" or "that activity was a lot of fun". The reflection should be written on the last page of the interactive notebook for that unit.

We encourage your students to take their notebooks home to share with their parents or adults living in the home with them. The adults should look through the notebook and read the reflection with the student.

Lesson 1, *Are all elements created equal?*

ACTIVITY 1-1. How Precious are Precious Metals?

Questions	What we Figure out	New Questions
Why are some elements worth more than others?	The worth of an element is due not only to its uses in society but to its abundance on earth. Supplies are limited.	Why are the supplies of some elements limited? Are there less precious metals available than other elements?

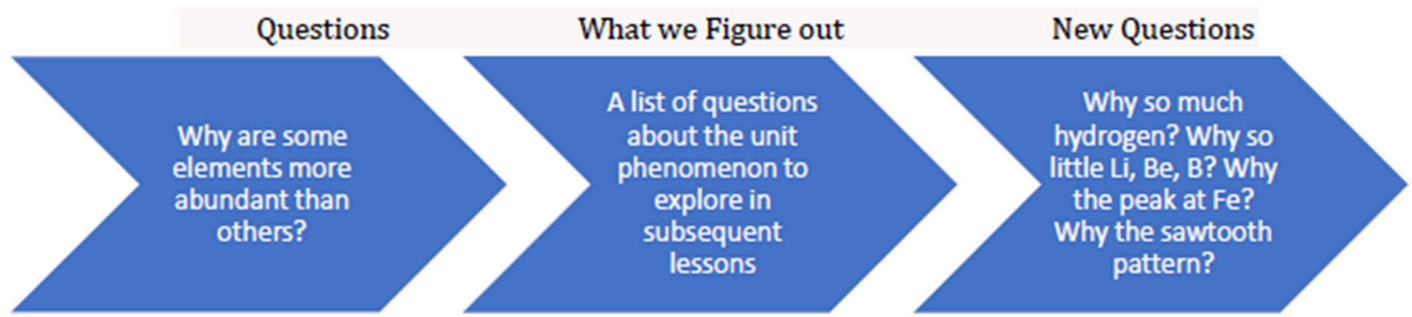
- **ACTIVITY** – Students will analyze economic data on five elements important to society and analyze their value to society and everyday life. They will examine predictions of when these elements will run out and consider possible solutions to this global problem.

ACTIVITY 1-2. What's It Worth?

Questions	What we Figure out	New Questions
Why are the supplies of some elements limited? Are there less precious metals available than other elements?	The correlation between solar system abundances and worth is weak; the correlation is stronger for crustal data.	Why are some elements more abundant than others? Could technology enable us to mine limited elements from space?

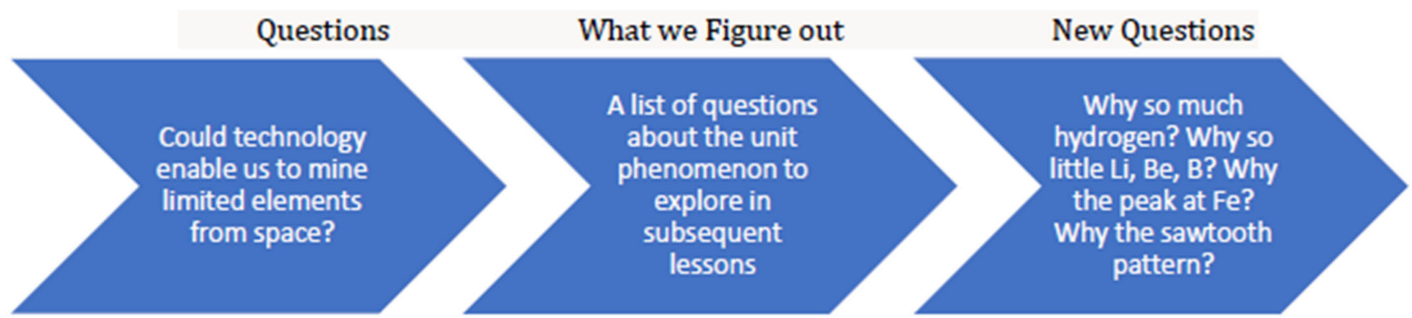
ACTIVITY – Students will be introduced to the anchoring phenomenon for the unit – data on the abundance of the elements in the solar system. They will re-examine the precious metals and look for correlations with abundance in the solar system and in the Earth's crust.

ACTIVITY 1-3. Exploring the Phenomenon



- **ACTIVITY** – Students attempt to make sense of the abundance of the elements in the solar system and develop questions in explore in future lessons.

ACTIVITY 1-4 (Formative Assessment). Space Mining, Inc.



ACTIVITY – Students propose a solution to the limited supply of one of the precious metals utilizing mining of asteroids.

Lesson 1	Are All Elements Created Equal?
Overview Standard(s) & Objectives	*This lesson should require one normal class period or part of a block period. The structure and flow of the lesson is given at the beginning of the Background Material section. DCIs, SEPs and CCCs for each activity are color-coded.* **Standards:** HS-ESS1-2: Construct an explanation of the Big Bang Theory based on astronomical evidence of light spectra, motion of distant galaxies and composition of matter in the universe. HS-ETS1-1. Analyze a major global challenge to specify qualitative and quantitative criteria and constraints for solutions that account for societal needs and wants. **Disciplinary Core Ideas:** • ESS1.A The Universe and Its Stars • ETS1.B Defining and Delimiting Engineering Problems **Science and Engineering Practices:** • Asking Questions and Defining Problems • Analyzing and Interpreting Data • Constructing Explanations and Designing Solutions **Crosscutting Concepts:** • Energy and Matter • Patterns • Influence of Science, Engineering and Technology on Society and the Natural World **Lesson Phenomenon:** abundance of elements in solar system (poster) **Lesson Level Learning Goals:** • Students will analyze economic data on five elements important to society and analyze their value to society and everyday life. They will examine predictions of when these elements will run out and consider possible solutions to this global problem. • Students attempt to make sense of the abundance of the elements in the solar system and develop questions in explore in future lessons. • Students propose a solution to the limited supply of one of the precious metals utilizing mining of asteroids. • Students will be introduced to the anchoring phenomenon for the unit – data on the abundance of the elements in the solar system. They will re-examine the precious metals and look for correlations with abundance in the solar system and in the Earth's crust.
Background Information and Reference Material	**Structure of Lesson:** 6. (PRE-LAUNCH) This unit starts with a pre-assessment which could be done the day before to save time. Students should be given a laminated periodic table along with the written assessment. They are not expected to know the content at this point, but the results should guide the teacher as to potential areas of misconception, lack of prior knowledge, etc. 7. (LAUNCH) Activity 1-1, *How Precious are Precious Metals?* is designed to

get students thinking about how certain elements which are important to society and their own lives are 'endangered' and could run out in their lifetime, a societal problem that needs a solution. Students work in pairs to examine the economic value and uses of five precious metals, and industry reports on the future supply.

8. (EXPLORE) In Activity 1-2, *What's It Worth?,* students are introduced to the unit anchoring phenomenon, data on the abundance of the elements in the solar system (laminated graph), and additional data on the abundance of the elements in the Earth's crust (in PowerPoint). They calculate correlations between abundances and 'worth' as defined by commodities prices for the precious metals. They make sense of the data and strength of the correlations in classroom discussions about the complexity of the societal problem.
9. (SUMMARIZE) In Activity 1-3, *Exploring the Phenomenon,* students examine the graph of abundances in more detail, looking for patterns and asking questions to explore in later lessons.
10. (FORMATIVE ASSESSMENT) In Activity 1-4, *Space Mining, LLC,* students have an opportunity to offer a solution for the global societal problem addressed in this lesson. They will be asked to make a case for mining a precious metal of their choice on a nearby asteroid.

(TEACHER TIP: The assessment activity 1-4 can be done in class, as an exit card or assigned as homework. Activity 1-3 and 1-4 could be interchanged if desired or if it fits better with the flow of the discussion following Activity 1-2.)

Content information for teachers: See the unit primer for Lesson 1

Examples of student work:

Activity 1-2, What's It Worth- EXPLORE

- Answers to questions in Slide 8 (class exercise)

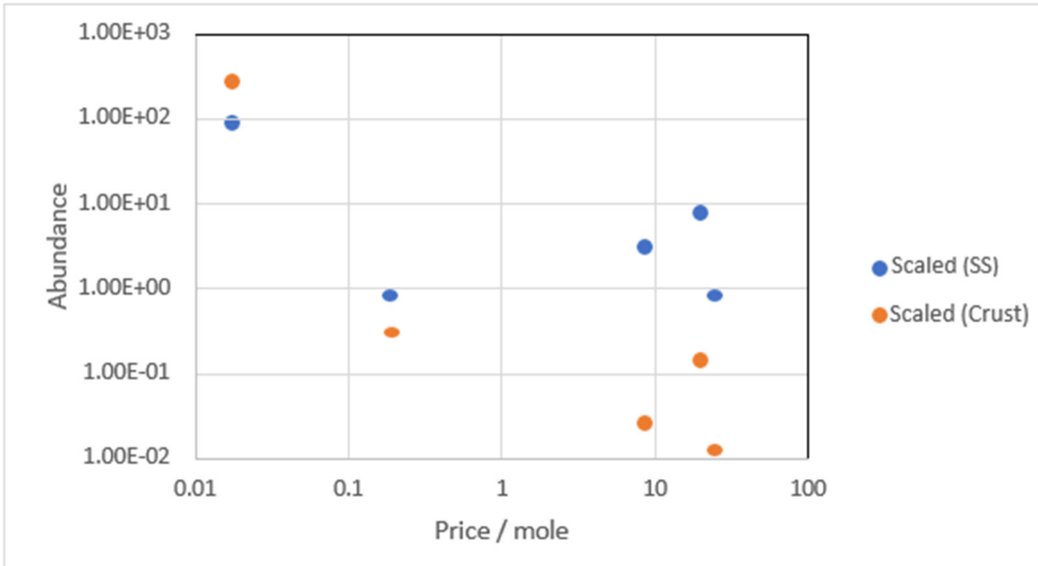
Element	*Relative Abundance*	*Ratio to Silicon*	*Atomic Mass*	*Mass Abundance*	*Ratio to Silicon*
H	$5x10^{10}$	*50,000*	*1*	$5x10^{10}$	*1,800*
Si	$1x10^{6}$	*1.0*	*28*	$28x10^{10}$	*1.0*
U	*0.01*	10^{-8}	*238*	*2.38*	$8.5x10^{-8}$

There are 5×10^{12} more hydrogen atoms that uranium atoms in the solar system.

- Answers to student exercise, abundance of their precious metals (reading off the plot won't be this accurate)
  - Cu – 85.7
  - Pd – 2.86
  - Ag – 0.857
  - Pt – 7.14
  - Au – 0.857
- Figure 1.1 gives an example of correlation graphs students might derive as part of this activity. The plot uses data from solar system abundances as well as data from abundances in the Earth's crust (Slide 9 of

PowerPoint). Both sets of data show a weak correlation with abundance, reflecting the importance of worldwide demand to determining prices.

Figure 1.1 – An example of a correlation plot made using Excel. Price/ounce has been converted to price/mole.



Materials

Pre-launch:

For each student:

- Periodic Charts (laminated)
- Pre-assessment (Print Master)

Launch (1-1):

For each pair of students:

- Precious Metals Cards (laminated)

Explore (1-2) & Summarize (1-3):

For each pair of students:

- Precious Metals Cards (laminated)
- Solar System Abundances Data Graph (laminated)

Assess (1-4):

- *(Optional) Index Card (Assessment Exit Card if not using notebooks)*

Optional Extension:

For each group of students:

- *Lesson 1 Task Card (laminated)*
- *Colored Pencils*
- *Ruler*
- Computers
- Large Paper/Poster Board

Prior Knowledge

Students should have a basic understanding of the structure of an atom, the difference between elements, and the organization of the periodic table. Depending

	on where they are in chemistry studies at the time this unit is introduced, they may have mental models that the nucleus of the atom always remains unchanged. This misconception will be addressed in the unit. Students will need a basic understanding of the logarithmic scale for this and other lessons in this unit. For comparison of linear vs. log scales, once could view this video, also located on the flash drive.
Pre-assessment	5.) (Slide 2) As students enter the room and get ready, have the periodic rap video playing, also located on the flash drive. *(Teacher Tip: All video and audio files for the unit are linked from the Power Point files, or available on the flash drive. If you are using Keynote in your classroom to display PPT files, the direct links may not work).* 6.) (Slide 3) Explain to students that they are going to be starting a unit that examines the elements of the periodic table in greater detail; pass out periodic charts and the pre-assessment. Emphasize to the students that they should make their best guess on the pre-assessment if they don't know the answers. They will be exploring the topic in detail in the next several class periods. Allow 10 minutes for the pre-assessment. 7.) Pick up the pre-assessments but have students keep their periodic charts for the next activities. 8.) **Optional: (slide 4)** Review the organization of the periodic table if students are unfamiliar with it.
Launch (10 minutes)	
Engagement	Activity 1-1. How Precious are Precious Metals? 4.) (Slide 5) Have students work with a partner and hand each pair a set of laminated precious metal cards. Ask them to brainstorm with their partner and write down three reasons why the prices of the five 'precious metals' are so different. Then have them write down three reasons one or more of these elements are important in their lives. *5.)* In a class discussion, have groups first comment on the importance of these five elements. How would it affect their lives if they didn't exist? Then have the groups share some of their reasons for the price differential and write them on the board. Why are they called precious metals? *6.)* (Slide 6) Show the slide of the ACS *Periodic Table's Endangered Elements.* Does this inform the previous discussion or raise additional questions? Have students add to or revise their reasons for the price differentials. *(Teacher Tip: Most groups should have considered that some of the elements are rarer than others and its effect on the price. If not, you will need to lead them to that possibility before continuing).*
Explore (15 minutes)	
Exploration	Activity 1-2. What's it worth? 6.) (Slide 7) Give each group a laminated graph of the abundances of the elements in the solar system. Discuss the fact that the y-axis is logarithmic. This would be a

	good point to review linear versus log scales with this video if the class needs it. Point out that the graph represents relative abundances and values are scaled randomly to the element Silicon at 1 million. 7.) (Slide 8) Have them pick out as a class the most and least abundant elements in the solar system and work out the examples on the board on how they compare to silicon. *(Hydrogen – Most Abundant = $5x10^{10}$ =50,000 x more abundant than silicon; Uranium – Least Abundant = 10^{-2}=10^{8}x less abundant than silicon)*. Work out as a class how many more atoms of hydrogen are in the solar system than uranium atoms ($5x10^{12}$). What about if you convert to mass? What would the ratio be? (~$2x10^{10}$). 8.) Have the pairs use the data to determine he relative abundance of the five precious metals on their cards. Is there a correlation between the price of the element and the abundance? Why or why not? *(Teacher Tip: There is a correlation but not strong. By this point some students should have thought about whether abundances on Earth are the same as those in the solar system. If not, lead them there by asking them about hydrogen and helium on Earth. Is it 98% of the elemental abundance?).* 9.) (Slide 9) Show the graph of the abundances of the elements in the Earth's crust and work through with the class: does this present a better correlation with the spot price? Why are the abundances on Earth so different than the abundances in the solar system as a whole? 10.) (Slide 10) To finish the discussion of the precious metals, show the timetables for running out of certain elements. What are some ways society could mitigate the potential effects of running out of important elements?
Questions	• Are all elements created equal? What makes some elements more valuable than others? • For the precious metals used as an example here, how would it affect our lives if they didn't exist on Earth? • Why are the abundances on Earth so different than the abundances in the solar system as a whole? • What are some ways society could mitigate the potential effects of running out of important elements?
Summarize (20 minutes)	
Communicate	*(Teacher Tip: Activity 1.3 & 1.4 can be interchanged if you wish to do the assessment in class. Both address questions students should have at the end of the Exploration. The assessment can also be assigned as homework or used as an exit card).* Activity 1-3. Exploring the Phenomenon 3.) Post the large version of *Abundance of the Elements in the Solar System* at the front of the room and inform students that for the next several lessons they will be exploring this data. Have them work with a partner and write down somethings they notice about the data. What patterns do they see? In a class discussion make a record of the patterns the students have noticed. Do they have any explanations for the patterns?

	4.) What questions do students have about the data that cold be answered by further investigation? Record everyone's questions. Do they have any ideas for investigations that could help answer the questions? Some questions students are likely to come up with are: • Why is hydrogen (and helium) so much more abundant than anything else? • Why is Li, Be, B so low compared to the neighboring elements? • Why is Fe higher than its neighbors? • Why are there bumps in the abundances above Fe? • Why is there a zig-zag pattern? *(Teacher Tip: The unit is set up to explore these question from the lowest mass elements up to the highest mass elements. Try to steer the students towards exploring it in that order. Keep the list of questions in the front of the room with the abundance poster during the unit. Each day students should add new questions.)* Activity 1-4. Space Mining, Inc. (ASSESSMENT) 3.) (Slide 11) To close out the lesson, show the students this video about Asteroid Cruithne, a near-earth asteroid. 4.) Pass out the Lesson 1 Assessment Card. Students can write a paragraph in their notebook or turn in a paragraph as an exit card.
Terminology and Concepts to Solidify	Abundance - a measure of the occurrence of the element relative to all other elements in each environment. Abundance is measured in one of three ways: by the mass-fraction (the same as weight fraction); by the mole-fraction (fraction of atoms by numerical count, or sometimes fraction of molecules in gases); or by the volume-fraction (for mixed gases).
Connection to Big Ideas (Phenomena)	The data on abundances is the big idea for the unit. The class will be revisiting it as they explore the formation of the elements at various locations and times in the universe.
Follow Up/Practice	Students might want to explore more about asteroid mining. A link to a video about the company Planetary Resources, Inc. is listed on the Lesson 1 Assessment card to get them started. See optional extension.
Optional Extension	Have students organize into larger groups (optimal 3-4) and collect a Task Card for a project to develop a model of a periodic table that will reflect elemental abundances. These can be presented orally or displayed in class.
Assessment	Activity 1-4. See lesson 1 Assessment Card for rubric.

NAME______________________________

'We are Made of Starstuff'

UNIT PRE-ASSESSMENT

Referring to the periodic table of the elements, give your best guess to the following questions:

1. Are the abundances (amount) of all the elements the same?
    a. On earth?
    b. Throughout the solar system?
    c. Beyond the solar system?
    d. Why or why not?
2. What is the most abundant element on earth?
3. What is the most abundant element in the Sun?
4. Do all elements occur naturally?
5. Why are there so many elements in the periodic table? Where did they come from?

RUBRIC FOR PRE & POST ASSESSMENT

'We are Made of Starstuff'

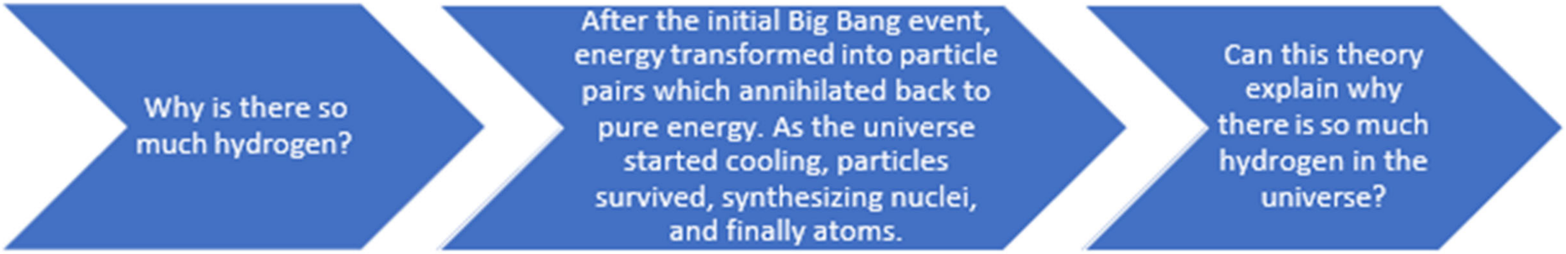
Name:__________________ **Score______/12**

	3 pts.	2 pts.	1 pts.	Score	Comments
Use of terminology	Most terms are used appropriately to show meaning	Some of the terms are used appropriately to show meaning	Few terms are used and/or are used incorrectly		
Nuclear Processes	Evidence of nuclear processes in the cosmos are included in a way that shows an understanding of the types and range of properties	Evidence of nuclear processes are mentioned but no details given	No evidence or incorrect evidence of nuclear processes in the cosmos		
Live Cycle of stars	The life cycle of our sun and other stars are included in a way that shows and understanding of the processes taking place	The life cycle of our sun and/or other stars are mentioned but no details given	No discussion or incorrect discussion of the life cycle of our sun and other stars		
Nuclear Astrophysics Studies	Experimental studies of nuclear astrophysics are included in a way that show understanding of work happening in the field	Experimental studies of nuclear astrophysics are mentioned but no details given	No discussion or incorrect discussion of Experimental studies of nuclear astrophysics to give evidence for our understanding		

Lesson 2, *In the Beginning: The Early Universe*

ACTIVITY 2-1. The Big Bang Theory

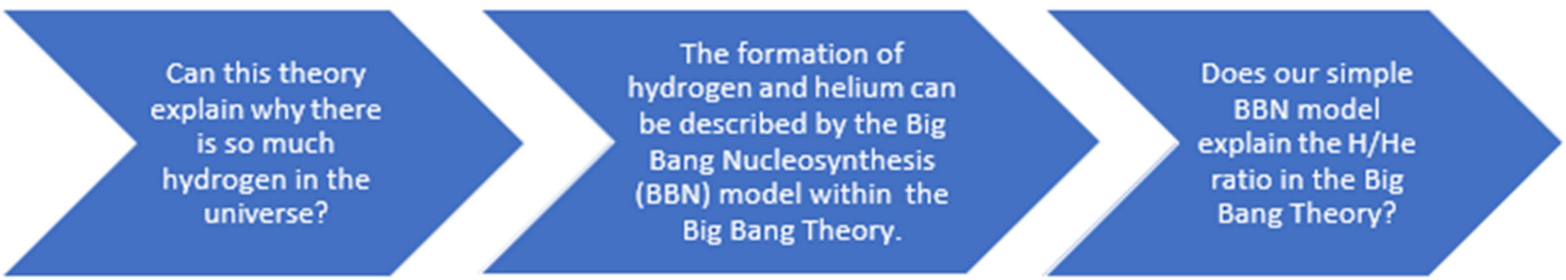
Questions	What we Figure out	New Questions



ACTIVITY – Students explore the Big Bang theory (lesson phenomenon) and generate questions about it and what it has to do with the formation of elements. They also make sense of the term nucleosynthesis, which will be used throughout the unit.

ACTIVITY 2-2. Modeling Big Bang Nucleosynthesis, Part 1

Questions	What we Figure out	New Questions



ACTIVITY – Within the Big Bang Theory, students will explore the transition from pure energy to the first nuclei (Big Bang Nucleosynthesis) in the first 3+ minutes of the universe. They will explore the role of neutron decay in the model.

ACTIVITY 2-3. Modeling Big Bang Nucleosynthesis, Part 2

Questions	What we Figure out	New Questions
Does our simple BBN model explain the H/He ratio in the Big Bang Theory?	Due to the number of neutrons available, He production in BBN is limited to 24%.	What about more massive elements (Li, Be, B)?

ACTIVITY – Using the game to develop their model, students will explore what parameters could change the ratio of H/He formed during BBN.

ACTIVITY 2-4. Energy and Matter

Questions	What we Figure out	New Questions
What about more massive elements (Li, Be, B)?	Mass-energy conservation, including the binding energy of a nucleus, limits production of heavier elements.	What happened next?

ACTIVITY – Students investigate the energetics of the fusion reactions that could lead to heavier elements in the Big Bang and construct explanations as to why most of the universe was comprised of hydrogen and helium at this time.

ACTIVITY 2-5. From nuclei to atoms to stars

Questions	What we Figure out	New Questions
What happened next?	The universe was dark for many millions of years until stars and galaxies began to form from clumps of gas.	Is there scientific evidence that can confirm the Big Bang Theory is accurate?

ACTIVITY – Using mathematical representations of gravitational and electromagnetic interactions, students explore models for the formation of the first atoms and stars, 100 million to a billion years after the Big Bang.

ACTIVITY 2-6. Connecting to evidence

Questions	What we Figure out	New Questions
Is there scientific evidence that can confirm the Big Bang Theory (and BBN) is accurate?	Many observations have confirmed the predictions of the Big Bang Theory, but we cannot probe all eras experimentally.	What happened next? Can stars make new elements?

ACTIVITY – Students research evidence for the BBN model and communicate using claims, evidence and reasoning. (Lesson Assessment)

Lesson 2	In the Beginning: The Early Universe?
Overview Standard(s) & Objectives	*This lesson is designed for two 50-minute class periods or one block period. The assessment for the lesson is a research piece which can be done outside of class or could take an additional class period. The structure and flow of the lesson is given at the beginning of the Background Material section. DCIs, SEPs and CCCs for each activity are color-coded.* **Performance Expectations:** HS-PS1-8: Develop models to illustrate the changes in the composition of the nucleus of the atom and the energy released during the processes of fission, fusion, and radioactive decay. HS-PS2-4. Use mathematical representations of Newton's Laws of Gravitation and Coulomb's Laws to describe and predict the gravitational and electrostatic forces between objects. HS-ESS1-2: Construct an explanation of the Big Bang Theory based on astronomical evidence of light spectra, motion of distant galaxies, and composition of matter in the universe. **Disciplinary Core Ideas:** • PS1.C Nuclear Processes • PS2.B Types of Interactions • ESS1.A The Universe and Its Stars **Scientific and Engineering Practices:** • Developing and Using Models • Using mathematical representations and computational thinking • Constructing Explanations and Designing Solutions **Crosscutting Concepts:** • Energy and Matter • Patterns **Lesson Phenomenon:** • The Big Bang Theory poster **Lesson Objectives:** VII. Students explore the Big Bang theory (lesson phenomenon) and generate questions about it and what it has to do with the formation of elements. They also make sense of the term nucleosynthesis, which will be used throughout the unit. VIII. Within the Big Bang Theory, students will explore the transition from pure energy to the first nuclei (Big Bang Nucleosynthesis) in the first 3+ minutes of the universe. They will explore the role of neutron decay in the model. IX. Students will investigate what parameters could change the ratio of H/He predicted by the BBN model. X. Students investigate the energetics of the fusion reactions that could lead to A>4 in BBN and draw conclusions as to why most of the universe was comprised of hydrogen and helium at this time. XI. Using mathematical representations of gravitational and electromagnetic interactions, students explore models for the formation of the first atoms and stars

	100 million to a billion years after the Big Bang. XII. Students research evidence for the BBN model and communicate using claims, evidence, and reasoning scaffolding.
Background Information and Reference Material	**Structure of Lesson:** 11. (LAUNCH) In Activity 2-1, *The Big Bang Theory,* students are introduced to the Big Bang Theory as the most widely accepted theory for the evolution of the universe. The poster representation of the theory is the phenomenon for the lesson and will be tied back to the anchoring phenomenon (data of solar system abundances) throughout the lesson. Students will make observations and ask questions about the Big Bang Theory based on the poster and explore the first microsecond of the universe. They will discuss key concepts (mass-energy equivalence (binding energy); conservation laws) that will be used in modeling activities later. 12. (EXPLORE A&B) Activities 2-2 and 2-3, In *Modeling Big Bang Nucleosynthesis, Parts 1&2,* students model the fusion reactions that create nuclei with more than one nucleon (neutron or proton), incorporating the role of temperature and energy in the early universe. They then plan their own investigation as a class to explore parameters within the model that could affect the number of elements made. They compare their results with the predictions of Big Bang Nucleosynthesis theories. *(Teacher Tip: For schools with a 50-55 minute class period, the end of Activity 2-3 is a natural stopping point for Day 1 of this lesson.)* 13. (SUMMARIZE B) In Activity 2-4, *Energy and Matter,* students are introduced to the crosscutting concept of binding energy and use conservation laws to construct explanations for why nuclei heavier than helium are seldom created in BBN. These major crosscutting concepts around the topics of energy and matter are introduced here and will be returned to throughout the unit. 14. (EXPLORE C) In Activity 2-5, *From Nuclei to Atoms to Stars,* students use mathematical representations of Coulomb's law and Newton's Law of Gravitation to develop simple models to describe and predict the evolution of the universe from hydrogen and helium nuclei to atoms and finally to stars. 15. (SUMMARIZE C) In Activity 2-6, *Connecting to Evidence,* students work in groups to research and communicate key evidence that lead most scientists to accept the Big Bang Theory as the most likely explanation for how matter and energy evolved from the early universe to the structures we have today. The product of the research constitutes the assessment for this lesson. **Content information for teachers:** See the unit primer for Lesson 2. **Examples of student work**: *Summary of information on back of cards:*

4) *10 billion degrees – p and n move freely and do not interact*
5) *1 billion degrees (100 sec) – deuteron (d) forms from p+p or p+n; triton (3H) forms from d + n*
6) *< 1 billion degrees (200 sec) – the following reactions can occur*
    1. *3He: from p+d;*
    2. *4He: from 3He+n or 3H+p or 3He + d*
    3. *7Be: from 3He + 4He*
    4. *7Li: from 7Be + electron*

The reactions included in the modeling activity are given in Table 2.1.

Table 2.1. BBN Reactions

100 seconds (10^9 K)	200 seconds ($<10^9$ K)
p + p → 2H + e+ + v	p + 2H → 3He
p + n → 2H	3He + n → 4He
n + 2H → 3H	2H + 3He → 4He + p
	2H + 3He→ 4He + n + e+
	3H + p → 4He
	3He + 3He → 4He + 2p
	3He + 4He → 7Be
	7Be + e- → 7Li
	7Li + p → 4He + 4He

Activity 2-4, Energy and Matter

SUMMARIZE

The table the students put on the board should look like Table 2.1. Students will discuss the role of deuteron formation in nucleosynthesis and what would happen of deuterons could form much earlier and much later. But why did deuterons form at 100 seconds, and not 10 seconds or 1000 seconds?

References:

- The *Kinesthetic Big Bang* activity was adapted from a NASA booklet, *What is your Cosmic Connection to the Elements,* which is included on the unit media, or can be found at https://www.nasa.gov/pdf/190387main_Cosmic_Elements.pdf.
- The information about the Big Bang eras is taken from Sky and Telescope online blogs at http://www.skyandtelescope.com/astronomy-resources/how-did-the-universe-begin-happened-big-bang/
- The Attribute table is taken from the Universe Adventure website, at http://universeadventure.org/index.html. Additional information is available here about the various eras of the Big Bang.

Materials

***For all activities*:**

- Lesson 2 PowerPoint

Launch (Activity 2-1)

For each pair of students:

- Big Bang graphic (laminated)

Explore (Activities 2-2 and 2-3) and Summarize (Activity 2-4) For classroom:

	• Set of Element Cards: ○ Proton (^{1}H) ○ Neutron (n) ○ Deuteron (D = ^{2}H) ○ Triton (T = ^{3}H) ○ Helium-3 Nucleus (^{3}He) ○ Helium-4 Nucleus (^{4}He) ○ Beryllium-7 Nucleus (^{7}Be) ○ Lithium-7 Nucleus (^{7}Li) ○ 1 ping-pong ball • Laminated temperature signs: ○ 1 billion K (or 1,000,000,000 KELVIN or 10^{9} KELVIN) ○ 10 billion K (or 10,000,000,000 KELVIN or 10^{10} KELVIN) ***Explore (Activity 2-5)*** ***For each pair of students:*** • Activity 2-5 task card • ^Computer with access to *Gravity Simulator* software (download to give more flexibility to students) ***Summarize and Assess (Activity 2-6)*** ***For each group of 3-4 students:*** • Lesson 2 Assessment card (one of three kinds) • ^Access to computer • ^Poster paper (optional)
Prior Knowledge	• From middle school standards, students should have a basic understanding that the concept of energy cuts across all science disciplines and energy is conserved in a system and atoms are conserved in chemical reactions. These conservation laws will extend to the nuclear and particle regime in this and following lessons.
Launch (15 minutes	
Engagement and Communication of Student Expectations	**Activity 2-1. The Big Bang Theory** 15) As students come in have the Big Bang Theory television theme song playing. Have the question of the day highlighted on the list of questions the students had. 16) (Slide 2) Write the question of the day on the board or highlight it in the list (*Why is the solar system mostly hydrogen?*) Remind students that starting today we are exploring the question about why the solar system is mostly hydrogen and we will start at the beginning by exploring the most widely accepted theory for the evolution of the universe, the Big Bang Theory (BBT). Over the next few days, we will also be exploring the evidence that has led scientists to accept BBT as the most likely scenario for the beginning of the universe. 17) (Slide 3) Pass out the Big Bang posters to each pair of students. Give them a few minutes to study the poster with their partner. A more detailed version of the chart is in the PowerPoint; students may wish to refer to it. Have them write observations and questions they have in their notebooks. 18) Starting with the earliest times in the Big Bang, have students report out on things

that they notice on the poster and questions they have. Record their questions on the board.

19) Do students see the ingredients of a hydrogen atom on the poster? (If necessary, review atomic structure and the definition of an isotope (Slide 4)). Have each pair of students work together and write down the time and temperature when each ingredient (electron, proton) of a hydrogen atom appears, and when the atom itself appears.

20) Students should have observed that while electrons are made early in time, protons and neutrons are not made until 1 microsecond after the initial event. Also, they should notice that protons and neutrons are formed from other particles. Solicit ideas as to what is happening and why.

21) (Slide 5) Then put-up Slide 5, which compares leptons and baryons and depicts neutrons and protons as each being made up of three quarks. Three fundamental particles make up an atom, up and down quarks, and electrons. Heavier cousins to these particles decay down to these fundamental particles. Solicit student ideas and understanding of what antimatter and what role it plays. Do students see particles in the Big Bang Theory poster that could possibly be antimatter?*(Teacher Tip: As far as scientists know the only difference between a particle and its antimatter partner is the electric charge. In the poster, there are equal numbers of electrons and positrons, a positive electron, in the early universe).*

22) (Slide 6) Among student ideas related to antimatter, some students have probably heard from popular culture that when matter and antimatter meet, it annihilates to pure energy. This is reflected in Einstein's famous equation, $E = mc^2$, called mass-energy equivalence. In the earliest epochs of the Big Bang, when the universe was very dense and very hot, particle/antiparticle pairs could pop into existence from energy, and immediately annihilate back to energy. There should have been equal amounts of particles and antiparticles created and they should have all immediately annihilated.

23) (Slide 7) The video should play automatically on this slide but can be found on the unit flash drive or here. Something happened to cause a slight imbalance of antimatter. The video addresses what scientists know had to have happened. They still do not know what caused the imbalance. This is one of the big physics questions that scientists are still trying to answer: where did all the antimatter go (why do we exist at all)?

24) Have student pairs revisit the Big Bang poster and the observations they made about the period approximately one microsecond (10^{-6} sec) after the Big Bang. What is left? *Protons, neutrons, electrons.* Where are the quarks that were left? What happened to the electrons? Can they draw any conclusions about the make-up of protons and neutrons? *Each is made from three quarks.*

25) (Slide 8) In this period, the universe cooled enough for the strong nuclear force to take over.

26) (Slide 9) One other crosscutting concept that students will need to consider while modeling the Big Bang Theory at these scales are conservation laws. In a class discussion, find out what conservation laws students are familiar with in other contexts? From middle school standards, they should be familiar with energy

conservation. Since at these scales energy and mass are equivalent, then the total mass-energy of the system must be considered. Electric charge is also conserved. Scientists discovered that other quantities are conserved only at the microscopic level, including lepton # and baryon #).

27) (Slide 10) Down quarks are more massive than up quarks (5 versus 2 MeV/c^2), so neutrons (udd) are more massive than protons (uud). By energy conservation, a neutron could decay into a proton and emit energy. Have each pair of students.

28) discuss and propose what other particles might be emitted if a neutron decayed to a proton, that could conserve charge, lepton number and baryon number. Share out in a class discussion. The second part of the PowerPoint slide shows that if a neutron decays into a proton + electron + anti-neutrino, all conservation laws are satisfied. This happens for a 'free' neutron (not inside a neutron). Statistically, a neutron will survive about 10 minutes before it decays.

Explore (15 minutes)

Activity 2-2. Modeling Big Bang Nucleosynthesis, Part 1

7.) (Slide 11) Introduce the vocabulary term, nucleosynthesis. In a class discussion, have students parse out what it means by breaking it down. In the next few activities, students will make sense of Big Bang Nucleosynthesis (BBN) – formation of nuclei during the Big Bang – to begin to answer some of the questions they have about the origin of the elements.

8.) (Slide 12) Introduce the next activity by having students look back at the poster and estimate when Big Bang Nucleosynthesis (BBN) began and ended. Solicit ideas as to why it is possible for complex nuclei to be made at this time? What do they think is the most likely thing to happen first? Why? (*They might think it is equally likely that p+p, n+p, n+n fuse, or if they are familiar with Coulomb's Law, they might think it is more likely for n+p or n+n to fuse.*)

9.) We learned earlier that free neutrons decay into protons (Slide 7) with an average lifetime of 10.3 minutes. Could this have an impact on what happens next? Can they speculate as to what it will be? *(They should figure out that the proton / neutron ratio changes with time and there will be more protons available than neutrons.)*

(Teacher Tip: More advanced students could do the math to get to the curves in Slide 10 but will have to be introduced to the concept of exponential decay. This exercise is included as an optional extension.)

10.) (Slide 13) By the time the universe has cooled down sufficiently for nucleosynthesis of heavier nuclei to begin, there is only one neutron left for every seven protons. The neutrons will continue to decay to protons until the universe has cooled down enough that a neutron and proton can stick together to make a deuteron nucleus (p+n).

11.) Pass out the proton and neutron cards; for every eight students, seven should get proton cards and one a neutron card. Have students look at the information on the back and discuss it as a class. Do they want to refine their estimate on the time when protons and neutrons began to combine to make nuclei? They should record their new thinking.

12.) Move into an open area for the modeling activity sequence. *(Teacher Tips: For the BBN Modeling activity, students will be moving around. The teacher should emphasize the need to be quiet to hear the directions. If possible, move to a large classroom, outside, hallway, or gym. Distribute the game cards. If you have a a large class, assign 1-2 students to help exchange cards during fusion events as the game progresses.)*

A. To begin, students arrange themselves in a tight central group representing the matter that emerges in the first second, a soup of elementary particles. Students in the model represent parts of forces that will explode apart to become protons (p's or normal H nuclei) and neutrons (n's). The teacher will handle the temperature cards and have student helpers to pass out heavier nuclei cards. Students have cards with names or formulas: p or n, Students hide all cards, since there are no elements before the Big Bang. If indoors, turn out the lights, representing the absence of electromagnetic energy before the Big Bang.

B. When the lights are turned on, the teacher or a student calls "Big Bang" and holds up the temperature sign with **10 BILLION DEGREES K**. Students hold up either the **PROTON** card or **NEUTRON**. Students start moving out from the dense center.

C. Some students should encounter (that is, safely bump) other students. The "particles" should not stick together.

D. Allowing time for the students to move and expand out a short way (which may be as short as 15 seconds in real time), the teacher gives the cue call of "100 seconds." The teacher pulls away the 10 BILLION K and sticks up **1 BILLION K**. Students hold their signs and continue to move outward. When two **PROTONS** meet, the two students decide if they want to bounce away or stick by locking arms to form a Deuteron nucleus. Then these students exchange their PROTON cards for a **DEUTERON (^{2}H)** card. Pairs representing Deuteron continue moving outward to encounter other **PROTONS**. Pairs representing Deuteron cannot stick to other single or couples of students until the next time cue is given (at step 6). The reaction is: p + p D + positron + neutrino.

E. A **PROTON** and **NEUTRON** may also decide to stick together to form **DEUTERON**. Those students can exchange their card for a **DEUTERON** card. This reaction is p + n D.

F. If a **DEUTERON** bumps into a **NEUTRON** and they join, **HYDROGEN 3** is formed. The three students should h lock arm) and exchange their cards for a 3 H. The reaction is: D + n → 3H

G. After seeing that students have started forming **DEUTERONS** and some **3H**, the teacher gives the cue call of "200 seconds." The **DEUTERON** couples do not have to join to other single or couples of students when they bump. However, now students can join if they wish. For a **DEUTERON** sticking to a free **PROTON**, the three students should all link arms, and turn in their cards, for a **HELIUM-3** (3He) card. This reaction is: D + p → 3He

	H. If two 3-Hes meet, only four of the six students should link, and trade their cards for a **HELIUM-4** (4He) card; the other two students should pick up a **PROTON** cards and go off on their own. This reaction is 3 He + 3 He → 4 He + p + p. I. Other possible reactions to produce 4 He are: 3 He + D → 4 He + p; 3 He + D → 4 He + n + positron; 3 He + n → 4 He 8. J. The teacher directs one of the remaining **HELIUM-3** (3 He) join with a HELIUM 4 (4 He). The teacher gives them the **BERYLLIUM-7** (7 Be) card, the **LITHIUM-7** (7 Li) card and a ping-pong ball representing an electron (e-). First this group should hold up the **BERYLLIUM-7** (7 Be) card and the ping-pong ball (e-). They then touch the **BERYLLIUM-7** (7 Be) to the electron, forming LITHIUM 7 (7 Li). They should then hide the **BERYLLIUM—7** (7 Be) card and the ping-pong ball, and hold up the **LITHIUM-7** (7 Li) card. This reaction is 3 He + 4 He → 7 Be, followed by 7 Be + e - → 7 Li *K.* The teacher gives the cue call of "End". Students freeze in position with their cards held up so that all can see what has occurred. Someone should record the number of different particles formed in your classroom BBN on the board. *(TEACHER TIP: Because students may want to stick more often than what correctly models the early universe, most likely, the outcome will be wrong. This will be addressed in the next investigation.)*
Questions for Student Exploration	• How does 'freezing' the motion at the end of the activity represent what's happening in the Big Bang Theory? • How are the numbers of particles and atoms we have formed different from what is predicted by BBN? • Why can't the groups keep combining like they did in this activity to form all the elements heavier than hydrogen, helium, and lithium?
Summary (5 minuts)	
Communicate	(Slide 14) Facilitate a class discussion to describe what was happening in their modeling activity. Why did nucleosynthesis end? What limited the formation of elements heavier than helium? As a class, record the results of the modeling activity in Row 1 of the table on Slide 11 and discuss reasons that the modeling in the game gives different results than the theory. What variables might lead to the discrepancies? Ask the students to think back. How did they decide whether to fuse with another nucleus or not? Did they choose one way more often than the other? As a class, can they come up with an investigation to determine whether this variable is important to the final abundances? Were there other variables that might affect the results?
Exploration (15 minutes)	
Facilitate	**Activity 2-3. Modeling Big Bang Nucleosynthesis, Part 2** 4) (Slide 11) Reset the game and run it one or more times under the conditions the class decided for their investigation. Record ratios in the table on Slide 14. *(Teacher Tip: One Example of a more rigorous challenge is given below, but the students should be*

	strongly encouraged to come to consensus on their own investigation and set it up). a. Reset the cards to the original proton/neutron ratio and run the model again. This time, when the teacher calls out 100 seconds and holds up the 1 billion K sign, students should count how often they meet another nucleon. They should only fuse every fifth time. Run the game this way until the teacher calls 200 seconds and freeze-out. Everyone hold up their cards and record the distribution of particles. Is it different? b. Repeat the game one more time. This time, nucleons should only fuse every 10^{th} time they meet. Record the distribution again. Is it different? Why should it matter how often the nucleons are allowed to fuse? Did students notice something different about the game in the three cases they ran? Have the students keep their cards at the end. 5) Were students able to find a set of parameters that gave the H/He ratio from the Big Bang theory? Did the parameter(s) they investigated change the results significantly? If not, can they suggest another scenario and try again? Is there a reason they can see that restrain the results to the ration predicted by the theory? 6) (Slide 12) How do these numbers compare with the abundance of hydrogen and helium in the solar system? Can students suggest reasons why they might be different? *(Teacher Tip: At first glance, students will probably use the abundance numbers directly from the chart and calculate 92% H / 7% He. However, one must consider that each 4He nucleus contains 4 nucleons. Taking that into account, the numbers are 76%/24%, just as the Big Bang Theory predicts.)*
Summary (15 minutes)	
Communicate	**Activity 2-4. Energy and Matter** 10) (Slide 15) Why was there so little Li, Be or heavier nuclei made in the Big Bang? Using reactions listed on the back of the game cards, make a table on the board for the reactions occurring at 100 seconds and 200 seconds (the two temperature regimes). Starting with the proton cards, have students write the reactions on the board. What do they notice about the two columns? Why do students think there so many more possible reactions as the universe cooled down? Is there one isotope that must form first before anything else can? *(2H - Deuterons)* 11) Working in pairs, have students discuss and speculate on two scenarios: 1. Deuteron began forming at 10 seconds after the Big Bang instead of 100 seconds as the game cards state. 2. Deuteron did not begin forming until 1000 seconds after the Big Bang. How might Big Bang Nucleosynthesis have proceeded in these two cases? Would the universe be different? Have groups share out what they think would be different in these two scenarios. *(There would be many more neutrons in the first case and close to zero in the second case. In the latter case, atoms as we know them would not exist)* 12) (Slide 16) Why is 100 seconds the magical time for when deuteron formed? The nuclear binding energy is defined as the mass of the constituent protons and neutrons minus the mass of the nucleus. The higher the binding energy, the more stable is the nucleus.

13) (Slide 17) Working in pairs, students should do the exercise of calculating the binding energy for a deuteron and for a 4-helium nucleus.
14) (Slide 18) The binding energy of all the light elements are given here. What is the least stable (d)? The most stable (4He)? These numbers have two major effects on the BBN theory. What else do students notice about this list? (*No A=5)*
15) (Slide 19) Since there are no mass 5 nuclei for proton fusion to proceed through, how were heavier things made. Look at the reactions that can jump over A=5 to make Li-6 or Be-7. Do they happen very often in the BBN model?
16) (Slide 20&21) Why are some nuclei more stable than others? Scientists puzzled about this for decades until they understood that there is nuclear shell structure, like the electron shells of an atom.
17) (Slide 22) Summarize BBN in the Big Bang Theory. If time permits, have each pair of students create a timeline of the first 3 minutes and 45 seconds of the Big Bang
18) in their notebooks, computers, or on larger pieces of paper. Students with access to computers can use the JinaWeb BBN movie/game to test their understanding of the BBN model.

Exploration (25 minutes)

Activity 2-5. From Nuclei to Atoms to Stars

10) (Slide 23) Ask students to remind you where they left off in the previous activity. At the end of the first few minutes of the Big Bang, the universe was 75% hydrogen nuclei, 25% helium nuclei, some free electrons, and very little else. Compare that with the abundance graph we have been using. Does the Big Bang tell the whole story about the formation of the elements?
11) (Slide 24) Facilitate a class discussion of when atoms can form. What would it take to form a neutral atom from a hydrogen or helium nucleus? Have students give their opinions, then introduce the formula for the electromagnetic interaction. Can students calculate the strength of interaction between an electron and a proton in a hydrogen atom? (Work through the formulas as a class or have them do them in their notebooks.)
12) (Slide 25) When BBN took place, the universe still had too much energy (□0.1 MeV) for an electron to stick. It took another 380,000 years for it to cool down enough so that atoms could form.
13) (Slide 26) At the point light was released, photons could escape the early universe and the universe was no longer opaque. Those original photons are present today in the ‘cosmic microwave background’, another piece of evidence for the Big Bang Theory.
14) How did we get from atoms to the first stars? Now the universe is filled with isolated neutral atoms; the electromagnetic force between atoms is negligible. Photons are not emitted so the universe is dark. What happens next? What other fundamental interaction could become important? *Gravity*.
15) (Slide 27) Facilitate a class discussion of whether or not students think gravity could make stars from atoms during this period? Remind students of the equation for the

	Law of Universal Gravitation and have them note similarities/differences with Coulomb's Law. As a class, have them fill in the table on the slide. 16) Have the students work in pairs on computers and distribute Task Card 2-5 which introduces the gravity simulator (http://www.testtubegames.com/gravity.html). Using PART A of the task card, students will set up their model of the universe with the H/He ratio at the end of the Big Bang. Can they get a random or uniform field of hydrogen and helium atoms to fall together into stars? *(TEACHER TIP: Students might need reminding that the 75%/25% H/He ratio was by mass.)* 17) (Slide 28) After students try to make stars out of their hydrogen/helium universe, have students make sense of why or why not it is working? What did they try and what happened? Based on the gravitation equation, why do they think stars aren't forming? Using PART B of the Task Card, have them introduce a new particle to their model universe - a heavy mystery particle. What happens then? What happens as they vary the mass of the mystery particle (leaving the mass 'census' at 63%)? Can they get mass to collapse into bigger objects? 18) Play the video in the PowerPoint which shows a supercomputer generated simulation, based on gravitational equations for the formation of the Milky Way galaxy. The video is also available here. (*TEACHER TIP: This video was in a format that could not be downloaded for the flash drive and is only available on YouTube.)*
	Summary (10 minutes + homework)
Communicate	**Activity 2-6. Connecting to Evidence** 2) (Slide 27) What evidence is there today – 13.7 billion years later - for BBN in the first 3 minutes of the universe? Discuss as a class what kind of evidence they think scientists could find to show that the timeline they have constructed is accurate. Break into groups of 3-4 students; each group will research one of three kinds of evidence for BBN (***Lesson 2 Assessment Card):*** 1. Light spectra 2. Motion of distant galaxies 3. Composition of matter *(Teacher Tip: There are resources on the assessment cards to get students started. They should present their results (in poster format or oral presentation) in the form of Claim, Evidence, Reasoning.)*
Terminology and Concepts to Solidify	Antimatter - **Antimatter** is composed of antiparticles. Each particle of matter has a corresponding antiparticle of antimatter. The antiparticle of an electron is known as a positron, and the antiparticle of the proton is called an antiproton (made up of antiquarks). Antimatter has the same mass as its matter partner, but opposite charge. Baryon – A **Baryon** is any of a family of subatomic particles composed of three quarks or three antiquarks. Big Bang Nucleosynthesis – Within the Big Bang theory, **Big Bang Nucleosynthesis** (BBN) the process by which the first nuclei were formed between 100 seconds and three minutes after the singularity that began the Big Bang. Big Bang Theory – The **Big Bang Theory** is a generally accepted theory for the

beginning of the universe, a transition from conditions of unimaginable density and temperature to conditions of lower density and temperature.

Binding Energy - The **binding energy** of a nucleus is the energy that holds a nucleus together and is equal to the mass of the nucleus minus the total mass of the individual protons and neutrons that make up the nucleus.

Conservation Laws - In physics, a **conservation law** states that a particular measurable property of an isolated physical system does not change as the system evolves over time. In classical physics, laws of this type govern energy, momentum, angular momentum, mass, and electric charge. In particle physics, other conservation laws apply to properties of subatomic particles that are invariant during interactions.

Cosmology – **Cosmology** is a branch of physics which studies the history, structure, and fate of the universe.

Coulomb's Law - **Coulomb's Law** is a law of physics that describes the interaction between electrically charged objects. This law states that the electrostatic force between two objects is proportional to the product of the charge of each of the objects and inversely proportional to the square of the distance between these two objects.

Dark Ages – The **dark ages** occurred in Big Bang cosmology after recombination. The universe was transparent and had cooled enough to allow light to travel long distances, but there were no light-producing structures such as stars and galaxies.

Dark Matter - Roughly 80 percent of the mass of the universe is made up of material that scientists cannot directly observe. Known as **dark matter**, this bizarre ingredient does not emit light or energy.

Free Neutron Decay – A **free neutron** (outside a nucleus) lives approximately 14.5 minutes, decaying to a proton, an electron, and an antineutrino. A down quark inside the neutron has decayed into an up quark in the process.

Fundamental (Elementary) Particles - In particle physics, an **elementary particle** or **fundamental particle** is a particle whose substructure is unknown; thus, it is unknown whether it is composed of other particles. In the Standard Model, there are two families of fundamental particles: quarks and leptons (which include the electron).

Isotope - **Isotopes** are forms of the same element that contain equal numbers of protons but different numbers of neutrons in their nuclei, and hence differ in relative atomic mass but not in chemical properties. Isotopes can be stable or radioactive.

Lepton – **Leptons** are a family of fundamental particles within the standard model of particle physics. Leptons have half-integer spin (spin ½) and does not undergo strong interactions. Leptons can be charged (electron, muon, tau) or neutral (neutrinos).

Magic numbers - When all the protons or neutrons in a nucleus are in filled ***shells***, the number of protons or neutrons is called a "magic number." Some of the magic numbers are 2, 8, 20, 28, 50, 82, and 126.

Mass-Energy Equivalence – **Mass-Energy Equivalence** is the physical principle that a measured quantity of energy is equivalent to a measured quantity of mass.
The equivalence is expressed by Einstein's equation $E = mc^2$, where E represents energy, m the equivalent mass, and c the speed of light.

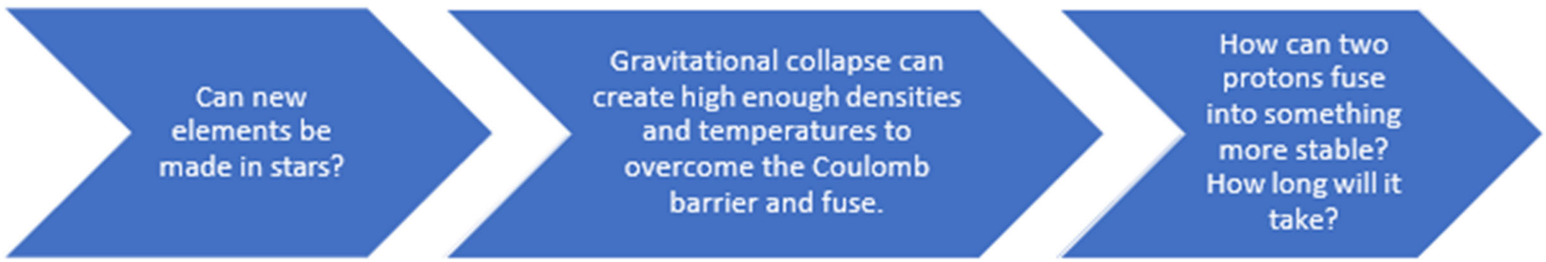
	Newton's Law of Universal Gravitation - **Newton's law of universal gravitation** states that a particle attracts every other particle in the universe with a force which is directly proportional to the product of their masses and inversely proportional to the square of the distance between their centers. Nuclear Mass – The mass of an atomic nucleus, which is usually measured in atomic mass units. It is less than the sum of the masses of its constituent protons and neutrons by the binding energy divided by the square of the speed of light. Nuclear Shell Model - A model of the atomic nucleus which uses the Pauli exclusion principle to describe the structure of the nucleus in terms of energy levels. Nucleosynthesis - **Nucleosynthesis** is the process that creates new atomic nuclei from pre-existing nucleons, primarily protons and neutrons. Pair Annihilation - **Pair annihilation** is an inverse process to pair production, in which a particle and its antiparticle collide and annihilate each other, the total energy of the two particles appearing as electromagnetic radiation. Pair Production - **Pair production** is a phenomenon of nature where energy is converted to mass. Energy is converted to a particle and its antiparticle partner. Quark – **Quarks** are a family of fundamental particles within the standard model of particle physics. Quarks combine to form composite particles called hadrons, the most stable of which are protons and neutrons, the components of atomic nuclei. There are six quarks (up, down, strange, charm, top and bottom). Recombination - In cosmology, **recombination** refers to the epoch at which charged electrons and protons first became bound to form electrically neutral hydrogen atoms. Reionization – In the Big Bang Theory, **reionization** ended the Dark Ages. This was a phase change that occurred once objects started to condense in the early universe that was energetic enough to re-ionize neutral hydrogen. The Standard Model - The **standard model** is the name given in the 1970s to a theory of fundamental particles and how they interact. It incorporated all that was known about subatomic particles at the time and predicted the existence of additional particles as well. Strong Nuclear Force - The **Strong Nuclear Force** (also referred to as the **strong force**) is one of the four basic forces in nature (the others being gravity, the electromagnetic force, and the weak nuclear force). As its name implies, it is the strongest of the four. However, it also has the shortest range, meaning that particles must be extremely close to feel it. The strong force is responsible for holding the quarks together to make protons and neutrons and for holding the nucleus together. In the Standard Model, the strong force is 'mediated', or carried, by a particle called a gluon. Weak Nuclear Force - In particle physics, the **weak interaction** (the **weak** **force** or **weak** nuclear **force**) is the mechanism of interaction between sub-atomic particles that causes radioactive decay, such as the decay of a neutron into a proton.
Connection to Big Ideas (Phenomena)	The formation of atoms and nucleosynthesis requires extreme amounts of energy to allow subatomic particles to interact at the nuclear level. These conditions existed at the beginning of the universe after the Big Bang and since then in the evolution of stars.

Follow Up/Practice	**See assessment.**
Assessment	Group research and communication in the form of a poster or oral presentation. Rubric is on the Lesson 2 assessment card.

Lesson 3, *From Stars to Atoms: Stellar Nucleosynthesis*

ACTIVITY 3-1. A Star is Born (LAUNCH)

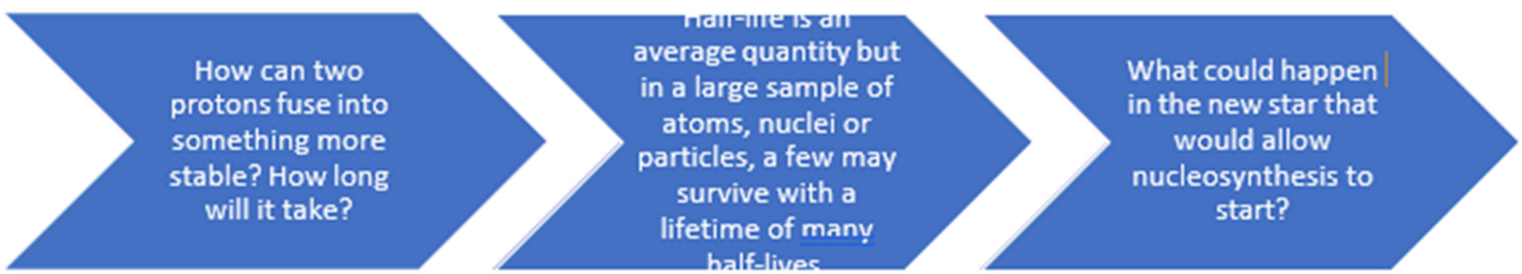
Questions | What we Figure out | New Questions



ACTIVITY – Using the understanding they gained in Lesson 2 about energy and matter, students compare the conditions matter is. subjected to during protostar and star formation (lesson phenomenon) with the conditions during Big Bang Nucleosynthesis.

ACTIVITY 3-2. Radioactivity: Lifetime versus half-life (EXPLORE 3a)

Questions | What we Figure out | New Questions



ACTIVITY – Students measure the half-life of a radioactive isotope, plot the data, and use mathematical representations to draw conclusions as to the statistical nature of half-life and the implications for production of new elements.

ACTIVITY 3-3. One in a Billion (SUMMARIZE 3a)

Questions	What we Figure out	New Questions
What could happen in the new star that would allow nucleosynthesis to start?	Most of the time, a diproton will fall back apart on a very fast time scale, but once in a billion times, a deuteron is formed.	What determines if a nucleus is stable or how it decays? Are there ways a nucleus can decay into a higher-Z nucleus?

ACTIVITY – In the context of the statistical nature of half-life and the weak nuclear force, students make sense of rare processes that can make neutrons in the sun, a necessary ingredient for nucleosynthesis.

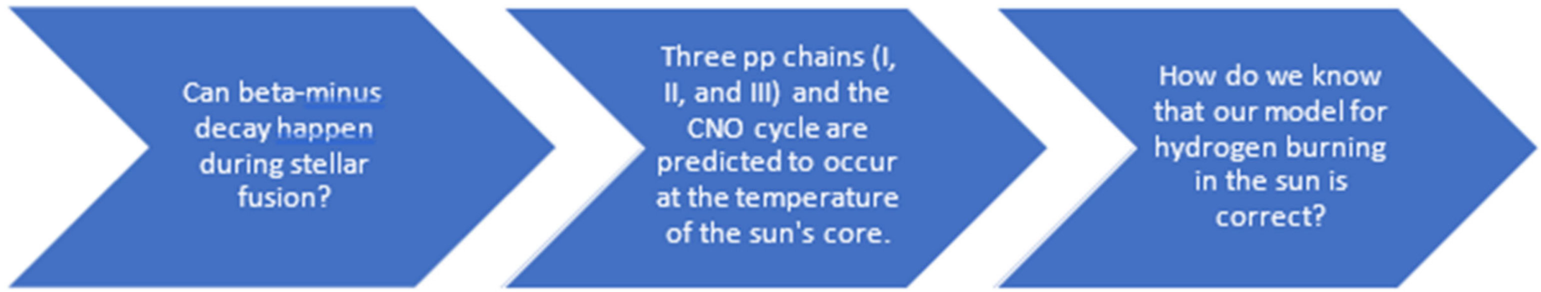
ACTIVITY 3-4. The Nucleosynthesis Game (EXPLORE 3b)

Questions	What we Figure out	New Questions
What determines if a nucleus is stable or how it decays? Are there ways a nucleus can decay into a higher-Z nucleus?	If conditions are right, beta-minus decay can lead to a higher-Z nucleus when a neutron transforms to a proton.	Can beta-minus decay happen during stellar fusion?

ACTIVITY – Students use the stellar nucleosynthesis game for sensemaking of the chart of the nuclides and the relative stability of nuclei.

ACTIVITY 3-5. Hydrogen burning stars: energy from the sun (SUMMARIZE 3b)

Questions | What we Figure out | New Questions



ACTIVITY – Students synthesize their understanding of nuclear fusion and decay into sensemaking of the nuclear reactions taking place in our sun and propose additional reactions that fit the model.

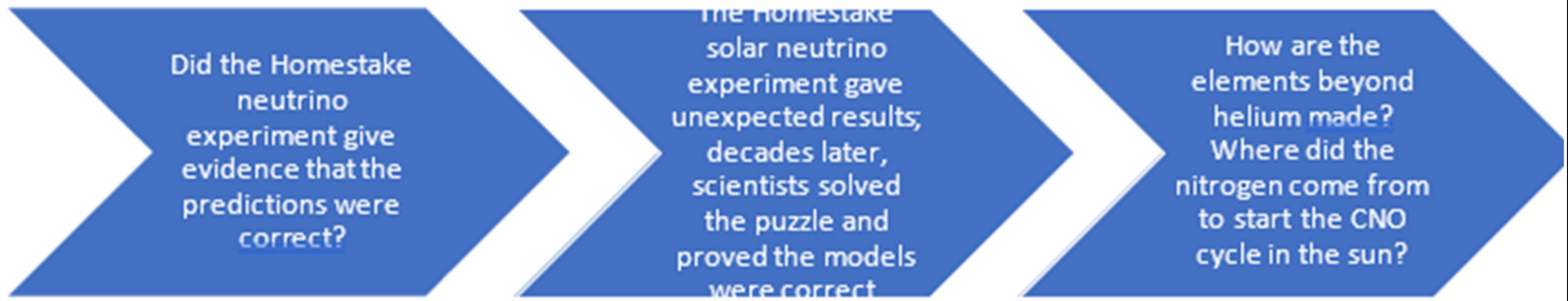
ACTIVITY 3-6. Connecting to evidence – Solar neutrinos (EXPLORE 3c)

Questions | What we Figure out | New Questions

ACTIVITY – Students will examine the Homestake solar neutrino experiment and the evidence that it provided for understanding nucleosynthesis in the sun. As part of their sensemaking of the experimental set up, they will plan and investigate on the properties of nuclear beta decay.

ACTIVITY 3-7. The Solar Neutrino Problem (SUMMARIZE 3c)

Questions | What we Figure out | New Questions



ACTIVITY – Students will examine the results from the Homestake solar neutrino experiment and will construct explanations based on Claims-Evidence-Reasoning for why the experiment did not give the results expected by scientists. (Lesson Assessment)

Lesson 3	From Stars to Atoms – Stellar Nucleosynthesis
Overview Standard(s) & Objectives	*This lesson is designed for three 50-minute class periods or two block periods. The structure and flow of the lesson is given at the beginning of the Background Material section. DCIs, SEPs and CCCs for each activity are color-coded.* **Performance Expectations:** HS-PS1-8: Develop models to illustrate the changes in the composition of the nucleus of the atom and the energy released during the processes of fission, fusion, and radioactive decay. HS-PS2-4: Use mathematical representations of Newton's Law of Gravitation and Coulomb's Law to describe and predict the gravitational and electrostatic forces between objects. HS-ESS1-1: Develop a model based on evidence to illustrate the life span of the sun and the role of nuclear fusion in the sun's core to release energy that eventually reaches Earth in the form of radiation. **Disciplinary Core Ideas:** • PS1.C Nuclear Processes • PS2.B Types of Interactions • PS3.D Energy in Chemical Processes and Everyday Life • ESS1.A The Universe and Its Stars **SEPs:** • Developing and using models • Using mathematical representations and computational thinking • Planning and carrying out investigations. **CCCs:** • Energy and Matter • Patterns • Scale, proportion, and quantity **Lesson Phenomenon:** Video of protostar formation and star formation. **Lesson Level Learning Goals:** VIII. Using the understanding they gained in Lesson 2 about energy and matter, students compare the conditions that matter is subjected to during protostar and star formation (lesson phenomenon) with the conditions during Big Bang Nucleosynthesis. IX. Students measure the half-life of a radioactive isotope, plot the data, and use mathematical representations to draw conclusions as to the statistical nature of half-life and the implications for production of new elements. X. In the context of the statistical nature of half-life and the weak nuclear force, students make sense of rare processes that can make neutrons in the sun, a necessary ingredient for nucleosynthesis. XI. Students use the stellar nucleosynthesis game for sensemaking of the chart of the nuclides and the relative stability of nuclei.

	XII. Students synthesize their understanding of nuclear fusion and decay into sensemaking of the nuclear reactions taking place in our sun and propose additional reactions that fit the model. XIII. Students will learn about the Homestake solar neutrino experiment and the evidence that it provided for understanding nucleosynthesis in the sun. As part of their sensemaking of the experimental set up, they will plan and investigate on the properties of nuclear beta decay. XIV. Students will examine the results from the Homestake solar neutrino experiment and will construct explanations based on Claims-Evidence-Reasoning for why the experiment did not give the results expected by scientists. (Lesson Assessment).
Background Information and Reference Material	**Structure of Lesson:** 5. (LAUNCH) Activity 3-1, *A Star is Born* starts with a video of protostar formation, the phenomenon for the lesson. Student return to some of the concepts of Lesson 2, developing questions about the transformation of gravitational potential energy to kinetic energy and the fusion process. They compare and contrast a rudimentary model for this process with that for the BBN process. 6. (EXPLORE) In Activity 3-2, *Nuclear Processes I,* students begin to make sense of competition between different nuclear processes important to nucleosynthesis - the concepts of lifetime and half-life – by collecting half-life data, then analyzing and interpreting the results. 7. (SUMMARIZE) In Activity 3-3, *One in a Billion,* students explore the implications of the statistical nature of half-life as they model the fusion of two protons into a diproton, with one in a billion diprotons undergoing nuclear beta decay to a deuteron, an essential ingredient of nucleosynthesis. *(Teacher Tip: For schools with a 50-55 minute class period, the end of Activity 3-3 is a natural stopping point for Day 1 of this lesson. If there is a little extra time, students can use it to figure out the game (Activity 3-4) ahead of actually playing it the next day.)* 8. (EXPLORE) In Activity 3-4, *The Nucleosynthesis Game*, students utilize magnetic marbles to build nuclei, to help make sense of models of the nuclear fusion processes that build up heavier elements in stars, and the competition between fusion and nuclear decay processes. In this game they are introduced to the Chart of the Nuclides. 8. (SUMMARIZE) In Activity 3-5, *Hydrogen-burning Stars,* students model the pp and CNO processes in hydrogen burning stars, and using energy-mass arguments, propose reactions for making nuclei beyond helium. *(Teacher Tip: for a S schools with a 50-55 minute class period, the end of Activity 3-5 is a natural stopping point for Day 2 of this lesson.)* 9. (EXPLORE) In Activity 3-6, *Connecting to Evidence: Solar Neutrinos,* students use the Homestake Solar Neutrino experiment as a case study for why and how technology enabled large detectors located underground to indirectly measure the presence of solar neutrinos as evidence of nucleosynthesis

	processes in the core of the sun. To make sense of the detection schemes they plan and conduct an investigation of the properties of nuclear beta decay. 10. (SUMMARIZE) In Activity 3-7, *The Solar Neutrino Problem,* students use Claim-Evidence-Reasoning scaffolding to examine two competing claims for the unexpected results of the Homestake Solar Neutrino Experiment. Was the experiment wrong, was the theory wrong, or is there another explanation? Student reasoning based on evidence will be used as the assessment for this lesson. **Content information for teachers:** See the unit primer for Lesson 3.
Materials	***For all activities***: ● Lesson 3 PowerPoint ● ALARA Poster ***Launch (Activity 3-1)*** *no materials needed* ***Explore (Activity 3-2)*** **For the classroom:** ● Cloud chamber (set up ahead of class) ● ^Ice bath (teacher provided) ● ^Isopropyl alcohol or ethanol, >70% (teacher provided) ● Geiger counter (digital) ● Pottery samples (two colors) ● Cs/Ba isogenerator ● Eluting solution ● Bealer ● Non-latex gloves ● Snack size baggies ● chem-wipes **For each small group (3 students optimal):** ● Geiger Counter Handout (Print Master) ● Geiger Counter (analog) ● Activity 3-2 Task Card ● Sample of radioactive material in a sealed baggie (see instructions for generating these from Cs/Ba generator) ● ^Computer with access to EXCEL, a graphing calculator or graph paper ● ^Stopwatch, room clock with second hand or Timer App on computer or tablet ***SUMMARIZE (Activity 3-3)*** *no materials needed* ***EXPLORE (Activity 3-4) and Summarize (Activity 3-5)*** **For each small group (4 student minimum and optimal)**: ● Two nucleosynthesis game boxes (10 each of four color-coded marbles, magnet, dice) ● Game rules chart and Chart of the Nuclides (laminated) ● Activity 3-5 Task Card (per pair of students)

	EXPLORE (Activity 3-6)
	For each small group (3-4 students)
	• Activity 3-6 Task Card
	• Geiger counter
	• Box containing
	  o Beta source and two unknown sources
	  o A set of degraders of varying material and thickness
	  o A ruler and protractor
	  o Clay (for holding sources & degraders)
	  o Binder clips (for holding sources & degraders)
	• Ruler
	SUMMARIZE (Activity 3-7)
	For each student
	• Lesson 3 Assessment card
	• Set of evidence cards
	• Reasoning Template (Print Master)

Prior Knowledge	This lesson builds on concepts that were introduced in Lesson 2: nuclear fusion reactions, conservation laws, binding energy, electromagnetic and gravitational interactions.
Launch (10 minutes)	
Engagement and Communication of Student Expectations	**Activity 3-1. A Star is Born** *(Teacher Note: Before class starts, set up the cloud chamber according to the directions in the Materials set up. You will need to provide ice, an ice chest, a source of water and a drain. If cooling is started just before class, it should be operating well by time the students get to it.)* 6) (Slide 2) Play the video protostar formation in the Orion Nebula (on the lesson PowerPoint (or at https://www.youtube.com/watch?v=jzkCFMkX-tM). Protostars are the last step before the star begins to shine. Ask students to brainstorm with a neighbor what is happening in the video as the atoms are pulled together by gravity. What will happen on the atomic level? Does the energy of the atoms change? If so, how is that manifested? 7) In a larger class discussion have groups suggest what they think will happen as the particles undergo gravitational collapse. Write the ideas on the board. *The gravitational potential energy converts to kinetic energy of the atoms. That causes the temperature of the system to rise. At high energy, the electrons will be stripped off, leaving a plasma of nuclei and free electrons.* 8) (Slide 3&4) As gravitational collapse increases, gravitational potential energy is converted to kinetic energy and the temperature continues to rise in the core of the protostar. The hydrogen and helium nuclei have higher and higher kinetic energy. At approximately 10 million K, the Coulomb barrier can be overcome for two protons. What happens next? Brainstorm as a class. 9) (Slide 5) Have students work with a partner to work out the components of the system in the core of the protostar. For every 100 atoms, how many are hydrogen? How much helium? How many total protons are there in the system? Neutrons?

	Electrons? Have students propose how heavier elements could be made in this system. Binding energies are given in the PowerPoint as reference. 10) (Slide 6) Discuss as a class. Students should conclude that there is a major difference between this system and the BBN processes they studied earlier because there are not enough neutrons in the system, and those that are there are tied up in helium nucleus. So can two protons fuse to make something heavier?
Explore (35 mintues)	
Procedure	**Activity 3-2. Radioactivity: Lifetime versus Half-life** 5. (Slide 7) Demonstrate how early scientists realized that certain materials emitted invisible particles by using the cloud chamber. Have students rotate in groups to the front of the room to observe the tracks in the chamber and draw what they see in their journal. Scientists like Henri Becquerel and Marie and Pierre Curie used film as the detector and the first observation happened accidentally. An understanding of radioactivity will help provide evidence for the formation of elements in stars. *TEACHER TIP: If the cloud chamber is unavailable, a video demonstration is available on the flash drive media or here.* 6. Demonstrate the use of a GO Direct Radiation Monitor and a Geiger Counter set with the audio turned on with two pieces of pottery, one radioactive and the other not. Move the two counters further away and closer and let them hear the difference. What is happening? Solicit student comments to facilitate a class discussion that may reveal some misconceptions about radiation. Without correcting these, make a note of them to refer to in the summary of the lesson. 7. Organize class into groups of 3 (optimum). Distribute a Go Direct Radiation Monitor and Go Direct Instructions Handout to each group. Point out the labeled diagram in the handout, in particular the active window. Suggest that students leave the audio off unless they are counting clicks. 8. Each group will complete the handout on the use of Go Direct Radiation Monitors, determining background radiation levels in the room as an exercise in the use of the meters, their sensitivities, and limitations. *Instructions on the handout describe how to connect the monitor to a computer using a USB cord. Students can also use the Bluetooth feature to connect, (instructions below).* *a) Install Vernier Graphical Analysis on your computer, chromebook, or mobile device. If using LabQuest, make sure the App is up to date. See www.vernier.com/ga4 for Graphical Analysis availability or www.vernier.com/downloads to update LabQuest app.* *b) Charge your sensor for at least 2 hours prior to use.* *c) Turn on your sensor by pressing the power button once. The LED will blink red.* *d) Launch Graphical Analysis or turn on LabQuest.* *e) If using Graphical Analysis, click/tap Sensor Data collection. If using LabQuest, choose Wireless Device Setup>Go Direct from the sensor menu.* *f) Select your Go Direct sensor from the list of discovered wireless devices. Your sensor's ID is located near the barcode on the sensor. The LED will blink green when it is successfully*

connected. Click/Tap Done to enter data collection mode.

(Teacher Tip: Because the background counting rate is very low, students will need to count light flashes or clicks in a minute period to fill in the table on their handout. Reading the scale will not work for backgrounds.)

5) Once everyone has finished the handout, stop and check in. What is the average background each group has calculated? Is it different in different parts of the room? Why might that be?

(Teacher Tip: Use the student results to check that each group is using the meter properly. It's possible that students will find actual differences in background radiation levels in different parts of the room due to building materials or other material stored in the room.)

14) Slide 7-9) Refer back to Slide 7. Once the early scientists discovered this mysterious result, we now call radioactivity, how could they learn more about it? What kind of measurements might they make? Solicit ideas, then switch to Slide 8. These are tracks from an early bubble chamber, like a cloud chamber. By putting the chamber inside a magnet, scientists were able to get quantitative as well as qualitative data. Using Slide 9, review the conservation laws (discussed in Lesson 2) as they apply to nuclear processes.

15) (Slide 10) Review with the class the basic ALARA principles listed on the safety poster. Tell them that to keep exposure to radiation 'as low as reasonably achievable' scientists use time (keep it short), distance (keep it distant) and shielding to minimize their exposure. They will be following these principles for all laboratories.

BASIC RADIATION PRECAUTIONS:

- Never use radioactive material around food or beverages.
- To minimize exposure when handling a radioactive source, keep it at an arm's length when possible.
- Wash your hands after working with radioactive sources.
- Pick up solid sealed sources holding their sides. Be careful to not pierce the plastic with a fingernail.
- Place solid sealed sources face down (label side up), and at a distance from live organisms when not in immediate use.
- Do not put any sources in your pockets.
- Handle sources with respect.

16) (Slide 11) Introduce the concept of half-life, then pass out a Lesson 3-2 task card to each group. Before beginning the investigation, facilitate a class discussion on the safe use of the Cs/Ba isotope generator (isogenerator), and a short explanation of how an isogenerator works. Remind students that in addition to the general ALARA principles there are special precautions to be made for this laboratory because the sample is in the form of a liquid (unsealed):
    - Do not have food and drink in work areas.
    - Do not ingest any of the liquid.

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- Leave the sample bag sealed, but if there is a spill, wear gloves while you wipe it up with a paper towel. Put everything (including the gloves) in a plastic bag and dispose of it in the trash.
- If any liquid solution splashes onto clothes, use a damp cloth to wipe off as much as possible. The remaining radioactivity in the solution will decay rapidly, producing minimal radiation exposure.
- Wash hands after handling.

17) Each group will spend 3-5 minutes planning their investigation, assigning tasks, preparing data table, etc. Suggest that measurements be taken every 20-30 seconds. Once students are set up and ready to begin, they should send someone from their group to retrieve a sample.
18) For safety reasons, the teacher should either prepare the samples themselves or closely supervise students, as they prepare them. To minimize spillage, all samples should be prepared together once students are ready. A few drops of the sample is enough for each group. After eluting the sample, seal the bag so that nothing can spill. Whomever is handling the solution should wear gloves, but once the bags are sealed it is not necessary.
19) Students will graph the counts versus time. They will then estimate the half-life from their graph. Students with advanced math skills (trigonometry) might use semi-log paper or prepare a log plot using EXCEL or Logger Pro. They could fit a curve to extract the half-life.
20) Students should include an error measurement on their graph. Can they estimate the error in their derived half-life due to the errors?

(Teacher Tip: If you are doing this lab with several class periods on the same day, you may have to be careful to not put too much liquid in each baggie early in the day so that there is still activity left in the generator for later classes. A couple of drops is enough to do the measurement.)

21) (Slide 12) Once the data is measured and graphed, ask each group to discuss the thought questions on the task card and answer in their journals. Share out with the full class. The slide shows the mathematical representation of the half-life equation.
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<tr><td>Questions for Student Exploration</td><td>

4) Why is it important to re-measure the room background before starting when it was done in a previous laboratory?
5) Is it important when you start measuring?
6) How important is the time interval you measure if you were doing it again, would you choose a different interval?
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<tr><td colspan="2">Summary (10 minutes)</td></tr>
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Activity 3-3. One in a Billion

4) (Slide 13) An example of a nucleus that decays by two different paths is shown. This isotope has very important medical applications. The Mo-99 is made in reactors in the form of an isogenerator (cow) which is milked by the hospital. The process is much like the one used to prepare the Barium sample in our
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</table>

	experiment. More information is available on the back of the task card. 5) (Slide 14) Remind students that before the class digressed to make sense of half-lives, they were examined what was happening in the core of a protostar as gravitational collapse proceeded, and protons had enough energy to overcome the Coulomb barrier. When that happens, a diproton forms. The half-life for the diproton to fall back apart into two protons is very short and 999,999,999 times out of a billion, it falls back apart into two protons. (Click again) However, because half-life is a statistical process, once in a billion times, the diproton will hold together long enough for another process to take place. 6) (Slide 15) The process by which a proton transforms to a neutron is called beta-plus decay. Have each group of students check that the conservation laws apply to this decay by answering the questions on the slide, speculating if necessary
Questions for Student Exploration	• Why is it so important that beta-decay can take place in the core of the protostar?
Exploration (30 minutes)	
Student Exploration	Activity 3-4. The Nucleosynthesis Game 6) Reorganize into groups of four or five at a table. Each pair of students will get a game box and each table will get a laminated rule sheet. Each group will divide into two teams and play against each other. 7) (Slide 16) Before students open their boxes, use the PowerPoint slide to walk through beta-plus decay (p→n) and the complementary process beta-minus decay (n→p). In both cases, the total number of protons + neutrons (nucleons) stay constant. That means the product nucleus will be on a diagonal in a matrix of neutron number versus proton number. 8) (Slide 17) Using the PowerPoint while students follow along with the Nucleosynthesis Rule Sheet, walk through some examples of what will happen if the students roll a 4 (nuclear decay). If their nucleus is white, it is stable and will not decay. Point out that beta-decay occurs for many isotopes. Most of the time, the nucleus will decay towards a more stable configuration, or towards the path of stability. 9) Have each group figure out how to set up the game to control their marbles if they roll a 6 (nuclear collision), and how they will then divide the marbles that remain on the magnets. Any marbles that fly off (are emitted) go back in their box. *(TEACHER TIPS:* • *If the nucleus undergoes nuclear beta decay, students will receive either a neutrino or antineutrino. These should be kept and counted at the end, but do not stick to the nucleus, since they have no charge.* • *During nuclear collision, students will roll their nuclei towards each other. Any neutrons or protons that shoot off go back into the game box. If the nuclei stick together. They should be broken in the middle and each team keeps the new nucleus closest to them.)* 10) *Students may need help with the decay chart the first couple of times they roll a four. If their nucleus is stable (white), nothing happens. If they have a nucleus not on*

	the chart (e.g., Be-4) it is because it does not exist, and they should take off protons or neutrons until they get to something listed.
Summary (25 minutes)	
Communicate	Activity 3-5. Hydrogen-burning Stars: Energy from the Sun 13) After calling the game, the teacher will poll each team to determine their final nucleus. Class bragging rights will go to the team with the biggest, most stable nucleus (aiming for C-12, O-16 or Ne-20). 14) Have each team add up the number of neutrinos and antineutrinos they have collected. That will determine the number of beta-decays that happened. Facilitate students to create a table on the whiteboard and record each groups' values and the average. On average, are the numbers of beta-plus and beta-minus decays approximately equal? Would this result be expected to happen in the center of stars? Why or why not? 15) Pass out a Lesson 3-5 task card to each pair. Utilizing the game kit, have students' model in their notebooks the pp-I chain shown on the front of the card step by step, noting places where energy and neutrinos are released, and answering the questions on the card. If a pair finishes early, or if time permits, have them also work through either the pp-II or pp-III chain on the back of the sheet, answering the additional questions. 16) (Slide 18) As a class, discuss the pp-I process. Were both neutrinos and anti-neutrinos created? Why or why not? Did every step release energy? How could we calculate the energy released at each step? Work through the first step as a class. Masses are listed on the slide. With their partner, students should work through the rest of the pp-I chain, calculating the total energy released when four protons fuse to make a 4-He nucleus. 17) (Slide 18) Can other nuclei besides 4He be made in hydrogen burning stars? Have students work with their partners to propose some reactions that might work to make nuclei with higher Z. (Remind them to consider binding energy in their discussion. students might want to use the game pieces and chart of the nuclides to try to figure out possible reactions. 18) (Slide 18) In a class discussion, groups should suggest what reactions they think might happen and write them on the board. Then as a class, discuss some of the proposed reactions. Keep Slide 18 up during the discussion to refer to the binding energy table and fusion temperature table. Come to a class consensus as to which reactions may be most likely to happen. 19) (Slide 19) The pp chain students worked through in detail is the most likely reaction to happen in the sun (83.3% of the time). It is called the proton fusion chain branch 1 (pp I). Slide 17 shows two other paths that happen in the sun. A 3He nuclei stays around the core of the sun approximately 400 years, so it has the possibility of encountering a 4He nucleus and fusing to make 7-Be. From there, two other paths can take place. Both end in two 4He nuclei. 20) (Slide 20) An additional path to 4He can take place if there are significant populations of nitrogen in the core of the sun. This is a 'catalytic' chain because the heavier nuclei are preserved. Walk through the steps of this chain starting at the top (p+12C) and working around the circle in a clockwise direction.

	(Teacher tip: If time permits, have students write in their journals the nuclear reactions for each step of one or more of the pp-II, pp-III or CNO chains, paying attention to conservation of lepton number, baryon number and charge.) 21) (Slide 19&20) Is there evidence that these three pp chains and the CNO cycle actually take place in the core of the sun? In a class discussion brainstorm what scientific data could be collected to prove or disprove the model for nucleosynthesis in the sun? Remind students that the density and temperature in the core of the sun is high. Can particles escape? Radiation? What kind? 22) (Slide 21) Could analyzing the light from the sun give evidence for which processes are taking place in the center? The problem is that the sun is very dense, and the photons of light undergo a lot of scattering before they escape. In fact, it takes approximately 10,000 years for a photon to reach the surface. Most of the spectral lines seen in a solar spectrum are coming from the chromosphere, so making claims about what is happening in the core from light spectra is problematic. 23) (Slide 22) What particle is made in during hydrogen fusion that has no charge so can move through matter with little interaction? *Neutrinos* If we can measure neutrinos from the sun (very hard) then maybe we could understand which processes are actually taking place and make conclusions about the temperature in the center of the sun. 24) (Slide 23) Show the short (2:28) video about the Ray Davis experiment at the former Homestake Gold Mine, the current home of the Sanford Underground Research Facility. The next activity will examine this landmark experiment in greater detail. *(Teacher tip: The video can be shown at the beginning of the following class period if preferred.)*
Exploration (45 minutes)	
Student Exploration	Activity 3-6. Connecting to evidence – Solar Neutrinos 14) (Slide 24) How can one detect a neutrino when it mostly goes right through everything without interacting? It can only be done indirectly. Refer to the bubble chamber photo on the slide while the class discusses what is meant by indirect detection. What are some clues that a neutrino caused the tracks seen? 15) Neutrino interactions are measured in a unit called a SNU (Solar Neutrino Unit) which is the neutrino flux that will give 10^{-36} interactions per target atom per second. That means if you had one atom, it would take 10^{36} seconds before a neutrino interacted. How long would one have to wait? *3×10^{28} years* What is the age of the universe? *4×10^{9} years* Brainstorm ways to get around this infinitesimally small number. 16) (Slide 25) Either together as a class, with a partner, or individually in their journals, students should work through the calculation of how many atoms of ^{37}Cl are in 100,000 gallons of C_2Cl_4. They need to consider the natural abundance of ^{37}Cl (approximately 25%). Density values are given on the slide. Does having a large detector solve the neutrino detection problems? Why couldn't Davis detect neutrinos with the ^{35}Cl? 17) (Slide 26) Davis proposed to extract the argon from the tank of liquid and look for radioactivity offline. This takes time. Look up as a class what the properties of the ^{35}Ar product from neutrino capture? *^{35}Ar has a decay of seconds so even though it happens, Davis couldn't detect it with his technique*.

18) (Slide 27) Theoretician John Bahcall predicted that 62 billion neutrinos per cm^2
19) reach the earth from the sun. However, most of those are lower energy proton neutrinos from the 83.3% pp-I process. Ray Davis calculated that his detector would produce 4-11 radioactive ^{37}Ar atoms per day from the higher energy ^{8}B neutrinos produced in pp-III. Those atoms beta decay back to ^{37}Cl with a half-life of 35 days. How could those few atoms be detected among the ~10^{30} atoms of C_2Cl_4? Brainstorm some possibilities as a class.

20) (Slide 28&29) When building such a large detector, interactions of charged particles can cause major background. Ray Davis proposed to use a mile of rock to stop cosmic ray showers in the atmosphere that would make his detection impossible. As a class or individually in a journal, plot the cosmic ray interactions as a function of depth that he published in his seminal 1964 paper proposing the experiment.

21) Does going underground get rid of all the background that might interfere with detecting neutrinos? In order to narrow down the possibilities and determine the best way to measure the ^{37}Ar, we will look more carefully at the properties of radioactive decay. Organize the class into groups of 3-4 students and pass out Activity Task Card 3-6. Groups will explore the properties of beta decay and other radioactive decays leading to background as input into the design of the Solar Neutrino Experiment. Each group should pick up a Geiger counter, ruler, container of degrader materials, a protractor, a baggie of binder clips and clay, and a set of three radioactive sources (a ^{90}Sr beta source plus two unknown background sources.

22) Students should first explore the behavior of the sources qualitatively using the materials at their disposal. (***Task A on card)***
23) After a few minutes, stop and have each group report in. Ask them what parameters they explored and list them on the board. Variables (parameters) that groups will hopefully mention are distance from Geiger counter, angle, density, or thickness of degraders. Make a table on the board following the sample table on the back of their task card and fill it in as a class; an example could end up looking like:

Parameter	Range of counts
Angle	0-45 degrees
Distance in air	0 – 10 cm
Degrader Type	Stops in Al, Brass, plastic
Degrader Thickness (pick one type as an example)	0 – 0.015

(Teacher Tip: The purpose of this table is so that when students design their experiment, they choose a set up that will work. For example, if they decide to use degrader type as their variable, they need to know that they cannot fix the distance for their experiment at >10 cm but need to get closer.)

	24) Each group will then discuss what information might help them in designing the Ray Davis experiment, decide which variable they want to explore quantitatively, then design the investigation and make a procedure and data table in their science notebooks. (***Task B on card)*** Conduct the investigation and analyze the data. 25) In a class discussion have groups report out on what they learned from their investigations. Based on what they learned do they think it will be easy to measure the beta decays coming from a few argon atoms a day? Would the beta particles escape the tank? Will there be issues with background radiation that might be coming from the rock or other locations in the area? 26) (Slide 30) Ray Davis was concerned about background radiation from the rock in the mine. To keep that radiation from getting into the tank, he filled the whole cave with water. Do you think this will be effective in stopping alpha, beta, and gamma decay? Why wouldn't the tank walls be sufficient?
Summary (10 minutes)	
Communicate	Activity 3-7. The Solar Neutrino Problem 5) (Slide 31) The early results came in from the experiment within a few months and were surprising. There were only 1/3 of the number of ^{37}Ar atoms as were predicted from the models. Most scientists thought that the experiment was just too hard, and Ray Davis was not getting all the argon out. He kept improving the system and testing the system – and collecting more data. He proved to many scientists that his data was accurate. What else could be wrong? 6) (Slide 32) Pass out a set of the solar neutrino problem card sort to each pair of students. With a partner, have students sort the cards by whether they support Claim 1 (the experiment gave credible results), Claim 2 (the model is credible, and something was wrong with the experimental data), neither or both. All the evidence comes from scientific literature. Does it strongly support one claim or the other? 7) Once each pair comes to consensus, pass out a Lesson 3 assessment card to each student. In their notebook or on a separate piece of paper, they should write a paragraph using evidence to support one of the four claims (experiment is credible, model is credible, neither are credible, both are credible). An evaluation rubric is on the back of the Assessment Card. When everyone is done, poll the class. Which claim did students believe was best supported by the evidence? 8) (Slide 33) After students have completed their paragraph, play the video interview with Nobel Prize winner Art McDonald, who explains how the 'Solar Neutrino Problem' was solved. Which claim turned out to be correct? *(Teacher Tip: The written assessment can be given as homework. In that case, wait until the beginning of Lesson 4 to play the video in Slide 33.)*
Terminology and Concepts to Solidify	Activity – **Activity** is a quantity related to radioactivity of an unstable isotope. The SI unit of activity is the Becquerel. Alpha Decay - **Alpha decay** is a form of radioactive in which a nucleus emits an alpha particle, or helium nucleus. The decay of a nucleus (Z,A) leaves a 'daughter' nucleus (Z-2, A-4).

Becquerel – A **Becquerel (Bq)** is the SI derived unit of radioactivity. One becquerel is defined as the activity of a quantity of radioactive material in which one nucleus decays per second.

Beta decay (β) – **Beta decay** is a form of radioactive decay caused by the weak nuclear force, in which a beta particle (electron or positron) and a neutrino or antineutrino is emitted from the nucleus of an atom. In β^+-decay, a proton in the nucleus transforms to a neutron; in β^--decay, a neutron in the nucleus transforms to a proton.

Bubble Chamber - A **bubble chamber** is a simple, visual detector of radioactive particles. The chamber is a vessel filled with a superheated transparent liquid (most often liquid hydrogen) used to detect electrically charged particles moving through it.

Cloud chamber **–** A **cloud chamber** is another visual detector of radioactive particles, that utilizes a supersaturated vapor instead of a liquid to detect electrically charged particles moving through it.
Coulomb Barrier – The **Coulomb barrier** is the electric potential energy between two nuclei at the distance where the attractive strong interaction takes over. In order to overcome the barrier and undergo fusion, the two nuclei must have sufficient kinetic energy, or temperature. Quantum mechanics allows for some nuclei to fuse at lower temperatures by 'tunneling' through the barrier.
Curie – A **Curie (Ci)** is a unit of radioactivity equal to 3.7×10^{10} disintegrations per second.

Gamma Decay – **Gamma decay** happens when an excited nucleus relaxes into a lower energy state through the neutrons and/or protons falling into lower energy shells. A high energy photon called a gamma ray is emitted with an energy equal to the energy difference between the two shells. Each isotope has its own characteristic gamma ray decay pattern which can be used as a finger print of the isotope.

Geiger (Geiger-Müller) Counter – The **Geiger counter** is an instrument for detecting ionizing radiation, consisting of a gas-filled tube in which electrical pulses are produced when a gas is ionized by radiation.

Gravitational Potential Energy - **Gravitational potential energy** is energy an object possesses because of its position in a gravitational field.

Half-life – The **half-life** for particle or nuclear decay is defined as the time in which half the (large number of) atoms of a particular radioactive nuclide disintegrate. The half- life is a characteristic property of each radioactive isotope.

Protostar - A **protostar** is a contracting mass of gas in a late stage of star formation, just before nuclear fusion takes over.

Radioactivity - **Radioactivity is** defined as the spontaneous emission of particles or electromagnetic radiation, or both at the same time, from the decay of certain atomic nuclei.

Specific Activity – **Specific activity** is the activity per quantity of atoms of a particular radioactive substance. The SI unit is Becquerels/gram (Bq/g)
Statistical Fluctuation – **Statistical fluctuations** are fluctuations in quantities derived from many identical random processes. They are fundamental and unavoidable. It can be proved that the relative fluctuations reduce as the square root of the number of

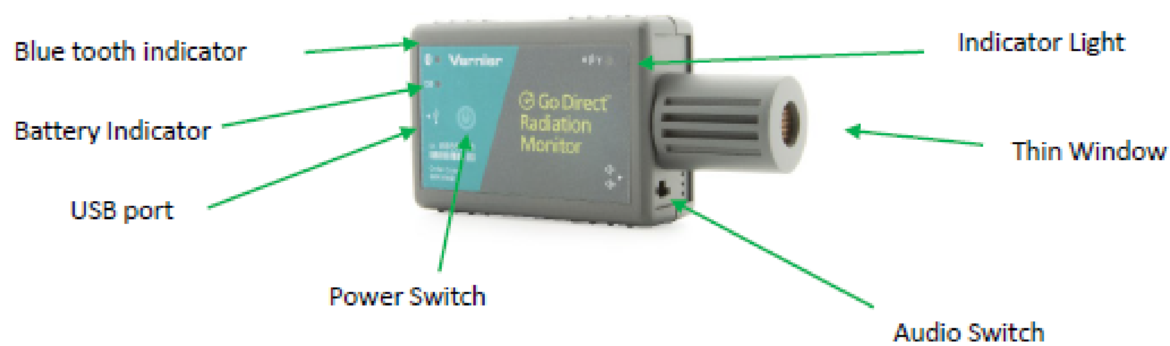
	identical processes.
Connection to Big Ideas (Phenomena)	At the end of nucleosynthesis in the Big Bang, the universe was predominantly hydrogen and helium. Could nucleosynthesis beyond helium happen in hydrogen burning stars the size of our sun? After studying models of hydrogen burning in the sun, the answer is no. We will have to look towards larger, hotter stars as sources of higher Z elements.
Follow Up/Practice	Nuclear Fission - Fission | Chain Reaction | Atomic Nuclei - PhET Interactive Simulations (colorado.edu) To learn about the process of fission, visit University of Colorado at Boulder PhFT simulations.
Optional Extension	Design and investigate to determine the effectiveness of water as a shield of background radiation surrounding the Davis tank. **Please do not put radioactive sources directly in the water (Fiestaware is okay.)**
Assessment	The lesson assessment is an individual Claims-Evidence-Reasoning paragraph about the Solar Neutrino Problem. The rubric is included on the assessment card.

'WE ARE MADE OF STARSTUFF'

LESSON 3. FAMILIARIZING YOURSELVES WITH A GEIGER-MULLER (GM) COUNTER

NAMES ____

In this investigation, you will be working with a Go Direct radiation monitor that contains a Geiger-Muller tube. You will explore how this monitor works by measuring the background radiation in your classroom.



The thin mica window at the front of the monitor window is fragile! Please do not let anything (especially a pointed object) touch the window.

1. **USB Connection**

   a. Install Graphical Analysis on your computer or Chromebook. If using LabQuest, make sure LabQuest App is up to date. See www.vernier.com/ga4 for software availability or www.vernier.com/downloads to update LabQuest App.

   b. Connect the sensor to the USB port.

   c. Launch Graphical Analysis or turn on LabQuest. You are now ready to collect data.

2. In the bottom left corner of the Graphical Analysis screen, you will see an icon with a set of axis and three points connected by a line. This is the Graph Tools icon. Click the Graph

Tools icon and then select Edit Graph Tools. In the Graph Options window that appears, change the end time for the x-axis from 600 to 360. You will see that the graph axis adjusts as well.

3. Start your data run by pointing the Go Direct Radiation Monitor away from any near objects, then press the collect button on Graphical Analysis.
    a. Every 10 seconds, the software will plot a point for the number of counts in that 10 second time interval. Let the trial run for the full 360 seconds.
    b. On the top left corner of the Graphical Analysis screen, you will see an icon with a square that has been divided into a rectangle and two smaller squares. It is the View Options Icon. Click the View Options Icon and turn on the data table. This will create a split screen view that will list all of your time intervals with counts and all of your trials.
    c. Using data from the data table add the counts for times 10 seconds through 60 seconds. That total is your Counts Per Minute (CPM) for the first minute. You can do the same for the next 5 minutes by adding the counts for each 60 second time interval (ie 70-120 seconds).
    d. If you add all the CPM and divide by 6, you will get your average CPM background.

Data Table

Time (sec)	Counts	Time	Counts	Time	Counts	Time	Counts	Time	Counts	Time	Counts
10		70		130		190		250		310	
20		80		140		200		260		320	
30		90		150		210		270		330	
40		100		160		220		280		340	
50		110		170		230		290		350	
60		120		180		240		300		360	
Total CPM											
									Average CPM		

4. What do you observe about the counts that are detected in the different time intervals?

5. Find another group and compare your results. Are they all the same? Why or why not? Do their values show the same patterns as yours did? Are their average values similar to yours? What statement could you make about the average background radiation counts in the room you are in?

6. Why are your counts not zero?

7. Suppose you need to determine the background radiation because it is your job to report this in a classroom safety report. Would it be better to measure and report the number of counts in a 5 second interval, 30 second interval, 60 second interval or 120 second interval? Why? Explain your choice.

8. Can you get the same background information you calculated above by reading graph and using the different graph tools functions?

MATH CHALLENGE: Try using an excel spreadsheet or graph tools to determine your average CPM background.

Rules of the Nucleosynthesis Game:

- The goal of the game is to be the first team to form a carbon (^{12}C) nucleus in stellar nucleosynthesis. The magnetic sphere is the 'strong force' center. of your nucleus. Start with that.
- Each group plays against one other team and rolls the dice to see who goes first.
- Groups take turns rolling the dice and building their nucleus according to the following rules.

Marble Color codes:

Yellow	proton
Green	neutron
Red	neutrino
Blue	Anti-neutrinos

Dice Codes:

Number	Action
1	Add a proton to your nucleus
2	Add a neutron to your nucleus
3	Your choice: add a proton or neutron to your nucleus
4	Nuclear decay: follow decay path on Chart of the Nuclides* (see back). If your nucleus decays to another shaded box, follow that decay also. Your nucleus should ultimately end up in a stable configuration. Collect your neutrinos in the lid of your box since they do not stick to the nucleus in the strong interaction.
5	Lose your turn
6	Collision! Each team at your table rolls their nuclei at each other's. Any nucleons that break off go back in your game box. Any nucleons you capture from the other side are added to your nucleus. If the two nuclei stick together, separate. in middle and each team gets what sticks to their magnet.

Chart of the Nuclides:

10	Ne							Ne16	Ne17	Ne18	Ne19	Ne20	Ne21	Ne22	Ne23	Ne24	Ne25	Ne26
9	F						F14	F15	F16	F17	F18	F19	F20	F21	F22	F23	F24	F25
8	O					O12	O13	O14	O15	O16	O17	O18	O19	O20	O21	O22	O23	O24
7	N				N10	N11	N12	N13	N14	N15	N16	N17	N18	N19	N20	N21	N22	N23
6	C			C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20	C21	C22
5	B		B6	B7	B8	B9	B10	B11	B12	B13	B14	B15	B16	B17	B18	B19		
4	Be		Be5	Be6	Be7	Be8	Be9	Be10	Be11	Be12	Be13	Be14	Be 15	Be16				
3	Li	Li3	Li4	Li5	Li6	Li7	Li8	Li9	Li10	Li11	Li12							
2	He	He2	He3	He4 (α)	He5	He6	He7	He8	He9	He10								
1	H	H1 (p)	H2	H3	H4	H5	H6	H7										
0	n		n1															
↑#p/#n→		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16

Decay Codes:

1p	$\beta^+ + \nu$	1n	α
2p	β- + anti-ν	2n	? (Unknown)
$\beta^+ p + \nu$	$\beta^- n$ + anti-ν		

SOLAR NEUTRINO CARD SORT

RESULTS OF EXPERIMENT (1970-1994): 2.56 ± 0.23 SNU (0.48 atoms/day)	RESULTS OF MODEL: 7.7 ± 1.3 SNU (1.5 atoms/day)
CLAIM: The experimentalists did everything they could to get rid of systematic errors in their experiment and the data was credible.	CLAIM: The theoreticians did everything they could to get rid of uncertainties in the input to their model calculations and the calculations were credible.
CLAIM: Both the experimentalists and theoreticians did enough to get rid of errors and uncertainties and both the data and models were credible. SOMETHING ELSE WAS GOING ON!	CLAIM: Neither the experimentalists and theoreticians did enough to get rid of errors and uncertainties. BETTER EXPEIMENTS AND MODELS ARE NEEDED!
The reaction rate was measured for. $^{3}He + ^{3}He \rightarrow ^{4}He + 2p$ and used as input to the solar model calculations.	In 1968, Bahcall and Shaviv calculated the uncertainty in the solar model by varying all the parameters for the nuclear reactions within what was then believed to be plausible limits.
The production rate for $^{7}Be + p \rightarrow ^{8}B$ was measured and used as input to the solar model calculations.	The detectors used at Brookhaven National lab for counting 37Ar were improved in 1970, reducing the background in the energy region of interest to 1 event per month.
Other paths from ^{37}Cl to ^{37}Ar (other than neutrino capture) were calculated and/or measured.	Flooding the chamber with water eliminated any possibility that 37Ar was made in the tank from fast neutrons from the surrounding rock wall.
The tank was carefully constructed and tested to make sure that air could not leak in because air contains 0.93% argon.	Adding a known amount of ^{36}Cl-labeled C_2Cl_4, which decays to 36Ar, Davis and collaborators showed that argon was removed from the tank with high efficiency.
40 'educators' provided vigorous agitation and thorough mixing of the helium purge gas with the liquid.	The theoretical capture rate of neutrinos on 37Cl is very sensitive to the rates of the two reactions: $^{7}Be + p \rightarrow ^{8}B$ and $^{3}He + ^{4}He \rightarrow ^{7}Be$
Before filling the tank, it was thoroughly cleaned, then selected areas were tested to make sure that the alpha emission rate from the inside walls was below acceptable limits.	There is no way (yet) to directly measure the temperature in the core of the sun.

ANSWER KEY (AUTHORS' OPINION BUT OTHER ANSWERS COULD BE SUPPORTED). Students will learn that both experiment and theory were finally proved correct, and that the discrepancy was explained by unknown properties of neutrinos (CLAIM 3).

The reaction rate was measured for. $^{3}He + ^{3}He \rightarrow ^{4}He + 2p$ and used as input to the solar model calculations.	In 1968, Bahcall and Shaviv calculated the uncertainty in the solar model by varying all the parameters for the nuclear reactions within what was then believed to be plausible limits.
The production rate for $^{7}Be + p \rightarrow ^{8}B$ was measured and used as input to the solar model calculations.	The detectors used at Brookhaven National lab for counting ^{37}Ar were improved in 1970, reducing the background in the energy region of interest to 1 event per month.
Other paths from ^{37}Cl to ^{37}Ar (other than neutrino capture) were calculated and/or measured.	Flooding the chamber with water eliminated any possibility that ^{37}Ar was made in the tank from fast neutrons from the surrounding rock wall.
The tank was carefully constructed and tested to make sure that air could not leak in because air contains 0.93% argon.	Adding a known amount of ^{36}Cl-labeled C_2Cl_4, which decays to ^{36}Ar, Davis and collaborators showed that argon was removed from the tank with high efficiency.
40 'educators' provided vigorous agitation and thorough mixing of the helium purge gas with the liquid.	The theoretical capture rate of neutrinos on ^{37}Cl is very sensitive to the rates of the two reactions: $^{7}Be + p \rightarrow ^{8}B$ and $^{3}He + ^{4}He \rightarrow ^{7}Be$
Before filling the tank, it was thoroughly cleaned, then selected areas were tested to make sure that the alpha emission rate from the inside walls was below acceptable limits.	There is no way (yet) to directly measure the temperature in the core of the sun.
SUPPORTS CLAIM 1 (Experiment was credible)	SUPPORTS CLAIM 2 (Theory was credible)
SUPPORTS CLAIM 3 (Both experiment and theory credible)	SUPPORTS CLAIM 4 (Neither experiment nor theory credible)

Lesson 4, *Beyond Helium*

ACTIVITY 4-1. When the Light Fades (LAUNCH)

Questions	What we Figure out	New Questions
What will happen to the sun once all the hydrogen is converted to helium?	During fusion, there is a balance of gravitational forces with radiation pressure that is disrupted when fusion stops.	What is the ultimate fate of the sun? Stars heavier than the sun?

ACTIVITY – After recapping what they learned about the sun and stellar fusion in Lesson 3, students will use mathematical representations to predict whether helium can undergo fusion in the core of the sun once the hydrogen is exhausted.

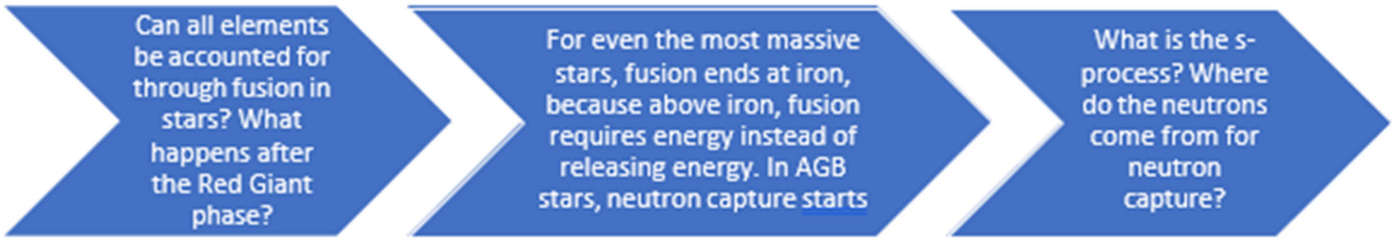
ACTIVITY 4-2. Star in a Box (EXPLORE 4a)

Questions	What We Figure out	New Questions
What is the ultimate fate of the sun? Stars heavier than the sun?	Depending on its mass, a star goes through many stages, some explosive, and ends up as one of several types of remnants.	Can all elements be accounted for through fusion in the stars? What happens after the Red Giant phase?

ACTIVITY – Students will utilize the *Star in a Box* simulation to diagram and compare the life cycle and properties of the sun and one other star of their choosing. They will research and communicate ideas for where and when nuclear fusion occurs in the evolution of stars away from the main sequence.

ACTIVITY 4-3. The end of Fusion (SUMMARIZE 4a)

Questions | What we Figure out | New Questions



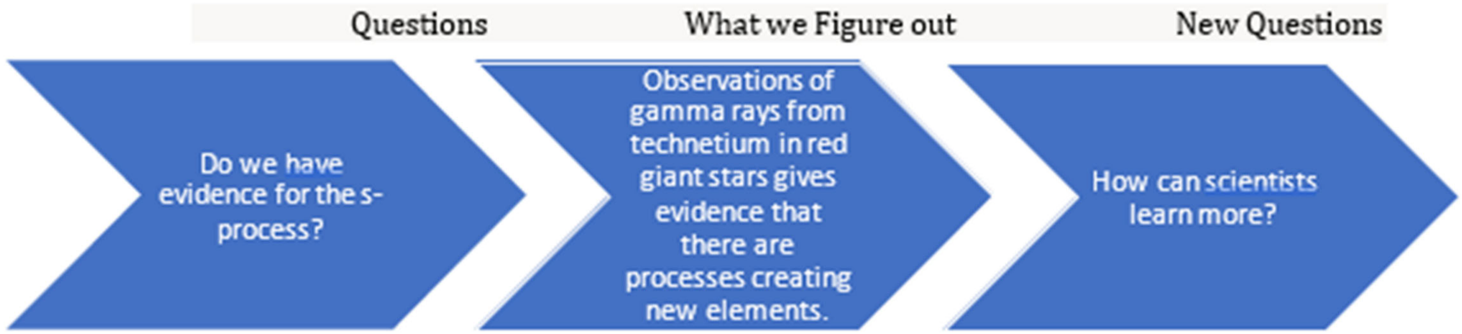
ACTIVITY – Students share out their discoveries from the last two activities, making connections back to the unit phenomenon.

ACTIVITY 4-4. The s-process (EXPLORE 4b)

Questions | What we Figure out | New Questions

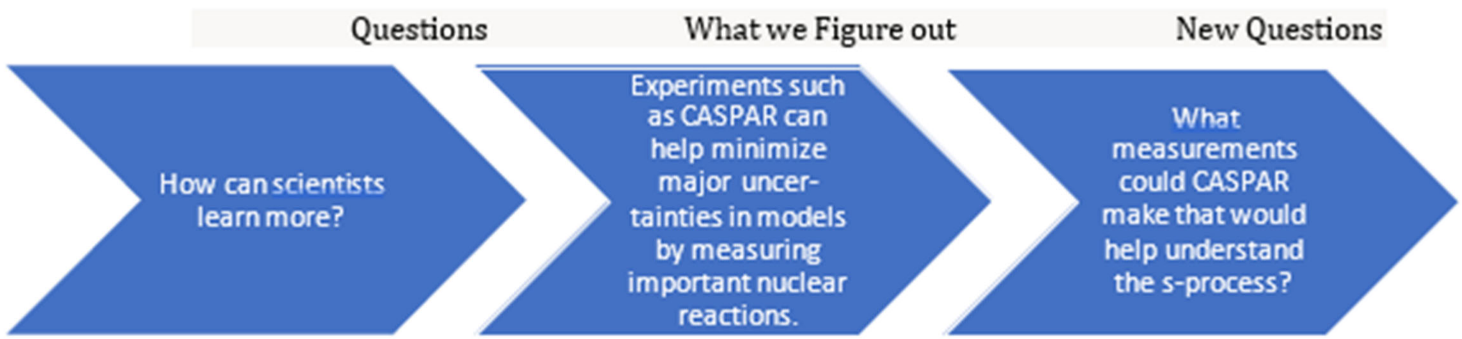
ACTIVITY – Students model the s-process (slow neutron capture) to explore whether it can account for all stable isotopes heavier than iron.

ACTIVITY 4-5. Connecting to Evidence: Revisiting Technetium (SUMMARIZE 4b)



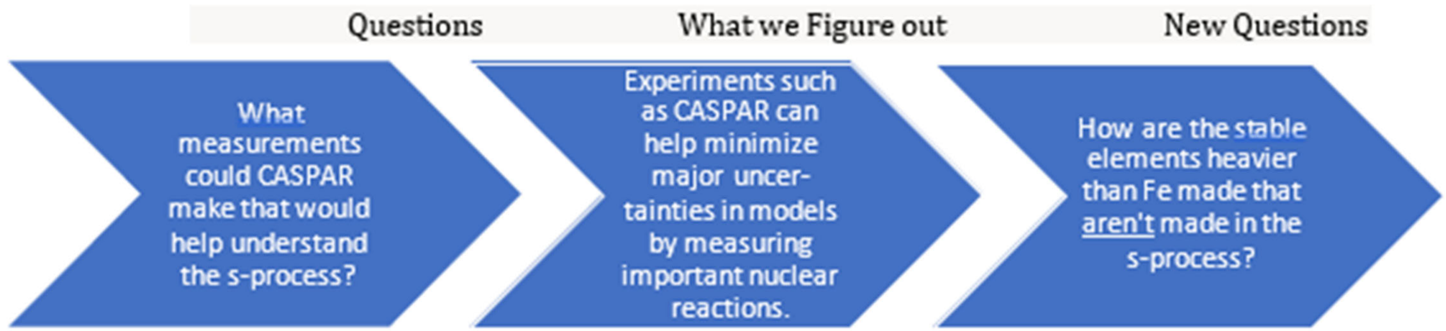
ACTIVITY – Students will examine evidence for the s-process happening in stars in the red giant (AGB) phase of their life.

ACTIVITY 4-6. Connecting to Sanford Lab: The CASPAR Experiment (EXPLORE 4c)



ACTIVITY – Students will explore earth-bound technology that is used to measure nuclear processes in order to develop and improve nucleosynthesis models.

ACTIVITY 4-7. Go Fund Me! (SUMMARIZE 4c)



ACTIVITY – Students will use evidence and reasoning to defend a nuclear reaction to be studied at CASPAR at Sanford Lab to improve s-process nucleosynthesis models. (Lesson Assessment)

Lesson 4	Beyond Helium
Overview Standard(s) & Objectives	*This lesson is designed for three 50-minute class periods or two block periods. The structure and flow of the lesson is given at the beginning of the Background Material section. DCIs, SEPs and CCCs for each activity are color-coded.* **Performance Expectations:** HS-PS1-8. Develop models to illustrate the change in the composition of the nucleus of the atom and the energy released during the processes of fission, fusion and radioactive decay. HS-PS2-4. Use mathematical representations of Newton's Law of Gravitation and Coulomb's Law to describe and predict the gravitational and electrostatic forces between objects. HS-PS3-3. Design, build and refine a device that works within given constraints to convert one form of energy into another form of energy. HS-PS3-5. Develop and use a model of two objects interacting through electric or magnetic fields to illustrate the forces between objects and the changes in energy of the objects due to the interaction. HS-ESS1-1. Develop a model based on evidence to illustrate the life span of the Sun and the role of nuclear fusion in the Sun's core to release energy that eventually reaches Earth in the form of radiation. HS-ESS1-3. Communicate scientific ideas about the way stars, over their life cycle, produce elements. **Disciplinary Core Ideas:** ● PS1.C Nuclear Processes ● ESS1.A The Universe and Its Stars **SEPs:** ● Developing and using models ● Using mathematical representations ● Constructing explanations and designing solutions ● Obtaining, evaluating, and communicating information **CCCs:** ● Energy and Matter ● Scale, proportion, and quantity ● Patterns **Lesson Phenomenon:** Video of the fate of the sun **Lesson Objectives:** ● After recapping what they learned about the sun and stellar fusion in Lesson 3, students will use mathematical representations to predict whether helium can start to fuse in the core of the sun once the hydrogen is exhausted. ● Students will utilize the Star-in-a-Box simulation to diagram and compare the life cycle and properties of the sun and one other star of their choosing. They will research and communicate ideas for where and when nuclear fusion occurs in the evolution of stars when they are off of the main sequence.

	● Students share out their discoveries from the last two activities, making connections back to the unit phenomenon. ● Students will model the s-process (slow neutron capture) to explore whether it can account for all stable isotopes heavier that Fe. ● Students will examine evidence for the s-process happening in stars in the red giant (AGB) phase of their life. ● Students will explore earth-bound technology that is used to measure nuclear processes to develop and improve nucleosynthesis models. ● Students will use evidence and reasoning to defend a nuclear reaction to be studied at the CASPAR experiment at Sanford Lab to improve s- process nucleosynthesis models.
Background Information	**Structure of Lesson:** 8. (LAUNCH) In Activity 4-1, *When the Light Fades*, the lesson is launched with a short video of the fate of the sun, the phenomenon for the lesson. Students recap what they learned about the sun and what questions they still have. They use their knowledge of the gravitational and electromagnetic interactions and energy transfer to propose an explanation for what will happen to the sun once hydrogen fusion in the core is exhausted. *9.* (EXPLORE) In Activity 4-2, *Star in a Box,* students explore stellar evolution models to determine the fate of the sun and one other star of their choosing. They then research and evaluate the dynamics of the evolution of their two stars from the main sequence to the red giant phase, including possible nuclear fusion and other reactions that can lead to nuclei more massive than helium, and communicate that information to their classmates in the form of a poster. *(Teacher Tip: For schools with a 50-55 minute class period, the group research and communication part of Activity 4-2 can carry over to Day 2 of this lesson (or be completed outside class)).* 10. (SUMMARIZE) In Activity 4-3, *The End of Fusion*, students revisit the concept of binding energy in order to make sense of why fusion reactions can only produce elements up to iron. *11.* (EXPLORE) In Activity 4-4, *The s-process in AGB Stars,* students model slow neutron capture (the s-process) in cool, luminous stars, determining the trends for which elements and isotopes can be created through the s-process. 12. (SUMMARIZE) In Activity 4-5, *Connecting to Evidence: Revisiting technetium)* Students examine data showing the presence of the element technetium in electromagnetic radiation from AGB stars, and draw conclusions whether those stars could be possible sites of the s-process. *(Teacher Tip: For schools with a 50–55-minute class period, this is a natural stopping place for Day 2 of this lesson. If the research activity was completed outside of class, then the next activity can be included in Day 2.)* 13. (EXPLORE) In Activity 4-6, *Connecting to Sanford Lab: The CASPAR*

<table>
<tr><td></td><td>Experiment) students construct models to explore the science and engineering behind underground accelerators which are used to provide input to the models for stellar evolution.

14. (FORMATIVE ASSESSMENT) In Activity 4-7, Go Fund Me! students will use evidence and reasoning to communicate the importance to s-process models of the next nuclear reaction to be measured with CASPAR.</td></tr>
<tr><td>Materials</td><td><u>Launch (4-1):</u>
No materials needed
<u>Explore (4-2):</u>
For each pair of students:
• Activity 4-2 Task Card
• Colored Pencils
➢ Computers
➢ Poster Paper
<u>Summarize (4-3):</u>
For each student:
• Periodic Table Template (Print Master)
• Colored Pencils
<u>Explore (4-4) & Summarize (4-5)</u>
For the classroom:
➢ Large Sheet of Paper/Whiteboard
➢ Colored Markers
For each pair of students:
• Nucleosynthesis Game Kits
• Chart of Nuclides
• Activity 4-4 Task Card
• 11x17 Chart of Nuclides
• Colored Pencils
<u>Explore (4-6):</u>
For each small group (3 students):
• Activity 4-6 Task Card
• Authorization to Proceed (ATP) Card
• Set of Magnets and Steel Balls
• Set of Accelerator Tracks
• Tape
• Measuring Tape
• Plastic Cup
For each student:

Safety Glasses</td></tr>
<tr><td>Prior Knowledge</td><td>This lesson expands on the concepts students explored with our own sun in Lesson 3 to all stars in the universe.</td></tr>
<tr><td>Engagement and Communication</td><td>Activity 4-1. When the Light Fades</td></tr>
</table>

of Student Expectations	2. Pass out the periodic table templates (one per student) and colored pencils (per pair of students). Give students a minute to get organized and decide on a color- coding scheme for the origin of each element. Use hydrogen as an example; it is made in the Big Bang. Anywhere else? Students should color in hydrogen with their choice of color for Big Bang nucleosynthesis. Helium is made in both BBN and stellar fusion, so that box should be split between two colors. *(TEACHER TIP: Students should be reminded to hang onto their periodic tables because they will be revisiting them several times during the next several activities.)* 8) (Slide 2) Play the video of the evolution of the sun. In a class discussion, have students recap what they learned about the sun in the previous lesson, and what questions they still have. Write them on the board. *Some questions they might think about are:* ➢ *Once hydrogen burning is complete, what will happen to the sun? Why? Will it cool down?* ➢ *Are there other processes that could replace helium as a fuel?* ➢ *We still have an open question of where the nitrogen came from to start the CNO process.* *9)* (Slide 3) Remind students that hydrogen fusion 'turning on' stopped the gravitational collapse of the protostar and stabilized the young star. The fusion process caused an outward pressure (radiation pressure) to counteract the force of gravity. *10)* Have students work with a partner and brainstorm what might happen when the hydrogen in the sun is exhausted. After a couple of minutes, facilitate a class discussion. What ideas do students have for what will happen next? What factors might be important to figure out what happens next? 11) (Slide 4) Introduce the 'virial theorem' which can be used to approximate the kinetic energy (temperature) change during the gravitational collapse of an 'ensemble' (group) of particles of identical particles such as protons. In studying this mathematical representation, what factors play a role in the collapse of particles? Can students calculate a maximum temperature for the center of the sun? What if a star with a mass of $10T_{\odot}$ collapsed? Would the temperature be higher or lower? By how much? 12) (Slide 4) Revisit the Coulomb barrier for fusion of two nuclei. How much harder is it to fuse two helium nuclei? If the temperature for hydrogen fusion to start is approximately 0.03 billion K, what is the estimated temperature for helium nuclei to fuse? 13) (Slide 5) Early astronomers classified stars by their brightness (luminosity) and their surface temperature. They found that most stars fell on a curve which they called the 'main sequence'. Where they fall on the curve depends on their mass. The life cycle of a star also depends on its mass. We will explore what happens to a star the mass of the sun and a heavier star. Break students into pairs for the Star in a Box activity and pass out an Activity 4-2 task card to each pair. Each group needs access to a computer and internet with the link at https://lcogt.net/education/starinabox/.

Exploration	**Activity 4-2. Star-in-a-box** *4)* Students will use the Star-in-a-Box model to explore the life cycle of a star of $M_\odot$ = 1 (equivalent to the sun) and one other star of their choosing from options given. There are three parts to the exploration: ○ PART A: Using questions on the task card, explore the life cycle of a $M_\odot$ = 1 star and their second chosen star. ○ PART B: They will create a Hertzsprung-Russell (H-R) diagram and draw the life cycle of the sun. Draw the second star on the same H-R diagram. From the observed luminosity and temperature of the star, students should be able to draw conclusions as to which stage it is at in its evolution. ○ PART C: For the sun, choose different three points during its evolution between the Main Sequence phase and the Red Giant phase and add substructure details, including size and, if nuclear fusion is taking place, show what and where. *(TEACHER TIP: Part C will require some research by students in or out of class. Before beginning Part C, take a break and do the next part to give them a starting point.)* 5) (Slide 6) When most groups are done or nearly done with their H-R diagrams, take a short break and revisit the effect of binding energy on fusion. Students learned in Lesson 2 that because of its low binding energy, 8-Be, the product of two helium nuclei fusing, has a lifetime of only 8 x 10^{-17} seconds, making it a bottleneck for fusion. In order to get past this bottleneck, a third helium nuclei must be fused to make C-12 (triple-alpha fusion). This requires a temperature of greater than 100 million K in the core of the star. Was there a stage in the sun's evolution where temperatures were that high? What about their second star? 6) (Slide 7) PART C of this task will require some research either in or outside of class. Working with their partners, students will expand their basic H-R diagram of the evolution of the sun to include details of at least three stages that the star will pass through, during its evolution to and through the Red Giant stage (the end-of-life stages will be addressed in Lesson 5). Some research references are given in the PowerPoint. Include the size and substructure of the sun at each stage, and if nuclear fusion is taking place, show what and where. If time is available, students can also do the same research for their second star. *(Teachers Note: Poster size sheets of paper can be made available for this activity; students could also use a computer. Part C of this task could be assigned for out-of-class time.)* (Slide 8, OPTIONAL) A sample of the kind of diagram students might generate fo the sun is shown in the PowerPoint as an example.
Questions for Student Exploration	Questions are listed on the Lesson 4-2 Task Card.
Summarize	

Communicate and Synthesize	**Activity 4-3. The End of Fusion** 5. (Slide 10) On the whiteboard or a large sheet of paper, draw and label axes for a class composite H-R diagram. Based on their research, each group should add at least one point along the path of a one solar mass star. The composite H-R diagram should look something like the diagram shown in the PowerPoint. Step through the fusion processes in the PowerPoint and have one student mark where those occur on the composite H-R diagram. When helium burning is exhausted and the star begins to cool again, it is on a path parallel to its original path. This is called the Asymptotic Giant Branch (AGB). 6. (Slide 8) Facilitate a discussion about which elements were made during fusion. All groups should have reached the same conclusions about the main elements made during the sun's time on the main sequence and its transition to a red giant (*He, C, O).* Students should take out their periodic table templates and color those in with their choice of colors for fusion reactions. Then have groups present the results of their research into other stars, starting with the lowest mass stars and working up. As new elements are made in the more massive stars, students can color those in. 7. What is the heaviest element made in the most massive stars? (*Fe or Ni).* Why can fusion not proceed to even higher Z elements? Have students suggest ideas. 8. (Slide 9) The answer to this puzzle again lies in the underlying property of nuclei-binding energy. The fusion of two silicon to make iron is the last set of fusion reactions which release energy. If you try to fuse two iron nuclei to make something heavier, it requires additional energy, so fusion cannot be sustained. 4. (Slide 9) The answer to this puzzle again lies in the underlying property of nuclei-binding energy.
Exploration	
Communicate	**Activity 4-4. The S-Process** 8) (Slide 11) Refer to the substructure of the sun that students researched and added to the large H-R diagram. Make note of the layers that form as the sun expands. As the star goes through stages of hydrogen burning in the outer shell, and helium burning, first in the core, then in an inner shell around a carbon core, sometimes there will be a thermal pulse of energy, which serves to mix up the layers, sending carbon outwards and hydrogen inwards. 9) Form groups of 4 students and give each group two Activity 4-4 task cards, two of the nucleosynthesis game kits used in Lesson 3, along with one Chart of the Nuclides from Lesson 3. In **Part A**, students will start with carbon, oxygen, helium, and protons and brainstorm some reactions that might happen once there is thermal mixing in the star. Is it possible to form new elements? Will some of these elements beta decay to other elements? 10) Share out ideas as a class and list on the board. (*Some possibilities are 4He + 12C→16O; 4He + 16O →20Ne; 1H + 12C → 13N (beta decays to 13C); 13C + 4He →16O + n*) 11) Students are not likely to come up with reactions that emit neutrons, but they do

happen when nuclei are made with extra energy. Why is it easy for an excited nucleus to emit a neutron? *No charge so no Coulomb barrier*

12) (Slide 11) Both protons and neutrons can combine with a heavier nucleus to make a new isotope or element. We call this 'capture'. Scientists refer to the p-process and the s-process for proton capture and 'slow' neutron capture, respectively. Using the slide, review neutron capture, proton capture and beta-decay, and which elements are made in each case. Have the class decide which square on the table should be colored for each process.

13) (Slide 12) In most cases, proton capture happens with very low probability. Why? To get an estimate of how difficult it is, estimate the Coulomb barrier for a 56Fe nucleus to capture a proton, compared to two protons to fuse. To overcome the barrier, the protons must be at very high energy, higher than found in the center of stars. There are some nuclei that are thought to be made through proton capture, but it is still a mystery where in the cosmos they are made.

14) Because there is no Coulomb barrier, neutron capture is much more probable. In AGB stars, neutrons can be captured by heavier nuclei to make new elements. For **Part B** of Task Card 4-4, split each group into pairs and give each pair, a laminated *Chart of the Nuclides (11" x 17"),* an 11" x17" student handout and a set of colored pencils. The 'rules' for the s-process are on the card. Have students circle Fe-56 on their chart, then pick one color to mark the path of the s-process following the rules on the task card. The half-lives for beta-decay are given on the laminated chart of the nuclides for each unstable element.

(TEACHER TIP: Students will be using the handout again in Lesson 5, so groups should write their names on them and hang on to them when done with this activity. Students should work with the same partner in Lesson 5.)

(TEACHER TIP: The Chart of the Nuclides (both versions) is broken into several pieces to fit everything on two pages. Students will be able to follow the s-process through all five precious metals by jumping from piece to the next. A picture of a completed Chart is given on the unit flash drive for reference).

(TEACHER TIP: If the beta-decay half-life equals the neutron capture rate (10 years), students can choose which process to follow. This is a branch in the path, but students will find whichever branch they follow, they meet up again. Be Careful: There are three isotopes shown in the chart (Zn65, Ge71, Kr81) which undergo beta-plus decay. If your path runs through one of those isotopes, it changes direction at that point).

10) (Slide 13) Once the path up to gold has been marked, students can write 'S' in the stable isotopes created during the s-process. These are s-process nuclei. Can all stable isotopes in this region of the chart of the nuclides be made in the s-process. What do they notice about the s-process path.

11) On each student's periodic table template, they should pick a color to color the s-process elements. If not all the stable isotopes of an element can be accounted for by the s-process, they should only partially color it – the missing isotopes must be made some other way.

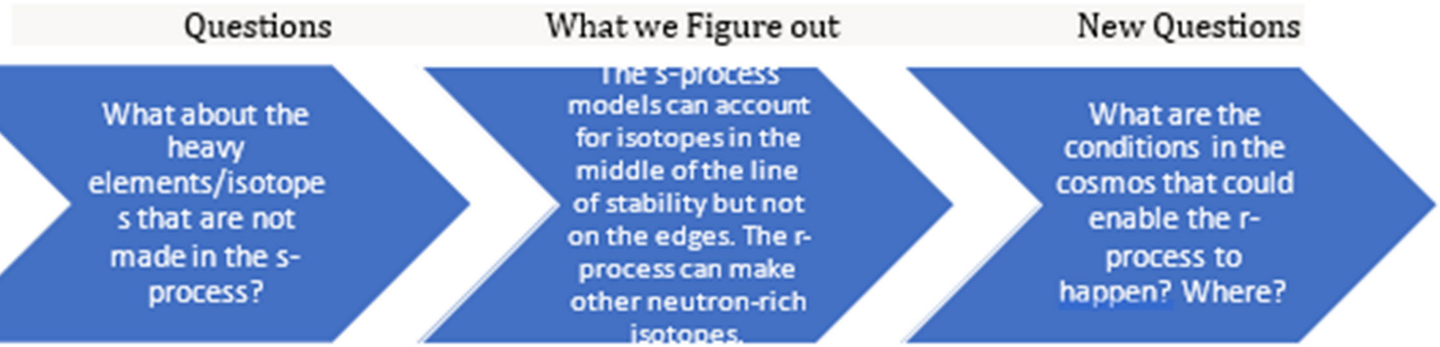
Summary

Student Exploration	Activity 4-5. Connecting to Evidence – Revisiting Technetium 3) In Lesson 3, students learned that Tc-99m is an important medical isotope with many applications. It is also unique in having no stable isotopes. So how can that give us evidence for the s-process? 4) In a class discussion, have students recall what they learned about Tc-99m and its use in medical applications. What isotope is made in reactors as a source of Tc? *Mo-99* *(TEACHER TIP: The back of the Activity 3-2 Task Card featured Tc-99m. You might want to pass it back out if students didn't read it or need review.)* 7) Have each pair of students study their s-process path. Does it go through Tc? Did everyone's path go through the same isotope(s) of Tc? Which isotope(s)? Go to this website as a class and look at the decay chain those isotopes. What is its half-life and how does it decay? 8) (Slide 14) If we saw evidence for Tc in the stars, what would that tell us? After a class discussion, show the data for Tc gamma rays in the Milky Way. Is this evidence for the s-process? This data gave very important early evidence that the models for the lifetime of the stars was correct. 9) (Slide 15) This slide shows a more contemporary measurement: a gamma ray map of the Milky Way galaxy for Fe-60, taken using the Integral Gamma Telescope. What is the half-life for Fe-60? Does this measurement give evidence for the s-process? 10) Are there any other elements lighter than gold that have no stable isotopes? Is there an isotope that is on the s-process path? Speculate on whether studying this element might give us additional information? *Promethium (Pm) has no stable isotopes. 147Pm is on the s-process path, but only has a half-life of 2.6 years so is unlikely to undergo the s-process.*
Exploration	
Communicate	**Activity 4-6. Connections to Sanford Lab: CASPAR** 6) Brainstorm ideas about how scientists could gain additional knowledge about nucleosynthesis at various sites in the cosmos, perhaps to answer the debate from the previous day. What questions need to be considered? *Some examples: "What types of elements come from what types of stars?" and "What are the conditions that exist in those stars to cause nucleosynthesis?" Could we reproduce those conditions in a lab? What tools would we need?* 7) (Slide 16) Play Steven Hawking video – 'The Birth of Stars' where he describes what it would take to make a star in a laboratory (on flash drive and linked from PowerPoint). Afterwards continue the discussion. Could we ever make a star in the laboratory? 8) (Slide 17) Break into small groups (3 students optimal) and introduce the magnetic accelerator activity by showing the video (on unit flash drive or at https://www.youtube.com/watch?v=UaQ8pcGMMsQ0. Use the video to facilitate class discussion on what is happening in the device. What are the sources of stored energy and how do they transfer to kinetic energy?

	9) Pass out Activity 4-6 Task Cards and materials for the Engineering Challenge. Once students have designed, tested, and refined their accelerator they will have an opportunity to see how their design compares to other teams by having a challenge to see which device transfers the most energy to a plastic cup. Guidelines are in the handout. 10) Emphasize to students that the magnets in their kits are very strong and very fragile. Students must get their design and procedure approved by the teacher before testing, and they must wear safety glasses while testing their device. *(TEACHER TIP: Before testing their device, groups must draw a diagram and write a procedure for 'firing'. If it appears that they are proceeding with safety in mind, give them an "Authorization to Proceed' card and let them begin testing.* Have students brainstorm what parameters they could vary as they design their own magnetic acceleration device.)
Summarize	
Communicate	**Activity 4-7. Go Fund Me! (Assessment)** 3) (Slide 17-20) Finish the PowerPoint which introduces the Sanford Underground Research Facility, the CASPAR facility and the experiments the CASPAR collaboration are pursuing to better understand nucleosynthesis in the s-process. 4) (Slide 21) Pass out the Lesson 4 Assessment Card. The CASPAR collaboration plans to measure the reaction $^{22}Ne + ^{4}He \rightarrow n + ^{25}Mg$. The assessment describes the stellar environment in which this reaction is thought to occur. Students will justify (in their notebook or to submit as an exit card) why this reaction is an important experiment using the CASPAR facility and should be funded. *(TEACHER TIP: The assessment could be done as a homework assignment. At the end of Lesson 4, remind students that they will be revisiting some of the topics of this lesson in Lesson 5. They should have the following products with them: i) their research on the life cycle of the second star (Activity 4-2), ii) the s-process pathway (Activity 4-4) and iii) their periodic table.)*
Terminology and concepts to Solidify	<u>Asymptotic giant branch star</u> – The **Asymptotic Giant Branch (AGB)** is a cool, luminous period of stellar evolution undertaken by all low- to intermediate-mass stars (0.6–10 solar masses) late in their lives. <u>Black hole</u> – A **Black Hole** is a region of space having a gravitational field so intense that no matter or radiation can escape. <u>Hertzsprung-Russell Diagram</u> – The **Hertzsprung-Russell (H-R) diagram** is a a two-dimensional graph, devised independently by Ejnar Hertzsprung (1873–1967) and Henry Norris Russell (1877–1957), in which the absolute magnitudes of stars are plotted against their spectral types. Stars are found to occupy only certain regions of such a diagram. <u>Main sequence star</u> –Stars that in the hydrogen fusion stage are found in a certain region of the H-R Diagram and are referred to as **Main Sequence stars**. <u>Nebula</u> – A **nebula** is an interstellar cloud of dust, hydrogen, helium and other ionized

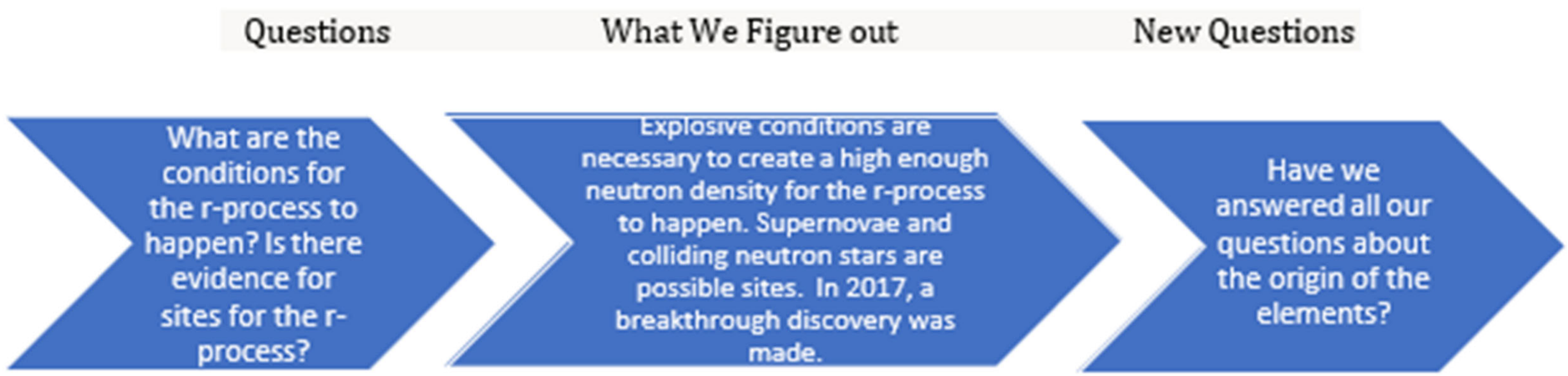
	gases; nebulae can come from a variety of sources – red giants, supernovae, etc. <u>Neutron-rich</u> – Isotopes of an element with more neutrons than the stable isotopes of that element are **neutron-rich**. Neutron-rich nuclei decay by beta-minus decay. <u>Neutron star</u> - a **neutron star** is a celestial object consisting of an extremely dense mass of neutrons, formed at the core of a supernova, where electrons and nuclei are compressed together so intensely by the force of gravity that protons and electrons merge together into neutrons. <u>Particle accelerator</u> – A **particle accelerator** is a device that uses electromagnetic fields to propel charged particles to high speeds and to contain them in well-defined beams. <u>Planetary nebula</u> – A **planetary nebula** is an expanding glowing shell of ionized gas ejected from old red giant stars late in their lives. <u>p-process nucleosynthesis</u> – **p-process nucleosynthesis** (slow proton-capture) occur in regions of the cosmos with free protons at low densities. Proton capture reactions are not very efficient because of the Coulomb barrier (electromagnetic repulsion). Initially the p-process was thought to happen during core-collapse supernovae but that has been disproven in models and alternative sites are not understood. <u>Proton-rich</u> – Isotopes of an element with fewer neutrons than the stable isotopes of that element are **proton-rich**. Proton-rich nuclei decay by beta-plus decay. <u>Red giant</u> **– Red giant stars** have exhausted the supply of hydrogen in their cores and switched to thermonuclear fusion of hydrogen in a shell surrounding the core. They have radii tens to hundreds of times larger than that of the Sun. However, their outer envelope is lower in temperature, giving them a reddish-orange hue. <u>s-process nucleosynthesis</u> – **s-process nucleosynthesis** (slow neutron capture) occurs in regions the cosmos with free neutrons being created at low densities, in which nuclei can capture a neutron approximately once every 10 years. Typical sites are during stellar fusion at the end of the He-burning or C-burning stage. <u>Stellar nucleosynthesis</u> – **Stellar nucleosynthesis** is the process by which elements are made within stars through various nuclear fusion reactions in the core and overlying mantle of stars.
Connection to Big Ideas (Phenomena)	Stellar nucleosynthesis can occur during several stages of a star's life, depending on the star's mass. Fusion in heavier stars than the sun leads to elements up to iron. Other elements near stability can be made in s-process nucleosynthesis. These processes cannot account for all the stable elements/isotopes in our solar system.
Follow Up/Practice	See assessment.
Optional Extension	The life cycle of stars is rich in content which can be explored further by interested students.
Assessment	See Lesson 4 Assessment card; rubric is on the reverse.

ACTIVITY 5-1. The Origin of Precious Metals (LAUNCH)



ACTIVITY – Students will begin synthesizing all they have learned by revisiting the precious metals from Lesson 1, and comparing neutron capture models that could lead to their formation.

ACTIVITY 5-2. Refining r-process models and sites (EXPLORE)



ACTIVITY – Students will examine details in data and models that depend on nuclear processes important to the r-process and compare two possible sites for the r-process, supernovae, and colliding neutron stars, arguing from evidence which is most likely. Then they will examine a new observation (2017) which has led scientists to conclude that most of the gold in the universe could come from colliding neutron stars.

ACTIVITY 5-3. 'We are Made of Starstuff' (SUMMARIZE)

Have we answered all our questions about the origin of the elements?

ACTIVITY – After revisiting the list of questions the class developed in Lesson 1, students will reflect on the famous quote on which this unit is based, 'We are Made of Starstuff', as a final assessment. (Unit assessment)

Lesson 5	A Breakthrough Discovery
Overview Standard(s) & Objectives	*This lesson is designed for one 50-minute class periods or one-half of a block period. The structure and flow of the lesson is given at the beginning of the Background Material section. DCIs, SEPs and CCCs for each activity are color-coded.* ***Building towards:*** **Performance Expectations:** HS-PS1-8. Develop models to illustrate the change in the composition of the nucleus of the atom and the energy released during the processes of fission, fusion and radioactive decay. HS-PS3-5. Develop and use a model of two objects interacting through electric or magnetic fields to illustrate the forces between objects and the changes in energy of the objects due to the interaction. HS-ESS1-3. Communicate scientific ideas about the way stars, over their life cycle, produce elements. **Disciplinary Core Ideas:** • PS1.C Nuclear Processes • ESS1.A The Universe and Its Stars **SEPs:** • Developing and using models • Using mathematical representations • Obtaining, evaluating, and communicating information **CCCs:** • Energy and Matter • Scale, proportion, and quantity • Patterns **Lesson Phenomenon:** Unit Phenomenon (graph of the abundance of the elements) **Lesson Objectives:** I. Students will begin synthesizing all they have learned by revisiting the precious metals from Lesson 1, comparing neutron capture models that could lead to their formation. II. Students will examine details in data and models that depend on nuclear processes important to the r-process, comparing two possible sites for the r-process, supernovae, and colliding neutron stars, arguing form evidence which is most likely. They will then examine a new observation (2017) which has led scientists to conclude that most of the gold in the universe could come from colliding neutron stars. III. After revisiting the list of questions, the class developed in Lesson 1, students will reflect on the famous quote on which this unit is based, ‘We are Made of Starstuff’. This is the final assessment for the unit.

Background Information	**Structure of Lesson:** 3. (LAUNCH) In Activity 5-1, *The Origin of Precious Metals*, students recap what they learned about the s-process and draw conclusions as to how well s-process models can explain the abundances of the precious metals studied in Lesson 1. They then explore a similar model, the r-process, in which higher neutron fluxes result in more neutrons capture and a different path to the heavier elements. *4.* (EXPLORE) In Activity 5-2, *Refining r-process models and sites,* students explore stellar evolution models to determine the fate of the sun and one other star of their choosing. They then research and evaluate the dynamics of the evolution of their two stars from the main sequence to the red giant phase, including possible nuclear fusion and other reactions that can lead to nuclei more massive than helium, and communicate that information to their classmates in the form of a poster.
Materials	*Launch (5-1) & Explore (5-2)* *For each pair of students:* • Precious Metal Cards • Abundance Curve (laminated) • 11x17 Chart of Nuclides • Colored Pencils • Research on Star from Activity 4-2 *Summarize (5-3):* *For each student:* • Periodic Table • Colored Pencils • Lesson 5 Assessment Card
Prior Knowledge	This lesson brings together all the concepts students have been working on throughout the unit.
Engagement and Communication of Student Expectations	**Activity 5-1. The Origin of the Precious Metals** 5) Pass out the precious metal cards and laminated abundance chart from Lesson 1, and have students pull out the s-process graph they made in Lesson 4. Check out the five precious metals. Are they totally s-process elements, partially s-process elements, or not at all s-process elements? Have pairs look up the isotopic ratios and calculate in their notebooks what percentage of each element could come from the s-process. 6) (Slide 2) Step through the slide and facilitate a class discussion about the five precious metals. Which isotopes are s-process? Facilitate the class to discuss what they notice about the isotopes that are 'missing'. *They are mostly either proton-rich or neutron-rich.* Could there be environments in the cosmos that could lead to those isotopes? For example, could there be environments that have many more neutrons or protons than in red giants/AGB stars? If there were, how might that change the process? *(Teacher Tip: Try to draw them to thinking about the rate of neutron capture in the s-process (once every 10 years). If the density of neutrons was greater, would that rate*

	change?)
	7) (Slide 3) A model for what could happen is called the r-process (rapid-neutron capture) Using a different color of pencil, have students draw the r-process for a model where neutron densities are high enough that a neutron could be captured every 100 microseconds. Before starting, each pair should discuss a plan for dealing with isotopes with beta decay rates near to 100 microseconds. How will they handle branching?
	8) When most students are finished, call time. Whatever explosive event that caused all the extra neutrons is over. Now the radioactive isotopes that were made will beta-decay to stability. With a third color of pencil, draw the beta-decay paths. Does the r-process account for some or all the isotopes missing from the s-process?
Exploration (20 minutes)	
Exploration	**Activity 5-2. R-process Sites: Explosive Nucleosynthesis** *19)* In a class discussion, have students examine the details of the abundance chart for elements heavier than iron. What features do they notice that would need to be explained by nucleosynthesis models for the heavier elements? *(Teacher Tip: You might suggest that students put a blank piece of paper over their laminated abundance graph and trace the average trend of the abundances above iron, ignoring the sawtooth patterns. They should notice two bumps, one around Z = 50 and one around Z=82.)* 20) (Slide 4) Nuclear shell structure is an important input for nucleosynthesis models. Early calculations showed that peaks in both the r-process and s-process occur around the closed shells at Z, N = 50, 82 and 126. In a class discussion, have students reason as to why the r-process peak is lower than the s-process peak in the calculations. (Note that the x-axis on the PowerPoint slide is Atomic Weight, not atomic number.). *Because the r-process peak is more neutron rich* *21)* (Slide 5) Current r-process models also show the effect of nuclear shell structure. More elements accumulate around the closed neutron shells because those nuclei are more stable. Play the r-process movie (on PowerPoint and unit flash drive) which is based on current models. Where could the r-process happen? That question puzzled scientists for decades. Scientists knew that it would take a very explosive environment to create a density of free neutrons large enough to make elements as massive as gold. 22) Scientists realized that any site for the r-process must be explosive, otherwise the neutron density would not be high enough. This is referred to as explosive nucleosynthesis. Working in the same pairs from Activity 4-2, have each pair pull out their research notes and H-R diagram for their second star (not the sun). Examining that star's life cycle, did the star ever go through a very explosive stage during its life? What stages might be explosive? After a short discussion, have groups share out in a class discussion. Did all groups find an explosive stage in their star's life cycle? Can they identify what is the property of a star that will determine whether it goes through an explosive stage? *A star must be more*

massive than the sun to go through an explosive supernova phase. After the supernova, the star ends up as a neutron star or black hole.

23) (Slide 6) For decades, supernovae were the leading candidate among scientists for the primary site of the r-process. Much effort has gone into modeling supernovae explosions. To better refine the models, astronomers observe the remnants of the supernova. Play the video on the PowerPoint as an example.
24) (Slide 7) What if we could observe a more recent supernova as it exploded? In 1987, a supernova explosion took place in one of our neighboring galaxies, the Large Magellenic Cloud. Scientists have been studying the nature and dynamics of the remnants for 30 years.
25) (Slide 8) SN1987a was notable because for the first time, underground detectors were in operation that saw an anomalous signal of low-energy neutrinos. After they compared notes and talked to astronomers, they realized that they were detecting neutrinos from the event, arriving at earth ahead of light. Now most neutrino experiments watch for these anomalies and are part of a worldwide network.

(TEACHER TIP: The next activity (#8) is optional if you have the time; this debate was the culminating event in the last revision of the unit. Copies of the articles, which are 10-15 years old, are included in the kit. The PowerPoint will examine prevailing theories as of 2018.)

26) Break the class into two groups and pass out copies of the two articles (in kit). Each group should spend a few minutes reading the article and writing down some points that favor that claim for the origin of gold. Then have a class debate.
27) (Slide 9&10) As astronomers collected more data and refined their models, it became more difficult to explain the abundances of the Z, N = 82 and 126 peaks through a supernova explosion. Scientists began to look for other sites for the r-process. To make the heaviest elements, models showed an environment with 75% neutrons was needed. But neutrinos interacted with neutrons during the supernova explosion, reducing their numbers to <55%. As early as 1999, scientists were looking at other possible sources of neutrons for the r-process.
28) (Slide 11&12). Many supernovae end life as a neutron star, which has very high neutron densities. More massive stars that undergo a supernova stage end life as a black hole. A neutron star is the size of a city, with densities so high that a teaspoon of material weighs a billion tons.
29) (Slide 13) Was it possible that a binary star system could end as two neutron stars, which could eventually collide? The prevailing theory was still supernovae because it was believed that they were much more abundant in the cosmos than binary star systems with two neutron stars.
30) (Slide 14) In October 2017, an announcement was made by scientists that on August 17, 2017, gravitational waves were detected from two colliding neutron stars. At the same time, the event was studied with telescopes across the electromagnetic spectrum. This momentous event changed the thinking that scientists had about the origin of gold and other heavy elements. Play the video which describes the discovery (linked from PowerPoint). The second video will give the ‘chirp’ signal in the gravity wave observatories as the two neutron stars finally merged.

	31) (Slide 15) The electromagnetic observations of the event showed two components, one signal from lighter elements and a longer duration, higher wavelength signal from heavier elements. 32) (Slide 16) When all the data was compiled, the picture emerging is that there were two jets - one emitted towards the beginning of the merger with a lower density of neutrons, and the second emitted during the actual merger with a higher density. Scientists think the first jet is a shock wave and is emitted along with a neutrino wind, similar to a supernova. The second one, with a higher neutron density, they call a tidal wave. 33) (Slide 17) The lower density could correspond to the 100 ms timescales we looked at earlier. What if there were 10x more neutrons and a nucleus encountered one every 1-10 ms? Returning to the neutron capture chart, and choosing another color of pencil, have students draw the path for a high neutron density r-process event. In a class discussion, discuss how this path could lead to heavier elements when it beta-decays. *(Teacher Tip: Students will quickly run off the left edge of the chart in this scenario. Think about what will happen when things way off the edge starts beta-decaying on the diagonal)* 34) (Slide 18) Studies of electromagnetic emissions in all wavelengths over several months gave scientists information about ejecta from both jets. They were able to measure the amount of mass ejected in each jet. 35) (Slide 19&20) This one discovery changed conclusions as to the origin of the heavy elements. These two slides are before and after the event. 36) (Slide 21) In order to really know for sure how all the elements are made, more data is needed, the masses and beta-decay half-lives for very neutron- rich elements. A new facility is coming on line in the near future to measure some of these important values.
Questions for Student Exploration	• Why is the Facility for Rare Ion Beams so much bigger than the CASPAR accelerator we examined in Lesson 4? • Is there one 'right' answer to the origin of heavy elements such as gold? Could there be multiple sites in the cosmos creating gold?
Summarize (10 minutes)	
Communicate and Synthesize	**Activity 5-3. 'We are Made of Starstuff'** 4) Have students pull out their periodic table templates and fill in the r-process elements. If they wish, they can distinguish between heavy r-process elements and light r-process elements. 5) Facilitate a class discussion about the various types of nucleosyntheses introduced in this unit. Are they necessary to make the precious metals that we rely on for our daily life. Is one step any more important than another? 6) Hand out the Lesson 6 Assessment Card (1 per student). Give them the remainder of the class period to work on their essay and finish at home.

Terminology and Concepts to Solidify	Ejecta – **Ejecta** is material ejected during an explosive event such as a supernova or colliding neutron stars. Explosive nucleosynthesis – **Explosive nucleosynthesis** occurs when a star, or some portion of the star, undergoes a thermonuclear runaway that results in an explosion. Supernovae are some of the most spectacular examples of this phenomenon. More common, however, are novae; these are thermonuclear runaways on the surface of a white dwarf star in a binary star system. Gravitational Wave Observatory – a facility that looks for ripples in space-time due to cataclysmic events happening in the universe, such as colliding black holes or neutron stars. The Laser Interferometry Gravitational-Wave Observatory (LIGO) is the **gravitational wave observatory** in the U.S., with sites at Hanford, WA and Livingston, LA. The VIRGO facility is in Italy. Multimessage Astronomy (MMA) – **Multimessage Astronomy** is a new field that combines data from multiple types of detectors to obtain information about events in the universe. Examples include GW170817, first detected in gravity waves, followed by gamma rays and other electromagnetic radiation. Another recent example is the detection of a very high energy neutrino in ICECube which was followed by gamma ray detection of a blazer from the same spot in the sky. r-process nucleosynthesis – Nucleosynthesis occurring in a region of high neutron densities, in which nuclei can capture a neutron approximately once every 0.1 second. Typical sites are core-collapse supernovae, colliding neutron stars and neutron stars colliding with a black hole. Scientists distinguish between the **heavy r-process**, which makes elements with A>130 and requires >75% neutron density, and **light r-process**, which makes elements with A<130 and requires 60-75% neutron density. rp-process nucleosynthesis – Nucleosynthesis occurring in a region of high proton densities, in which nuclei can rapidly capture protons before undergoing beta-decay. The **rp-process** is thought to end at tellurium because alpha decay begins to dominate. A possible site of the rp-process is an accreting binary system where one of the stars is a neutron star.
Connection to Big Ideas (Phenomena)	Explosive nucleosynthesis, such as the r-process, is necessary to explain the existence of the heavier elements. Before 2017, the predominant site for r-process nucleosynthesis was thought to be supernova explosions. However, models were failing to fit observational data. On August 17, 2017, a ripple in space-time was observed which was followed closely by a burst of gamma rays, and later by electromagnetic radiation at all wavelengths.
Follow Up/Practice	This is the end of the unit. Students are encouraged to research questions that they still have unanswered.
Optional Extension	The readings and debate are an option to be done after the breakthrough discovery is revealed. The readings are included in the kit.

Assessment	An essay on Carl Sagan's famous quote which provides the title of this unit is the final assessment for the unit. As an alternative, the post-assessment (duplicate of pre-assessment) can be given.

NAME_______________________________

'We are Made of Starstuff'

UNIT POST-ASSESSMENT

Referring to the periodic table of the elements, answer the following questions to the best of your ability:

6. Are the abundances (amount) of all the elements the same?

    a. On earth?

    b. Throughout the solar system?

    c. Beyond the solar system?

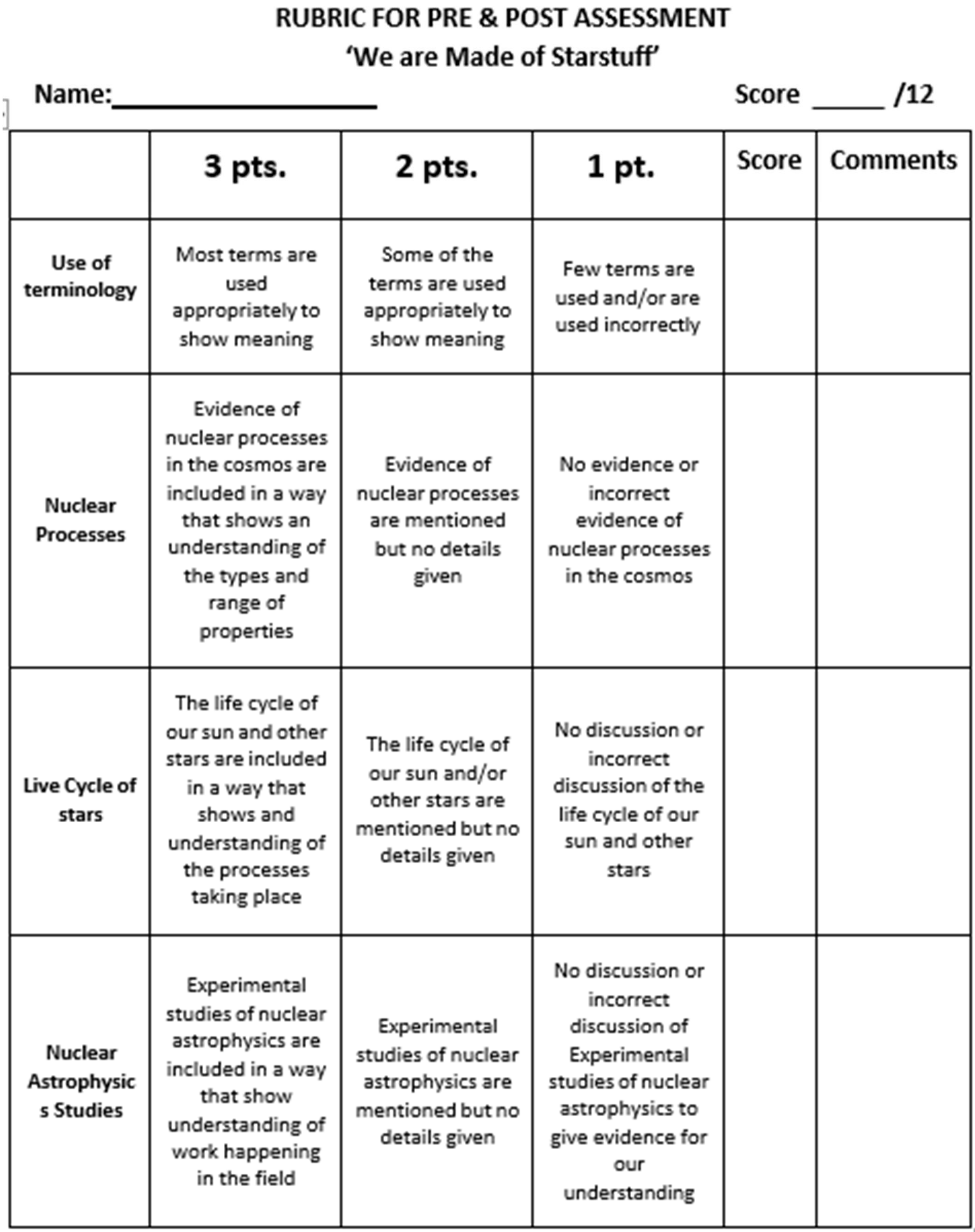
    d. Why or why not?

7. What is the most abundant element on earth?

8. What is the most abundant element in the Sun?

9. Do all elements occur naturally?

10. Why are there so many elements in the periodic table? Where did they come from?


RUBRIC FOR PRE & POST ASSESSMENT
'We are Made of Starstuff'

Name:__________________ Score _____ /12

	3 pts.	2 pts.	1 pt.	Score	Comments
Use of terminology	Most terms are used appropriately to show meaning	Some of the terms are used appropriately to show meaning	Few terms are used and/or are used incorrectly		
Nuclear Processes	Evidence of nuclear processes in the cosmos are included in a way that shows an understanding of the types and range of properties	Evidence of nuclear processes are mentioned but no details given	No evidence or incorrect evidence of nuclear processes in the cosmos		
Live Cycle of stars	The life cycle of our sun and other stars are included in a way that shows and understanding of the processes taking place	The life cycle of our sun and/or other stars are mentioned but no details given	No discussion or incorrect discussion of the life cycle of our sun and other stars		
Nuclear Astrophysics Studies	Experimental studies of nuclear astrophysics are included in a way that show understanding of work happening in the field	Experimental studies of nuclear astrophysics are mentioned but no details given	No discussion or incorrect discussion of Experimental studies of nuclear astrophysics to give evidence for our understanding		

We are Made of Starstuff B (30 Students) Refurbishment Inventory

Lesson	*Quantity*	*Item*	
All	1	Facilitator Binder w/ USB	
	1	Shipping Tote	
	1	Abundance Curves (laminated)	
	10	Rulers	
	15 sets of 5	Colored Pencils	
	30	Periodic Chart	
Lesson 1	15	Abundance Chart (laminated)	
	15 sets of 5	Precious Metal Cards	
	30	Index Cards	
	10	Optional Task Card	
	30	Lesson 1 Assessment	
	15	Big Bang Poster	
Lesson 2	1 set	Element Cards	
		21 x Protons	3 x Neutrons
		2 x d	2 x t
		1 x 3He	1 x 4He
		1 x 6Li	1 x 7Be
	1	Golf Ball	
	1 set of 2	Temperature Signs	
	15	Activity 2-5 Task Card	
	10	Lesson 2 Assessment	
Lesson 3	OPTIONAL	Cloud Chamber w/ Pump & Light	
	1	Digital Geiger Counter	
	2	Pottery Samples	
	1	Cs/Ba Generator	
	1	Eluting Solution	
	1	Beaker	
	30+	Gloves (Large, Medium)	
	100+	Snack Size Baggies	
	1 Box	Chem-Wipes	
	10	Activity 3-2 Task Card	
	10	Vernier GoDirect Radiation Monitor	
	1	ALARA Poster	
	15	Nucleosynthesis Game Box	
	8	Game Rules Chart (laminated)	
	15	Activity 3-5 Task Card	
	10	Activity 3-6 Task Card	
	10	Radiation Degrader Kit	
		Protractors	Degrader Sets (30 slides)
		Clay	Clips
	10	Radiation Sources	
	15	Card Sort	
	30	Lesson 3 Assessment	
Lesson 4	15	Activity 4-2 Task Card	

	15	Activity 4-4 Task Card
	15+	Student Handout (11x17)
	10	Activity 4-6 Task Card
	10	Cup, Tape, Tape Measure
	10	Accelerator Tracks
	10	Set of Magnets (2) and Steel Balls (12)
	10	ATP Card
	30	Lesson 4 Assessment
	15 each	Debate Articles (2 envelopes)
	30	Final Assessment Cards

We are Made of Starstuff C (24 Students) Refurbishment Inventory

Lesson	*Quantity*	*Item*	
All	1	Facilitator Binder w/ USB	
	1	Shipping Tote	
	1	Abundance Curves (laminated)	
	8	Rulers	
	12 sets of 5	Colored Pencils	
	24	Periodic Chart	
Lesson 1	12	Abundance Chart (laminated)	
	12 sets of 5	Precious Metal Cards	
	24	Index Cards	
	8	Optional Task Card	
	24	Lesson 1 Assessment	
	12	Big Bang Poster	
Lesson 2	1 set	Element Cards	
		21 x Protons	3 x Neutrons
		2 x d	2 x t
		1 x 3He	1 x 4He
		1 x 6Li	1 x 7Be
	1	Golf Ball	
	1 set of 2	Temperature Signs	
	12	Activity 2-5 Task Card	
	8	Lesson 2 Assessment	
Lesson 3	OPTIONAL	Cloud Chamber w/ Pump & Light	
	1	Digital Geiger Counter	
	2	Pottery Samples	
	1	Cs/Ba Generator	
	1	Eluting Solution	
	1	Beaker	
	30+	Gloves (Large, Medium)	
	100+	Snack Size Baggies	
	1 Box	Chem-Wipes	
	8	Activity 3-2 Task Card	
	8	Analog Geiger Counter	
	1	ALARA Poster	
	12	Nucleosynthesis Game Box	
	6	Game Rules Chart (laminated)	
	12	Activity 3-5 Task Card	
	8	Activity 3-6 Task Card	
	8	Radiation Degrader Kit	
		Protractors	Degrader Sets (30 slides)
		Clay	Clips
	8	Radiation Sources	
	12	Card Sort	
	24	Lesson 3 Assessment	

Lesson 4	12	Activity 4-2 Task Card
	12	Activity 4-4 Task Card
	12+	Student Handout (11x17)
	8	Activity 4-6 Task Card
	8	Cup, Tape, Tape Measure
	8	Accelerator Tracks
	8	Set of Magnets (2) and Steel Balls (12)
	8	ATP Card
	24	Lesson 4 Assessment
	12 each	Debate Articles (2 envelopes)
	24	Final Assessment Cards

We are Made of Starstuff D (18 Students) Refurbishment Inventory

Lesson	*Quantity*	*Item*	
All	1	Facilitator Binder w/ USB	
	1	Shipping Tote	
	1	Abundance Curves (laminated)	
	6	Rulers	
	9 sets of 5	Colored Pencils	
	18	Periodic Chart	
Lesson 1	9	Abundance Chart (laminated)	
	9 sets of 5	Precious Metal Cards	
	18	Index Cards	
	6	Optional Task Card	
	18	Lesson 1 Assessment	
	9	Big Bang Poster	
Lesson 2	1 set	Element Cards	
		21 x Protons	3 x Neutrons
		2 x d	2 x t
		1 x 3He	1 x 4He
		1 x 6Li	1 x 7Be
	1	Golf Ball	
	1 set of 2	Temperature Signs	
	9	Activity 2-5 Task Card	
	6	Lesson 2 Assessment	
Lesson 3	OPTIONAL	Cloud Chamber w/ Pump & Light	
	1	Digital Geiger Counter	
	2	Pottery Samples	
	1	Cs/Ba Generator	
	1	Eluting Solution	
	1	Beaker	
	30+	Gloves (Large, Medium)	
	100+	Snack Size Baggies	
	1 Box	Chem-Wipes	
	6	Activity 3-2 Task Card	
	6	Analog Geiger Counter	
	1	ALARA Poster	
	9	Nucleosynthesis Game Box	
	5	Game Rules Chart (laminated)	
	9	Activity 3-5 Task Card	
	6	Activity 3-6 Task Card	
	6	Radiation Degrader Kit	
		Protractors	Degrader Sets (30 slides)
		Clay	Clips
	6	Radiation Sources	
	9	Card Sort	

	18	Lesson 3 Assessment
Lesson 4	9	Activity 4-2 Task Card
	9	Activity 4-4 Task Card
	9+	Student Handout (11x17)
	6	Activity 4-6 Task Card
	6	Cup, Tape, Tape Measure
	6	Accelerator Tracks
	6	Set of Magnets (2) and Steel Balls (12)
	6	ATP Card
	18	Lesson 4 Assessment
	9 each	Debate Articles (2 envelopes)
	18	Final Assessment Cards

NOTICE: THE HEADER/FOOTER AND REVISION HISTORY OF THIS ATTACHMENT IS NOT INCLUDED IN THE PRINTED DELIVERABLE.ANY BLANK PAGES ARE LEFT SO INTENTIONALLY. THIS KIT HAS TWO DIFFERENT VERSIONS AND FOUR SEPARATE MATERIAL LISTS. ONLY WHAT IS INTENDED FOR THE KIT IS INCLUDED IN EACH PRINTED DELIVERABLE.

Revision History

Rev	Date	Section	Paragraph	Summary of Change	Authorized by
01	2/27/2024	NA	NA	Initial Release	CCR 911