ACTIVITIES TEACHER GUIDE

Learn Nuclear Science
with Marbles

A JINA/NSCL outreach service by Zach Constan

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The following activities use the marble nuclei to model:

• Fragmentation (the process by which labs like NSCL generate rare, radioactive isotopes)
• Stellar nucleosynthesis (nuclear fusion in a star that contributes to energy production while also creating heavier elements from lighter ones)
• Big Bang Nucleosynthesis (reactions that occurred among the first nucleons shortly after the beginning of the universe)
• Qualities of isotopes (reading the Chart of the Nuclides to identify differences and similarities among nuclei)

Read and do everything in each section (marked by horizontal lines) before moving on, and if you need help, ask!

Instructions and questions will be italicized like this and you can write your answers in the outside margins or on a separate sheet of paper. Also keep your Quick Reference Sheet handy.

Depending how motivated your students are, you may either give them these instructions and let them guide themselves, or you may lead them through step by step, possibly using the “marble nuclei guided activities” PPT.

Send your notes and suggestions for the following activities, or any other marble nuclei exercises to constan@nscl.msu.edu, and thanks in advance.

Introduction

Teacher’s notes will appear in this margin.

This is part of a series of documents related to the Marble Nuclei Project, downloadable from: http://www.jinaweb.org/outreach/marble/

One included file, “Marble nuclei guided lesson” PPT slides, may be useful with or in place of this document.

Each activity could be printed/copied independently of this document.

These activities were featured in AAPT’s The Physics Teacher: http://dx.doi.org/10.1119/1.3293660

It is preferred that students have covered the atom previously in class, and it helps to have completed the “Learn Nuclear Science with Marbles” Lesson.

The Marble Nuclei lessons/activities are only one of the outreach programs offered by JINA, and would serve well as an introduction before touring.

You may want to reinforce that the marbles will serve as a model, which does suffer from some inconsistencies with physical facts about the nucleus. For instance, protons aren’t necessarily yellow, and the magnetic force between marbles is modeling the strong force that holds the nucleus together.

Marbles and magnets can be purchased from various internet sources—see accompanying document “Teacher Instructions”
Isotope BINGO

This game is intended to help students understand isotopes and read the Chart of the Nuclides.

The following clues can be selected by printing them out and picking from a hat, or some other method.

“Choose an isotope that:”
- Exhibits (choose one) stable/proton decay/beta-plus decay/beta-minus decay
- Has mass number (choose one) 10/11/12/13/14
- Is the most common for its element (highest percentage)
- Has a half-life (choose one) less than a second/more than a second
- Has (choose one) more neutrons than protons/more protons than neutrons
- Is the element (choose one) beryllium/boron/carbon/nitrogen/oxygen
- Has (choose one) 4/5/6/7/8 neutrons
- Has an equal number of protons and neutrons
- Invent your own clues!

Because each “clue” has multiple matching isotopes on the game card, students have some choices and a chance to use strategy as they play.

The “BINGO card” on the opposing page is self-contained, and could be reproduced/used independently of this document.

Using chips or scraps of paper to mark the board preserves the game card for future use. By asking students to mark a number on each picked isotope to indicate which clue it satisfies (“1” for the first clue called, etc.), the job of checking a BINGO is made easier.

For a longer BINGO game, require that the students get two BINGOs to win. For a slightly shorter game, allow four corners to be a BINGO.

For this game, students play on their own (or work in teams of two if they are meant to build the nuclei, so they’ll have enough marbles).

Each team needs:
- A BINGO card (next page)
- A highlighter/chips to mark the squares
- (Optional) Two nuclei to build the isotopes, containing a total of 12 yellow marbles, 12 green marbles, and two silver magnets

To play the game, listen for the leader to call out a “clue”, a description of a particular kind of isotope. For example, the leader may say: “an isotope with four protons.”

Your team must choose ONE and ONLY one isotope on your BINGO card that matches that description (in this example, any isotope of beryllium, bottom row), and then:
- Build that isotope (if the leader has required it)
- Mark that isotope (using a chip or a scrap of paper) with a number that indicates which clue the isotope fits (write “1” for the first clue, “2” for second, etc.).
- It might be a good idea to also write down the clue and the isotope you chose to meet it in the margin on this page or on scrap paper.

Note that each clue will have multiple possible answers, so you should choose isotopes that are most likely to give you a BINGO!

To win: mark off five isotopes in a row (vertically, horizontally, or diagonally, and carbon-12 is a free space). NOTE: four corners does NOT win in Isotope BINGO. When you mark five isotopes in a row, call “BINGO!” or do something to get the leader’s attention. The leader will then check your card to make sure your marked isotopes match up with the clues called. You must be prepared to show this with your notes!

The first team to get a BINGO may win a prize, at the discretion of the leader.

Figure 1. A model of a carbon-12 nucleus made from magnetic marbles

Figure 2. Students pick an isotope to build with their marbles

Because each “clue” has multiple matching isotopes on the game card, students have some choices and a chance to use strategy as they play.
Isotope BINGO!
(board made from Chart of the Nuclides)

Proton number (Elements)

8

O 12
<0.001s
2 protons

O 13
0.009s

O 14
70.5s

O 15
0.122s

O 16
99.758%

Oxygen

N 11
<0.001s

N 12
0.011s

N 13
9.97m

N 14
99.63%

N 15
0.37%

Nitrogen

C 10
19.3s

C 11
20.3m

C 12
98.8%

C 13
1.11%

C 14
5730y

Carbon

Be 9
<0.001s

Be 10
20%

Be 11
80%

Be 12
0.020s

Be 13
0.017s

B 12
0.011s

Boron

B 9
<0.001s

<0.001s

Be 8
<0.001s

Be 9
100%

Be 10
>1 million years

Be 11
13.8s

Be 12
FREE SPACE

Beryllium

Neutron number (Isotopes)

4 5 6 7 8

N

O 12
<0.001s
2 protons

O 13
0.009s

O 14
70.5s

O 15
0.122s

O 16
99.758%

Oxygen

N 11
<0.001s

N 12
0.011s

N 13
9.97m

N 14
99.63%

N 15
0.37%

Nitrogen

C 10
19.3s

C 11
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Carbon

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0.017s

Be 14
0.017s

B 12
0.011s

Boron

B 9
<0.001s

<0.001s

Be 8
<0.001s

Be 9
100%

Be 10
>1 million years

Be 11
13.8s

Be 12
FREE SPACE

Beryllium

DO NOT WRITE ON THIS CARD

Rules: the bingo master will call out an isotope of a certain kind. Use the Chart/Game board above and instructions to the right to pick one that works and build it with your marbles (if requested). Mark it with a small piece of paper numbered in the order that clue was called (First clue = “1”, etc.) Get five in a row and yell “BINGO” to win!

LEGEND

Box color/shape indicates how the isotope decays (comes apart):
Black square = stable, won’t decay
Pink diamond = unstable, beta-plus decay
Blue circle = unstable, beta-minus decay
Yellow triangle = unstable, proton decay
Green checkerboard = unstable, alpha decay

Time period in which isotope has a 50% chance of decaying (only for unstable isotopes, boxes with colored shapes)
s = seconds   m = minutes
d = days   y = years

Abundance: percent of element found on Earth that will be this isotope (only for stable isotopes, white boxes)
Nuclear reactions are the way that many different elements are created! Stars, which are giant balls of mostly hydrogen/helium gas, can actually fuse those light elements together to form heavier ones. This is called “nucleosynthesis”. We have good evidence to show that this is where the heavy elements in your body came from. You are made of “star stuff”.

Note: this is also the way stars produce the light we see (among other things): when fusing nuclei into something bigger, some of the mass of those protons and neutrons is actually converted into energy. As Einstein pointed out, E=mc², so a small amount of mass can become a large amount of energy! Part of that energy is emitted as visible light.

How do fusion and other processes in a star make heavy elements? How do we get from hydrogen, the lightest element, to a heavier one that is a major part of your body, like oxygen? To explore nuclear fusion in a star, you’re going to play “The Nucleosynthesis Game” created by Donald J. Olbris and Judith Herzfeld* and modified for JINA.

You and your partner will play against another team of two. Each team will require:
• Two six-sided dice
• Two complete marble nuclei for game pieces (containing a total of 12 yellow marbles, 12 green marbles, and 2 silver magnets)
• The Chart of the Nuclides on your Quick Reference Sheet

The game is simple: both teams start with a hydrogen nucleus (1 proton). The first team to build a nucleus that is oxygen (8 protons) or heavier wins. You’ll build your nucleus through nuclear reactions: fusion/capture, decay, and fragmentation. If your game ends too quickly, try best two out of three. If you run into trouble, re-read the instructions before asking your teacher for help.

NOTE: this game is not intended to represent the actual process of stellar fusion, rather to familiarize you with some of the reactions involved. The rules on the next page include simplified versions of common nuclear processes (fusion, decay, etc.) and allow them to take place at all atomic numbers. This makes the game easier to play, while in reality, each step of nucleosynthesis would be dominated by one process.

http://people.brandeis.edu/~herzfeld/Nucleo.html
1. Each team builds a hydrogen nucleus (stick one yellow marble on your silver magnet). Roll to determine which team goes first.

2. On your turn, roll two dice and check the numbers in the right-hand column to see what happens to your nucleus, then follow the appropriate directions for your roll below.

3. Once you've changed your nucleus: check your Reference Chart of the Nuclides to see what isotope you made! If your isotope doesn’t exist and thus doesn’t appear on the Chart, reverse what you did (go back to your last nucleus).

4. Continue taking turns, following the process of fusion, decay, and fragmentation to build heavier and heavier nuclei (like a star does).

5. The first team to build oxygen or heavier (8 or more protons) wins!

Game Rules

To avoid confusion, make sure your players know to reverse their action if it will result in going off the Chart!

Die Roll 3-4
This has a low probability due to the Coulomb repulsion between them.

Die Roll 5-6
This reaction is more likely; how much so depends on neutron density.

Die Roll 7-8
Students often get stuck on this, so make sure to demonstrate it once before starting. This step keeps students from making wildly unlikely isotopes — thus, it is the most likely die roll.

As nuclei build into heavier and likely more unstable isotopes, their half-lives become shorter and shorter, meaning it is more likely that they will decay before the next reaction with another particle.

Die Roll 9-10

Die Roll 11
This has a very low probability due to the Coulomb repulsion between them.

Die Roll 2 or 12
Interactions between heavy nuclei are very unlikely, but still possible. Plus, this reaction (along with “your choice” above) introduces some much-needed strategy into the game.

Adjust this height if necessary, depending on your floor covering, or drop into a box.
According to the Big Bang theory, about 14 billion years ago the universe went through a huge explosion and started expanding. In this stage, the universe was made up of a hot and dense soup of energy and particles (a plasma). As the universe expanded and cooled down, neutrons and protons were formed. After about 2 minutes the universe was cool enough so that protons and neutrons could combine to form nuclei without being disintegrated, and thus the process of Big Bang Nucleosynthesis (making elements) began.

At this point there was only one neutron (12.5% of matter) for every 7 protons (87.5% of matter). A series of nuclear reactions combined these neutrons and protons into $^4$He nuclei (2 protons and 2 neutrons). Most of the helium that we see today in the universe was produced in this time. Also traces of other light isotopes were made ($^2$H, $^3$He, $^7$Li).

For this activity, you will re-create the kind of reactions that occurred shortly after the Big Bang.

1. Start with 7 loose yellow protons in your left hand and 1 loose green neutron in your right hand (same ratio of abundance as the early universe).
2. Move around the room, reacting once with each person you meet.
3. Only perform the allowed reactions listed below, using one of your particles and one of theirs, rock-paper-scissors to see who keeps the new particle (always keep loose protons in left hand, anything else you make in right hand).
4. After reacting (or if you can’t react), move on to react with another person.
5. If you have a He-4 in your right hand, you win! Stop and sit down.

Note that the reactions above are the only ones allowed because a) proton + proton immediately decays and b) it all happens too fast for beta decays to change a particle.

Count what’s left: how has the composition of the universe changed?

<table>
<thead>
<tr>
<th>isotope</th>
<th>2 minutes after BB</th>
<th>15 minutes after BB</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>12.5%</td>
<td></td>
</tr>
<tr>
<td>p</td>
<td>87.5%</td>
<td></td>
</tr>
<tr>
<td>$^2$H</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^3$He</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^4$He</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Stars produce energy through fusion - the combining of light nuclei to make heavier ones. The “ashes” of fusion “burning” are new elements! While the Big Bang produced a lot of hydrogen, helium and a bit of lithium, all the heavier elements were made by nuclear reactions. **Stars are nucleus factories.**

Our Sun is currently fusing hydrogen nuclei (protons) to make helium. You can recreate this “proton-proton chain” process using marbles.

Follow these rules to model how a star fuses nuclei to make energy!

1. **Start with 4 loose yellow protons in your left hand.** (Stars are mostly hydrogen, so this is your fuel.) You will also need one six-sided die.
2. Move around, reacting **once** with each person you meet, using one of your particles and one of theirs. **Keep anything you make in your right hand!**
3. How you react with a partner depends on what each of you have:

   **If both only have loose protons:**
   
   ![Diagram](image)
   
   Put them together on the table. Now you each roll one die.

   - **Got different numbers?** Your protons don’t stick.
     
     ![Diagram](image)
   - **Same numbers (doubles)?** You got beta-plus decay!
     
     ![Diagram](image)

   **If one of you has something else:**

   **See if you can perform one of the allowed reactions below! If not, perform the reaction on the left.**

   ![Diagram](image)

   **Roll to see who keeps the helium-3 (in your right hand), then move on to another person.**

   ![Diagram](image)

   **Roll to see who keeps the helium-4, (in your right hand), the other person gets two leftover loose protons, then move on to another person.**

   ![Diagram](image)

   **If both only have loose protons:**

   ![Diagram](image)

   **4. If you have a He-4 in your right hand, you win! Stop and sit down.**

   Which reactions happened often? Which reactions were rare (difficult)? Why were those reactions rare (there are two different reasons)? **Because** those reactions are difficult, the sun fuses hydrogen slowly and hasn’t used it all up - that’s a good thing for us.

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**Stellar Fusion: the p-p chain**

There are four p-p chains, but **p-p I** (used here) dominates at the core temperature of the sun, about 14 MK.

**How to Play**

Don’t hesitate to adjust the rules based on your group size or any other variable!

Note: keeping larger (created) nuclei separate from their starting particles is often students’ biggest challenge, remind them that loose protons stay in the left hand and any new products go in the right hand!

Because the helium-4 is tightly-bound and has slightly less total mass than the four protons this process started with, energy is released: 26.72 MeV.

You can vary the chances of a beta-plus decay by changing what rolls allow it - for a shorter game, try doubles and sevens. For a longer game, try ONLY double sixes! In reality, the chance of a beta-plus decay is almost zero, which is why the sun “burns” very slowly.

Often: He-2 breaks into two protons. Rare: All the other reactions! Beta-plus decay of He-2 is rare because they had to roll low-probability numbers, while there were few non-proton particles available for other reactions.
Often, when we want to study a particle in physics, we make it go fast using an accelerator. Usually accelerators are big and expensive. Your marbles, however, can use a gravity-based accelerator like the one in Figure 5... set up your accelerator and box as shown, but don’t attach a target nucleus in the box yet.

You’ll first test your accelerator with a proton (single yellow marble). What will be different if you drop that proton in the lowest or highest openings in the tube? Why? Try it.

For the rest of this experiment, particles dropped in the lowest opening will be called “low energy”, while those dropped in the opening on top are “high energy.” Accelerated particles are called “beam”.

You’ve just tried out your accelerator by giving the proton different energies (depending on which opening you dropped it in). Let’s see how those energies can be important by smashing the proton into a target.

Build a carbon-12 nucleus (6 yellow protons, 6 green neutrons). Hang your nucleus in the plastic fragmentation box (the silver magnet should stick to the nail hanging through the metal mesh). You may need to place your target closer to the pipe than shown in Figure 7! C-12 is now your “target” nucleus into which the proton “beam” will smash.

What will happen if you hit the “target” with a low-energy “beam” proton? Try it, and describe the result. (NOTE: if your beam misses, you might need to reposition the target.)

What will be different if you use a high-energy proton? Try it (reset your C-12 nucleus if necessary) and describe the results.

Breaking real nuclei is difficult, because they are tightly-bound (tough) and both beam and target nuclei are positively-charged, repelling each other. You can solve those problems by smashing with an accelerator!
Maybe your fast proton (also known as a hydrogen nucleus) did some damage to a C-12 nucleus, or maybe not. Let’s see what something bigger can do!

Reset your target C-12 nucleus in the box. Construct a helium-4 as in Figure 8 (two protons and two neutrons, held together with the silver magnet) to act as your beam nucleus.

How will smashing a He-4 “beam” into the C-12 be different than just a proton beam? What do you think will happen to each nucleus (both beam and target)?

Try it at low energy. What happened? Is your beam nucleus still He-4? If not, what is it now? (use your Reference Chart of Nuclides) Is your target nucleus still C-12?

What do you think will change if you give the beam high energy? Try it and describe the results. Were you right? Are the beam and target the same isotopes after the collision as they were before? If not, what are they now?

You’ve explored different beam energies and masses, but there’s another variable: how directly the collision occurs (head-on or glancing) between beam and target!

Set up your target at a short distance directly in front of the beam pipe (Figure 9 top). Drop a low-energy He-4 into a C-12 this way, then try it again at high energy. What would you say is the most likely result of this collision (try it as many times as you like to be sure)?

When real nuclei pass through a target, the chance of a head-on collision with another nucleus is low. Move your target to one side (Figure 9 bottom) so less than half of it is in the beam path. Drop a low-energy He-4 into a C-12 this way, then try it again at high energy. What would you say is the most likely result of this collision (try it as many times as you like to be sure)?

Note that because of gravity, moving your target nucleus to one side is the same as moving it farther from the beam tube. As the beam leaves the tube, its trajectory will curve downward as it falls toward the bottom of the box. If the target is far enough away, the beam will likely pass right under it or just clip the bottom.

More mass/energy

For a shorter activity, one could skip pages 9 and 10.

Nucleons will likely be knocked off one or both nuclei in the collision, though there is still the possibility of fusion

The “beam nucleus” may have “fused” together with the target!

Higher energy is likely to cause greater changes in isotopes

Impact parameter

Beam and target may well fuse.

Beam will probably fragment on the target, removing marbles from one or both nuclei.
Nuclear interactions

By now you’ve probably seen a few kinds of interactions these “marble nuclei” can have:

- **Scattering**, where the beam bounces off the target with no change to either nucleus, though the beam does change direction. Common with low-mass beams and low energies.
- **Fusion**, where the beam combines with the target. Usually occurs in head-on, low-energy collisions.
- **Fragmentation**, where the beam nucleus loses some particles in a collision with the target. Likely at high-energy and/or glancing collisions.

At accelerator laboratories like NSCL, changes in fast beam nuclei are usually what matters. The beam nuclei will go on to an experiment, while the target is stationary.

Neutron capture

Look up the “r-process”: http://en.wikipedia.org/wiki/R-process or have students do the Neutron Capture activity on pages 12 and 13.

Pick up one green marble - this will be your model of a “free neutron” travelling on its own. Nuclear astrophysicists study neutrons in exploding stars (supernovae) to see how often they are captured by a nucleus, thus making neutron-rich unstable isotopes (that can decay into heavier elements - the elements in your body may have been made this way)!

Let’s test the chances that your neutron will be absorbed by target nuclei. **Set up a helium-4 target (two yellow protons and two green neutrons on a silver magnet) right in front of the accelerator exit tube.** Make sure there’s less than an inch separating them! **Drop your neutron in the low-energy opening ten times, recording how many times it sticks to the target.** It’s a crude measurement, but what is the percentage chance for your helium-4 to capture the neutron?

Next, **set up a carbon-12 target in the fragmentation box, less than one inch away from the exit tube.** Repeat the experiment: **drop your neutron in the low-energy opening ten times, recording how many times it sticks to the carbon nucleus.** What is the percentage chance for carbon-12 to capture the neutron?

Which target is more likely to capture neutrons? In this case, it is obvious why: helium-4 leaves the silver magnet exposed so it can catch an extra neutron. Real nuclei can capture particles easily or rarely for many different reasons: size, binding energy, shell structure...

If you have time, **experiment to find the maximum number of times out of ten you can get a neutron to stick to a He-4 target.**

Hopefully greater than zero percent! Of course, there are a lot of variables.

He-4 should have caught more neutrons, since its strong silver magnet was exposed.
Now you’re going to try beam fragmentation - crashing nuclei into a target to break them into something smaller. This is how the National Superconducting Cyclotron Laboratory at Michigan State University creates rare isotopes!

In the activity below, you will fragment your beam nucleus on a target. Afterwards, collect the remains of the beam nucleus (whatever is still attached to the silver magnet core) from the floor of the box, ignoring the target. If the two nuclei have fused together, pull the bottom silver magnet off and count it (and any marbles that come with it) as the beam. Identify your new beam nucleus with a Chart of Nuclides.

Build a carbon-12 beam nucleus. Now the beam is as big as the target. How will smashing this beam into the target be different than when the beam was a smaller nucleus? Try it at low energy and describe the results. Were you right? What isotope is the beam nucleus now?

Rebuild your C-12 beam and target nuclei and try that collision again at high energy. Was the collision different? What isotope is the beam nucleus now?

Rebuild a C-12 beam and target. You are going to try fragmenting C-12 on C-12 at high energy several times and see what you produce. Do you think you will get the same result each time? Why or why not?

Resetting your beam and target each time, drop your C-12 in the high energy opening three times and find out what it has become after each fragmentation. Record the three resulting isotopes wherever your leader indicates (your whole class may be combining results). Compare your three results with each other and those of other people. Are the resulting fragmented beam nuclei all the same? Can you think of one or more reasons for that result?

Check your Reference Chart of the Nuclides. Are the beam isotopes you made all stable (black boxes)? Are they lighter (fewer protons and/or neutrons) than C-12?

Now you will do what NSCL operators do: try to make a specific isotope through fragmentation. Specifically, you will attempt to fragment carbon-12 and make carbon-11. What do you need to knock off your beam to do that? Try it, using any beam energy, target nucleus and target position you like. Were you successful? If not, why? Try again if you like - if you have the time, change what you need to and see how few tries it takes you.

This is usually the most confusing part... students want to examine and quantify the target. Make sure they understand that the beam is key!

There will likely be more damage to beam and target nuclei.

Again, more particles will likely break off of their nuclei: “fragmentation”

Creating rare isotopes

Statistically, students are likely to produce a variety of final isotopes in their beam. It might be interesting to have all teams put their results together and chart a distribution.

While beam, target and energy were the same, many other variables weren’t controlled.

The beam isotopes will usually be lighter after fragmentation, having lost some particles. To generate rare isotopes, NSCL scientists nearly always fragment a heavier stable isotope.

This is a difficult task - it may require a LOT of tries! That’s why NSCL fragments a billion nuclei per second.
Many elements are created by fusion in stars, but heavy elements can’t be! Those elements may result from neutron capture processes:

1. Free neutrons are created by nuclear reactions in a red giant star.
2. A stable nucleus in the star (Be-9 in the example at right) absorbs a neutron, making a neutron-rich and unstable Be-10.
3. The Be-10 nucleus releases energy/becomes stable by beta decay, turning a neutron into a proton and forming B-10.
4. Thus, a Beryllium nucleus has been turned into a heavier element, Boron!
5. This new stable Boron nucleus might absorb a neutron, and the whole process continues.

In a star with loose neutrons around, stable nuclei might absorb them every so often. Unstable nuclei might too, as long as they didn’t decay first. Consider the Be-10 above... its half-life is over 1 million years. If neutrons were abundant enough that a nucleus would normally capture one every ten years, would Be-10 be more likely to capture or decay first?

A Be-10 nucleus capturing a neutron would become Be-11, which has a half-life of 13.8 seconds. With the same assumptions above, would it be more likely to capture or decay first?

The number of neutrons available and the half-life of each isotope determines whether it is more likely to capture a neutron or decay!

Note the “legend” at right: on a chart of the nuclides, neutron capture moves a nucleus to the right, while beta decays go up & left or down & right. Remember this for the next part!

Let’s construct a simple model of how neutron capture occurs in a red giant star. In our model:

1. Neutrons capture every 10 yr
2. Isotopes with half-lives longer than 10 yr will capture, while isotopes with half-lives shorter than 10 yr will decay.

Using that model, you can make a prediction of the “s-process”, a set of slow neutron capture reactions that may occur in a red giant star!
Use your own “Neutron Capture Processes” Chart, but work with a partner to share ideas:
1. Assume a starting nucleus of Fe-56, and that neutron capture occurs every 10 years.
2. Decide whether Fe-56 will capture or decay first (hint: it’s stable, so the half-life is forever) & draw an arrow to the resulting nucleus.
3. Decide whether the resulting nucleus will decay or capture first & draw an arrow; repeat!
4. Continue until you make the heaviest Sr (strontium) isotope you can.

Did your s-process calculation create nuclei that were close to the line of stable (grey) isotopes, or far from it?

When the s-process ends, all unstable nuclei will decay back to stability (generally beta-minus, up and to the left). If you have time, draw arrows (in a different color) from the unstable isotopes you created to the stable isotopes they will become.

Remember, we’re trying to understand if the s-process can create the heavy elements we see in nature. Were all stable isotopes in this part of the chart created during the s-process (or after its unstable isotopes decay)?

According to your s-process simulation, red giants may be able to make many heavy elements. However, it didn’t produce all the heavy stable isotopes, so it can’t explain why they are found in nature. There may be other nuclear processes responsible!

In a supernova or neutron star merger, the density of free neutrons is likely much higher than in a red giant star. In those environments, neutron capture would proceed much faster! This is called the rapid-neutron-capture or “r-process”.

Use your own Chart, but work with a partner to share ideas:
1. Assume a starting nucleus of Fe-56, and neutron capture every 100 ms.
2. Again, for your starting nucleus and each one you make, decide whether it will capture or decay first & draw an arrow to the resulting nucleus.
3. Continue until you make the heaviest Sr (strontium) isotope you can.

When the r-process ends, all unstable nuclei will decay back to stability (generally beta-minus, up and to the left). If you have time, draw arrows (in a different color) from the unstable isotopes you created to the stable isotopes they will become.

Maybe the r-process can also create the heavy elements we see in nature. Which stable isotopes could be made by the r-process or s-process? Which could only come from the r-process? Which were only made by the s-process?

S-process simulation
If you go through the first few steps with the students, maybe using the marble nuclei guided activities slides, they should be able to recognize the pattern and carry through.

Creating new isotopes
The s-process, because of the slow capture rate, can’t make many short-lived isotopes. Thus, it stays near the valley of stability.

All stable isotopes exist in nature, but this s-process simulation only creates some of those heavier than iron. This would indicate that some other process is responsible for making the others...

R-process simulation
Again, it may be valuable to go through the first few steps with the students, which will help them recognize how the r-process can create very neutron-rich isotopes.

The r-process, because of the rapid capture rate, creates many isotopes far from the valley of stability.

The two processes overlap on many stable isotopes, but many more are just from the s-process, while a few outliers require the r-process.
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