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)
- 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.
Isotope BINGO

For this game, students work in teams of two.

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 called, “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.
## Isotope BINGO!

(board made from Chart of the Nuclides)

<table>
<thead>
<tr>
<th>Proton number (Elements)</th>
<th>Neutron number (Isotopes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>O 12 &lt;0.001s 2 protons</td>
</tr>
<tr>
<td>7</td>
<td>N 11 &lt;0.001s</td>
</tr>
<tr>
<td>6</td>
<td>C 10 19.3s</td>
</tr>
<tr>
<td>5</td>
<td>B 9 &lt;0.001s</td>
</tr>
<tr>
<td>4</td>
<td>Be 8 &lt;0.001s</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Time period in which isotope has a 50% chance of decaying (only for unstable isotopes, boxes with colored shapes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>s = seconds</td>
</tr>
<tr>
<td>m = minutes</td>
</tr>
<tr>
<td>d = days</td>
</tr>
<tr>
<td>y = years</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Box color/shape indicates how the isotope decays (comes apart):</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black square = stable, won't decay</td>
</tr>
<tr>
<td>Pink diamond = unstable, beta-plus decay</td>
</tr>
<tr>
<td>Blue circle = unstable, beta-minus decay</td>
</tr>
<tr>
<td>Yellow triangle = unstable, proton decay</td>
</tr>
<tr>
<td>Green checkerboard = unstable, alpha decay</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Abundance: percent of element found on Earth that will be this isotope (only for stable isotopes, white boxes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>s = seconds</td>
</tr>
<tr>
<td>m = minutes</td>
</tr>
<tr>
<td>d = days</td>
</tr>
<tr>
<td>y = years</td>
</tr>
</tbody>
</table>

**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 find 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!
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=mc\(^2\), 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.

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!

### Hydrogen fusion
Add one proton (yellow marble) to your nucleus.

### Absorb a neutron
Add one neutron (green marble) to your nucleus.

### Radioactive Decay
Find your nucleus on the Chart of the Nuclides and follow the instructions below based on its symbol.
- **White box**: do nothing
- **Pink diamond**: remove 1 proton, add 1 neutron (beta-plus decay)
- **Blue circle**: remove 1 neutron, add 1 proton (beta-minus decay)
- **Yellow triangle**: remove 1 proton
- **Green checkerboard**: remove 2 protons and 2 neutrons (alpha decay)

### Your choice - add either one proton or two neutrons to your nucleus.

### Helium fusion
Add two protons and two neutrons to your nucleus.

### Bombardment!
You may choose to “smash” your nucleus and your opponents’ nucleus, fragmenting one or both.

Hold your nucleus and your opponents’ nucleus, one in each hand, three feet apart and six inches off the ground (your opponents can check the height), then drop them simultaneously. Any marbles that are not directly touching the silver magnet on either nucleus are removed.
According to the Big Bang theory, about 15 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 expand-ed 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 for every 7 protons. A series of nuclear reactions combined these neutrons and protons into $^4\text{He}$ 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 ($^2\text{H}$, $^3\text{He}$, $^7\text{Li}$).

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

1. **Start with 7 protons and 1 neutron (same abundance as early universe).**
2. **Move around the room, reacting with each person you meet.**
3. **Only perform the allowed reactions listed below, using one of your particles and one of your partner’s, with one of you keeping the product (and keeping it separate from your other particles!).**
4. **Immediately move on to react with another person.**
5. **Stop if you were unable to react with the last three people you met.**

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>$\text{n}$</td>
<td>12.5%</td>
<td></td>
</tr>
<tr>
<td>$\text{p}$</td>
<td>87.5%</td>
<td></td>
</tr>
<tr>
<td>$^2\text{H}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^3\text{He}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^4\text{He}$</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 protons.** (stars are mostly hydrogen, so this is your fuel) You will also need one six-sided die.
2. **Move around the room, reacting with each person you meet, using one of your particles and one of theirs. Keep your larger nuclei separate from protons!**
3. **How you react with a partner depends on what each of you have:**

   - **If you both only have protons:**
     
     ![Diagram of proton-proton chain](image)
     
     **Now you each roll one die.**
     
     - Got different numbers? Your protons don’t stick.
       
       ![Diagram of different numbers](image)
       
       Take your proton back & move to another person.
     
     - Same numbers (doubles)? You were lucky to get beta-plus decay!
       
       ![Diagram of beta-plus decay](image)
       
       Switch one of the protons for a neutron from your extra marbles (or the box).

   - **If one of you has something else:**
     
     ![Diagram of helium-3](image)
     
     Roll to see who keeps the helium-3 *(separate from your protons)*, then move on to another person.

4. **Stop if you were unable to react with the last three people you met.**

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.
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 in Figure 5, but don’t attach a target nucleus in the box yet.

Let’s test the accelerator with a proton (a single yellow marble)
If you drop the proton into the lowest opening in the tube, predict what will happen to it and explain why. Try it. Were you right?

What will be different if you drop that proton in the opening on top? Why? Try it. Were you right?

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.” Particles accelerated either way 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 protons, 6 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 as 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.
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 (two protons and two neutrons, held together with the silver magnet) to act as your beam nucleus.

What will change when you smash a He-4 “beam” into the C-12, rather than just a proton? What do you think will happen to each nucleus (both beam and target)?

Try it at low energy. What has 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 (head-on or glancing) the collision between beam and target occurs!

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 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.
**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**

*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 - we think many were 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...
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.

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 proton or He-4 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?

Now drop your C-12 in the high energy opening and find out what it has become after fragmentation. Mark it on your Reference Chart of the Nuclides (or wherever your leader indicates - your whole class may be combining results). Try C-12 at high energy two more times, recording what isotope the beam becomes each time. Are the three resulting fragmented beam nuclei all the same? What do you think is the reason for that result?

Check your Reference Chart of the Nuclides. Are the beam isotopes you made all stable (white boxes)? Did all the isotopes in your beam change into a nucleus that is 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, you can see how many tries it takes.