ACTIVITIES TEACHER GUIDE
Learn Nuclear Science with Marbles

A JINA/NSCL outreach service by Zach Constan

Version 4.3 • January 2019

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: https://www.jinaweb.org/educational-outreach/marble-nuclei-lessons

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: http://www.jinaweb.org

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 helps students understand isotopes & read the Chart of Nuclides

Estimated time: ~10-15 minutes

The following clues can be selected by printing them out and picking from a hat, or some other method.
"Choose one 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*
- *Is on the chart (ANY isotope)*
- *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

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

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

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 neutrons."

Your team must choose ONE and ONLY one isotope on your BINGO card that matches that description (in this example, any isotope of lefthand column), 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.

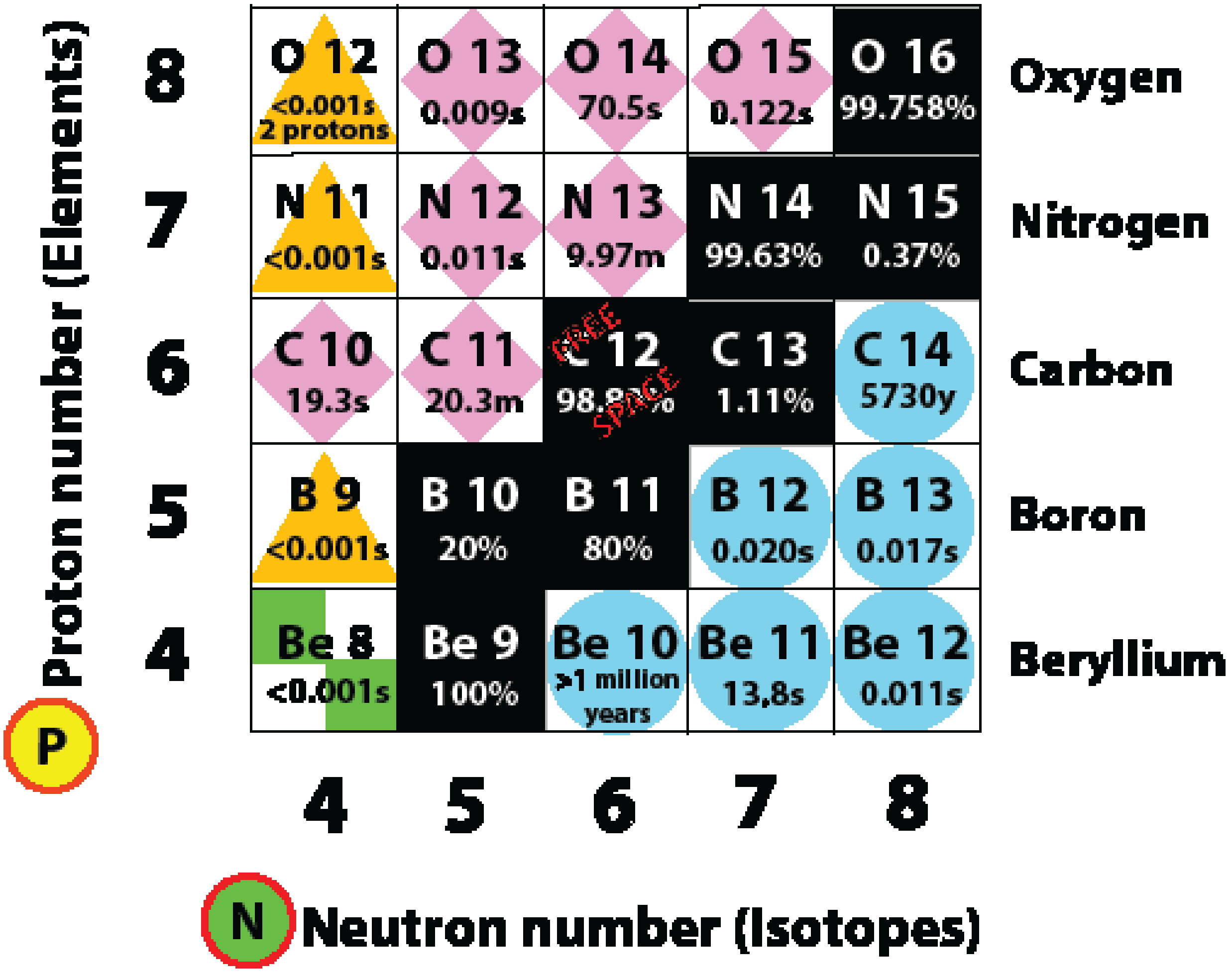
Note that each clue will have multiple possible answers, so you should choose isotopes that are most likely to give you a BINGO!

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.

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**
7	N 11 <0.001s	N 12 0.011s	N 13 9.97m	N 14 99.63%	N 15 0.37%	**Nitrogen**
6	C 10 19.3s	C 11 20.3m	FREE SPACE C 12 98.89%	C 13 1.11%	C 14 5730y	**Carbon**
5	B 9 <0.001s	B 10 20%	B 11 80%	B 12 0.020s	B 13 0.017s	**Boron**
4	Be 8 <0.001s	Be 9 100%	Be 10 >1 million years	Be 11 13,8s	Be 12 0.011s	**Beryllium**
	4	**5**	**6**	**7**	**8**	

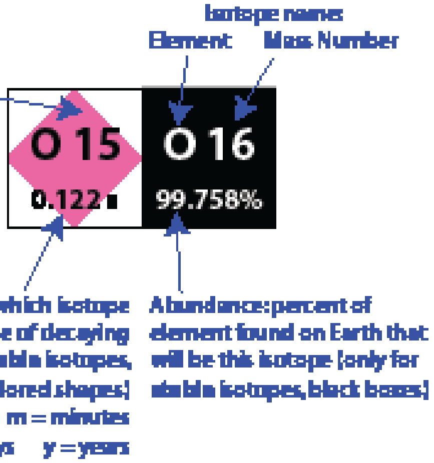
N Neutron number (Isotopes)

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, black boxes)

Nucleosynthesis Game

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

Estimated time: ~15-20 minutes

This process is very important, because it helps us understand how our sun can continue to burn and produce massive amounts of energy for many billion years. By comparison, one solar mass of coal burning to produce energy at the same rate as the sun would only last a few thousand years.

How to Play

Important caveat: for simplicity, this game deviates significantly from what really happens as a star fuses lighter elements into heavier ones. We don't want your students to become confused. For more information, look up the "p-p chain" and the "CNO cycle": http://library.thinkquest.org/17940/texts/ppcno_cycles/ppcno_cycles.html Also, check out the website at the bottom of the page for more info about the original game!

It helps to walk the students through some example rolls to demonstrate actions in the game before starting!

Feel free to adjust some rules and/or which die rolls produce which nuclear reactions to make this game work better for your students. As designed, odds are that teams will get to 8 protons by undergoing a significant number of beta-minus decays changing neutrons into protons, which is realistic.

Students may come up against situations not covered in these game rules… in that case, be creative!

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".

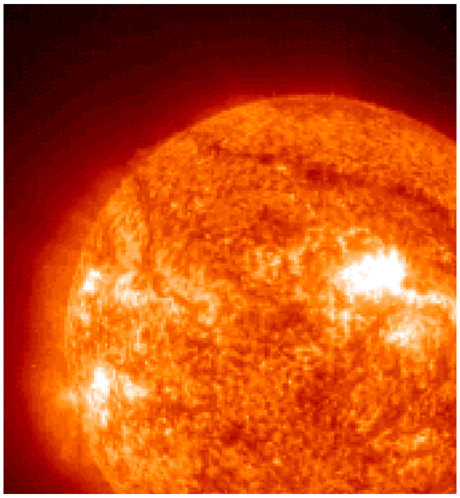


Figure 3. A place for nucleosynthesis.

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.

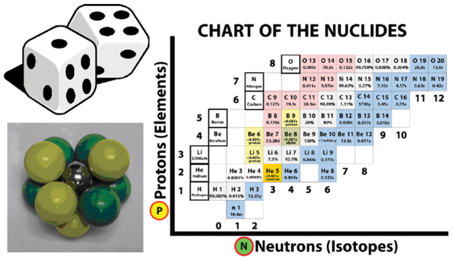


Figure 4. Items needed to play "The Nucleosynthesis Game."

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

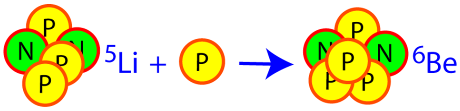
The game is simple: both teams start with a hydrogen nucleus (1 proton). The first team to build a nucleus that is oxygen (8 protons) or heavier wins. You'll build your nucleus through nuclear reactions: fusion/capture, decay, and fragmentation. If your game ends too quickly, try best two out of three. 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.

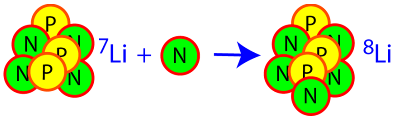
*Olbris, D.J. and Herzfeld, J., J. Chem. Ed. 1999, Vol. 76, pp 349-352.
https://pubs.acs.org/doi/abs/10.1021/ed076p349

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.

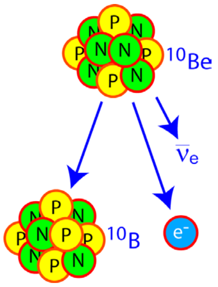


Absorb a neutron
Add one neutron (green marble) to your nucleus.



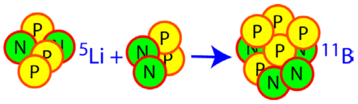
Radioactive Decay
Find your nucleus on the Chart of Nuclides and follow the instructions below based on its symbol.

- *Black 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)

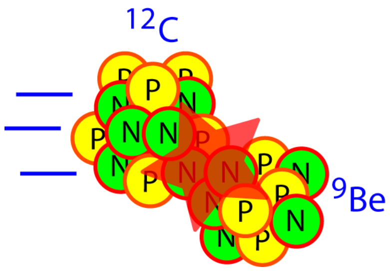


Your choice - add either one proton or two neutrons to your nucleus.

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.

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, 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.

Big Bang Nucleosynthesis

This simple game lets the students move around and work with others. They will quickly realize that the low number of neutrons makes nuclear reactions difficult!

Estimated time: ~10 minutes

(developed by Dan Coupland) 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).

How to Play

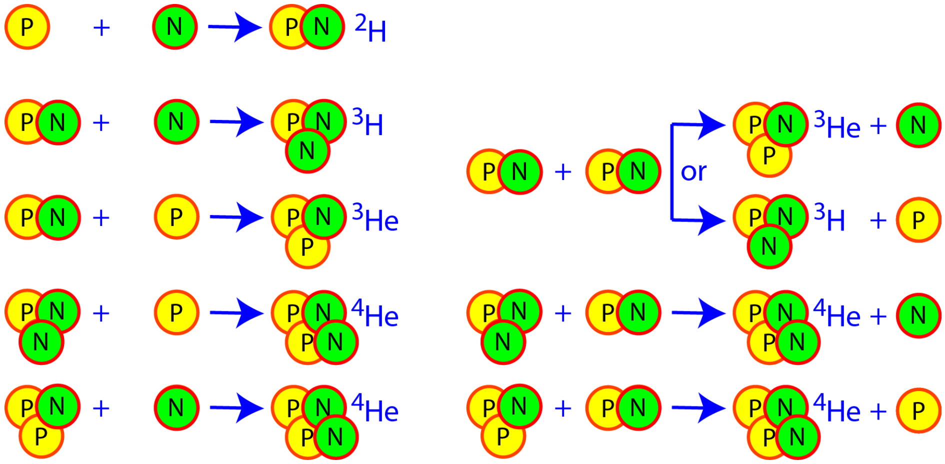
Don't hesitate to adjust the rules based on your group size or any other variable!

Note: keeping larger (created) nuclei separate from their starting particles is often students' biggest challenge, so remind them to keep loose protons in left hand separate from the larger particles they make.

To make the marbles go farther and make it eaasier to keep the loose particles separate from reaction products, you could have students work in teams of two!

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.

Initial composition is 7 free protons for every one free neutron (represented by the percentages in the second column) - final composition should have no free neutrons, but still a lot of protons!

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

isotope	2 minutes after BB	15 minutes after BB
n	12.5%	
p	87.5%	
^{2}H		
^{3}He		
^{4}He		

Stellar Fusion: the p-p chain

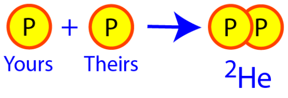
(developed in collaboration with Dan Coupland) Stars produce energy through fusion - the combining of light nuclei to make heavier ones. The "ashes" of fusion "burning" are new elements! While the Big Bang produced a lot of hydrogen, helium and a bit of lithium, all the heavier elements were made by 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!

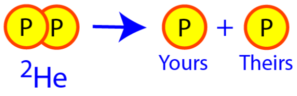
1. *Start with 4 loose yellow protons in your left hand.* (Stars are mostly hydrogen, so this is your fuel.) *You will also need one six-sided die.*
2. *Move around, reacting **once** with each person you meet, using one of your particles and one of theirs. **Keep anything you make in your right hand!***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

If both only have loose protons:



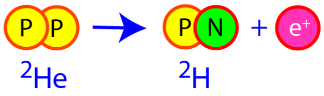
Put them together on the table. Now you each **roll one die**.

Got different numbers? Your protons don't stick.



Take your proton back & move to another person.

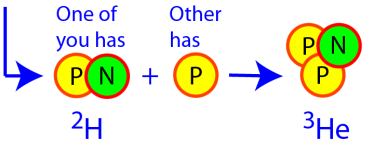
Same numbers (doubles)? You got beta-plus decay!



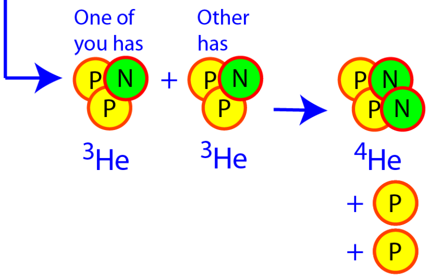
Switch one of the protons for a neutron from your extra marbles (or the box).

Roll to see who keeps the proton + neutron (^{2}H) *(in your **right hand**)*, then move to another person.

If one of you has something else: see if you can perform one of the allowed reactions below, **no rolling required**! If not, perform the reaction on the left.



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



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.

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.

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

Estimated time: ~10 minutes

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!

To make the marbles go farther and make it eaasier to keep the loose particles separate from reaction products, you could have students work in teams of two!

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.

Fragmentation Box

Acceleration

Co-developed by Jonathan Delauter

For maximum student attention, you may want to have them play with the marbles and fragmentation box for a few minutes before starting!

This works best with teams of no more than 4. Have at least one teammate take the responsibility of reading the instructions, and tell the teams to make sure that everyone gets a turn smashing marbles.

The further it drops, the faster it goes - more potential energy translates into more kinetic energy.

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".

Figure 5. Your marble accelerator.

Collision

Directions for building a simple, inexpensive, and portable fragmentation box as shown in the pictures is included in the "Fragmentation Box building instructions" document included with these Marble Nuclei Project documents.

A simpler, shorter two-page version of this activity is included in the marble nuclei downloads!

Estimated time: ~25 minutes, or ~15-20 minutes skipping pages 9 and 10

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.

Figure 6. A carbon-12 nucleus.

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.

Figure 7. The carbon-12 nucleus set up as the "target" in the plastic fragmentation box, beam tube on left.

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.*)

The beam will probably scatter off, doing no damage to 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.

The beam will probably still scatter, but it might "fuse" to the target

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!**

More mass/energy

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

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!

Figure 8. A helium-4 marble nucleus

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)?

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

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?

The "beam nucleus" may have "fused" together with the target!

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?

Higher energy is likely to cause greater changes in isotopes

Impact parameter

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!

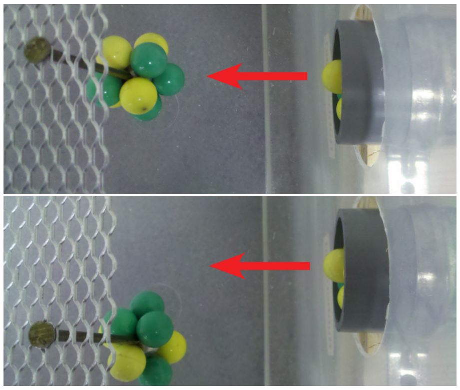


Figure 9. (top) a top-down view of the target suspended directly in the beam path, (bottom) the target offset so the beam will only make a glancing collision. Arrows indicate beam path.

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)?*

Beam and target may well fuse.

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)?*

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

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.

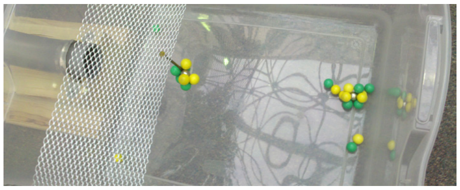


Figure 10. After a collision. The target nucleus remains suspended on the left, while the fragmented beam nucleus lies on the floor at right.

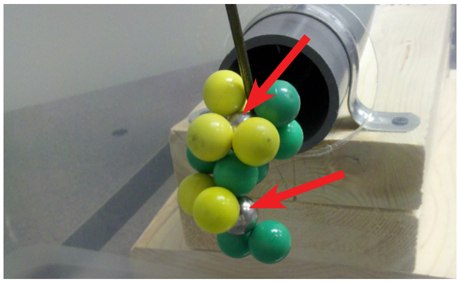


Figure 11. A He-4 beam fused with a C-12 target. Note the two silver magnets (red arrows) that serve as cores for the two "marble nuclei".

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 - the elements in your body may have been made this way)!

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.

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?*

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

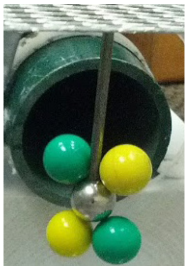


Figure 12. A helium-4 target set up very close to the beam pipe exit.

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...

He-4 should have caught more neutrons, since its strong silver magnet was exposed.

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.*

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!

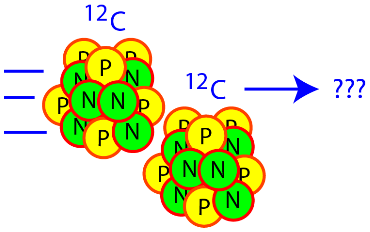
Figure 13. (top) C-12 "beam" leaving the accelerator, (bottom) beam hits target nucleus, knocking off protons and neutrons and making a new isotope.

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 all 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.*

Fragmenting the beam

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.

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