LESSON TEACHER GUIDE
Pennies are Protons

Learn nuclear science at home

A JINA/NSCL outreach service by Zach Constan

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You are made of atoms. Atoms are tiny building blocks of matter that come in many different types (elements) and make up all the objects you know: pencils, cars, the Earth, the Sun. Atoms consist of a core of protons and neutrons called the "nucleus" which is surrounded by a "cloud" of electrons. The electrons are MUCH farther away than in the picture at right!

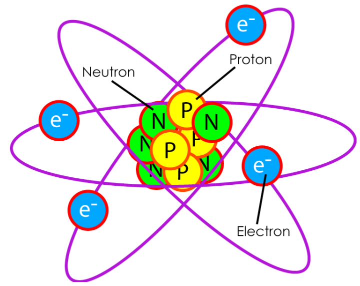


Figure 1. A schematic of the atom (Bohr model, not to scale).

The nucleus of the atom is **small**: if an atom was the size of a football field, the nucleus would be a golf ball sitting on the 50-yard line. Yet the nucleus is critical to how our universe works, and so scientists in the Joint Institute for Nuclear Astrophysics (JINA) study it every day. They need advanced research facilities such as the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University (and its upgrade, the Facility for Rare Isotope Beams, or FRIB).

You can picture what a nucleus is like by building a model. Scientists use models to envision things they can't look at easily, like how galaxies form over billions of years or how a low-pressure front will affect the weather tomorrow. We can never see the nucleus directly, so it helps to make a model and consider how it is (or is not) like a real nucleus!

For your model of a nucleus, you'll need a few small items to represent protons and neutrons, eight of each. For example:

- Coins: pennies could be protons while nickels are neutrons
- Two colors of LEGO bricks
- Two colors of beads
- Two kinds of cereal
- Two colors of M&Ms – just don't eat them until after you've mastered nuclear science

The examples in this document will all use coins. Remember: whatever items you choose to represent protons and neutrons, they really ARE made of protons and neutrons!

Figure 2. A penny-nickel nucleus

You'll also need paper or plastic plate, a periodic table and the Chart of Nuclides (both attached at the end of this document).

Introduction
The Atom

Teacher's notes will appear in this margin.

This was adapted from a series of documents related to the Marble Nuclei Project, downloadable from https://www.jinaweb.org/educational-outreach/marble-nuclei-lessons

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

The Marble Nuclei lessons/activities are only one of the outreach programs offered by JINA at https://www.jinaweb.org/education-outreach

This material is based upon work supported by the National Science foundation uner Grant No. PHY-1430152 (JINA Center for the Evolution of Elements)

You may want to reinforce that the student will be using a model which doesn't accurately represent the nucleus or its behavior.

Part 1
Naming Nuclei

Students will learn about matter on the subatomic scale
- examining the nucleus
- identify the nucleus according to its element and isotope

The Periodic Table

1 H Hydrogen																		2 He Helium
3 Li Lithium	4 Be Beryllium												5 B Boron	6 C Carbon	7 N Nitrogen	8 O Oxygen	9 F Fluorine	10 Ne Neon
11 Na Sodium	12 Mg Magnesium												13 Al Aluminum	14 Si Silicon	15 P Phosphorus	16 S Sulfur	17 Cl Chlorine	18 Ar Argon
19 K Potassium	20 Ca Calcium		21 Sc Scandium	22 Ti Titanium	23 V Vanadium	24 Cr Chromium	25 Mn Manganese	26 Fe Iron	27 Co Cobalt	28 Ni Nickel	29 Cu Copper	30 Zn Zinc	31 Ga Gallium	32 Ge Germanium	33 As Arsenic	34 Se Selenium	35 Br Bromine	36 Kr Krypton
37 Rb Rubidium	38 Sr Strontium		39 Y Yttrium	40 Zr Zirconium	41 Nb Niobium	42 Mo Molybdenum	43 Tc Technetium	44 Ru Ruthenium	45 Rh Rhodium	46 Pd Palladium	47 Ag Silver	48 Cd Cadmium	49 In Indium	50 Sn Tin	51 Sb Antimony	53 Te Tellurium	53 I Iodine	54 Xe Xenon
55 Cs Cesium	56 Ba Barium	* 57 - 70	71 Lu Lutetium	72 Hf Hafnium	73 Ta Tantalum	74 W Tungsten	75 Re Rhenium	76 Os Osmium	78 Ir Iridium	79 Pt Platinum	80 Au Gold	81 Hg Mercury	81 Tl Thallium	82 Pb Lead	83 Bi Bismuth	84 Po Polonium	85 At Astatine	86 Rn Radon
87 Fr Francium	88 Ra Radium	** 89 - 102	103 Lr Lawrencium	104 Rf Rutherfordium	105 Db Dubnium	106 Sg Seaborgium	107 Bh Bohrium	108 Hs Hassium	109 Mt Meitnerium	110 Ds Darmstadtium	111 Rg Roentgenium	112 Cn Copernicium	113 Nh Nihonium	114 Fl Flerovium	115 Mc Moscovium	116 Lv Livermorium	117 Ts Tennessine	118 Og Oganesson
*Lanthanide series		57 La Lanthanum	58 Ce Cerium	59 Pr Praseodymium	60 Nd Neodymium	61 Pm Promethium	62 Sm Samarium	63 Eu Europium	64 Gd Gadolinium	65 Tb Terbium	66 Dy Dysprosium	67 Ho Holmium	68 Er Erbium	69 Tm Thulium	70 Yb Ytterbium			
**Actinide series		89 Ac Actinium	90 Th Thorium	91 Pa Protactinium	92 U Uranium	93 Np Neptunium	94 Pu Plutonium	95 Am Americium	96 Cm Curium	97 Bk Berkelium	98 Cf Californium	99 Es Einsteinium	100 Fm Fermium	101 Md Mendelevium	102 No Nobelium			

The Periodic Table features the known elements in our universe. Each element has a unique "atomic number" - all atoms of that element have that number of protons in their nucleus. For example, the element beryllium has four protons. Having four protons is what *makes* it beryllium!

Figure 3. The Periodic Table of the Elements (above) and the Table entry for the element beryllium (Be). The atomic number appears at the top.

4
Be
Beryllium

Build a model beryllium nucleus by arranging four of your "proton" pieces together in a group.

Almost all nuclei contain neutrons as well as protons, so your model should too! Examine the nucleus at right. It has 4 protons, which makes it the element beryllium. It also has 5 neutrons, for a total of 9 particles. We call that nucleus beryllium-9.

Build a beryllium-9 nucleus by adding five "neutron" pieces!

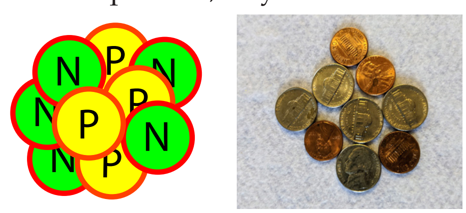


Figure 4. Schematic of a beryllium-9 nucleus (left) and a corresponding "nucleus" of coins (right)

You could imagine the beryllium nucleus having fewer neutrons; for instance, only 4, for a total of 8 particles. *Change your nucleus into beryllium-8 (4 proton pieces and 4 neutron pieces), then a beryllium-10 to see the difference.*

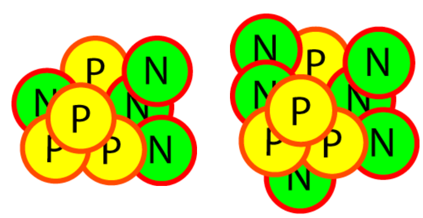


Figure 5. Comparison of beryllium-8 (left) versus beryllium-10 (right)

Compare the two varieties of beryllium you made (and in the figure); both are the same element with the same chemical properties - they could serve the same function in your body, for example.

The number of neutrons can go farther up or down, making many varieties of beryllium, also known as "isotopes". Just as the number of **protons determines what element** your nucleus is, the number of **neutrons determines which isotope of that element**.

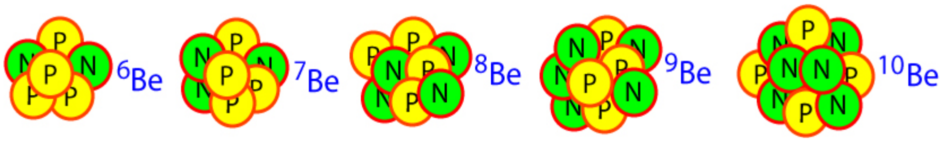


Figure 6. Several nuclei with a common number of protons (same element), but varying numbers of neutrons (different isotopes of that element).

You can name any nucleus (like the example at right) in a few steps:

1. *Count the number of protons in it.* This atomic number (also called "Z") represents the protons that determine what element this nucleus is.
2. Give it an element name or a "symbol" (short version on the Periodic Table). A nucleus with this many protons is the element boron, or symbol "B". *Find it in the Periodic Table and check the atomic number.*
3. *Count the number of neutrons in it.* Neutrons determine what isotope the nucleus is. This number is often called "N".
4. The number of neutrons plus protons determines what isotope of boron it is. This total is also called "mass number" and represented by the letter "A". *Add the protons and neutrons to get the total number of particles in this nucleus*: Z + N = A
5. *Write the name of this nucleus* using the element name/symbol and isotope/mass number as "Name-A" or "Symbol-A" or "^{A}Symbol".

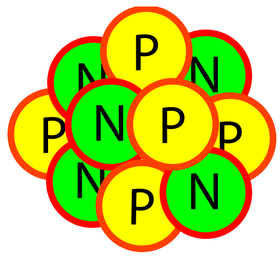


Figure 7. Name this nucleus: what element/isotope?

Checkpoint: Find out if students can specify how to name an isotope.

Answer: Proton number represents element, and adding neutrons yields the total number of particles to determine the isotope.

This is the step that is most often missed! The isotope is the SUM of protons and neutrons.

Answer: boron-10, B-10, ^{10}B

Try the opposite way: starting with the name of a nucleus, carbon-12 (also known as C-12 or ^{12}C), *build it with your proton and neutron pieces.*

Answer: 6 pennies, 6 nickels

Chart of the Nuclides

By adding or taking away neutron pieces, you can make many different isotopes of one element. You could imagine organizing all of these isotopes on a graph, according to the number of neutrons on the horizontal x-axis and the number of protons on the vertical y-axis.

Laying out isotopes this way is great for visualizing their organization. Of course, it's easy to imagine far more isotopes than actually exist!

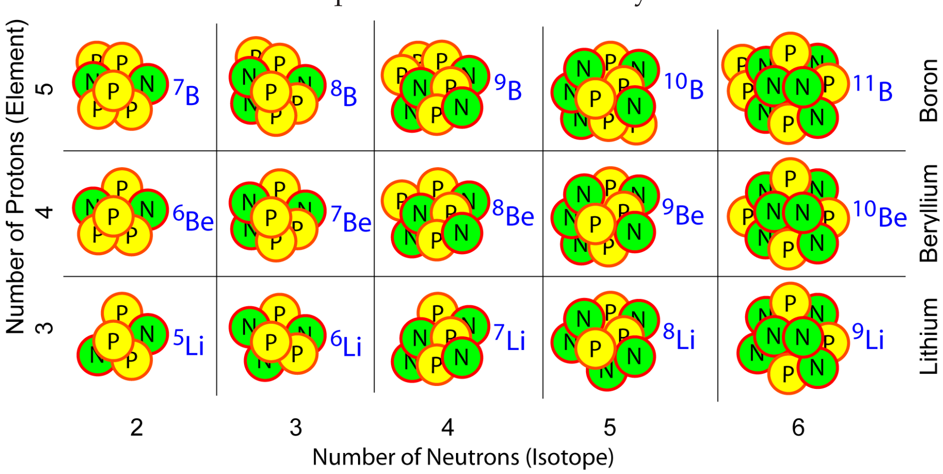


Figure 8. A chart of nuclei according to their numbers of neutrons and protons.

Students can spend time learning to read the Chart of the Nuclides with the "Isotope BINGO" activity later in this document, though they should learn more about decay and half-life in Part 2 (below) first.

Scientists who study the nucleus have done this: it's called the "chart of the nuclides". A simple Chart is attached inside this document.

A full (and current) Chart of the Nuclides can be found at http://www.nndc.bnl.gov/chart/

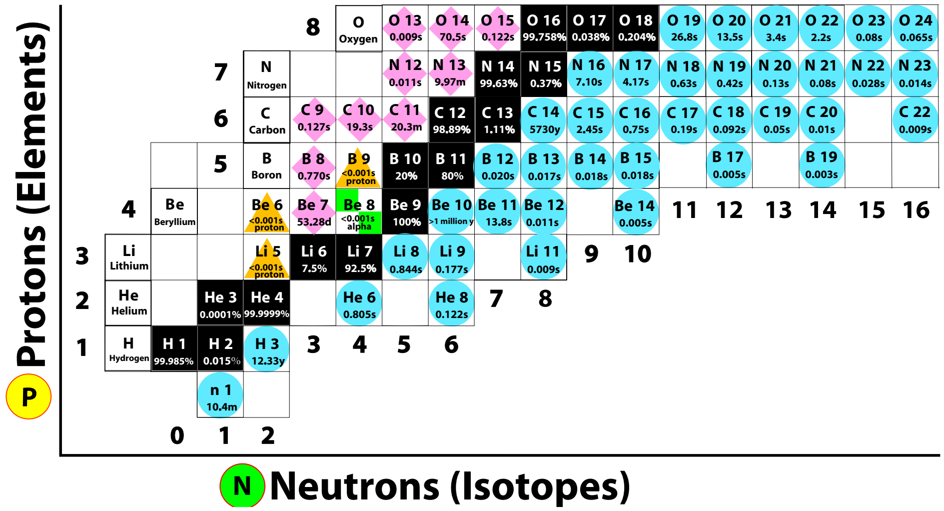


Figure 9. A portion of the Chart of the Nuclides

The Periodic Table has no information about isotopes, instead it is organized according to the elements' chemical properties governed by the number of valence (outer) electrons.

Each row on the Chart represents one element, with all the boxes being different isotopes named for the element and mass (total particles). This is actually just the first eight elements of the whole Chart (see below), which presents all known isotopes for each element and is very useful for nuclear scientists.

Answer: lithium-9

Quick quiz: *what is the name of the isotope* that has 3 protons and 6 neutrons (hint: find the box on the full-size Chart)? *Build it!*

Part 2

How to read the Chart (and what it means)

Students will learn the difference between stable and unstable isotopes, the significance of half-lives, and how nuclei change through radioactive decay

The periodic table only lists 118 elements, but the whole Chart of the Nuclides (at right) shows over 3000 known isotopes! The simplified version on your Chart only shows the tiny bottom left corner. Each box specifies the element and mass number, plus details depending on the type of isotope:

Stable isotopes (like O-16, at right) have black boxes. "Stable" means unchanging and permanent. They list an abundance: what percent of that element on Earth is this specific isotope.

Half-life actually indicates the time in which the nucleus has a 50/50 chance of decaying

Unstable isotopes (like O-15, see next page) don't last forever. They list half-life times (like lifetimes, some short and some long) and colored shapes indicates how the nucleus will change itself by releasing a particle (type of radioactive decay).

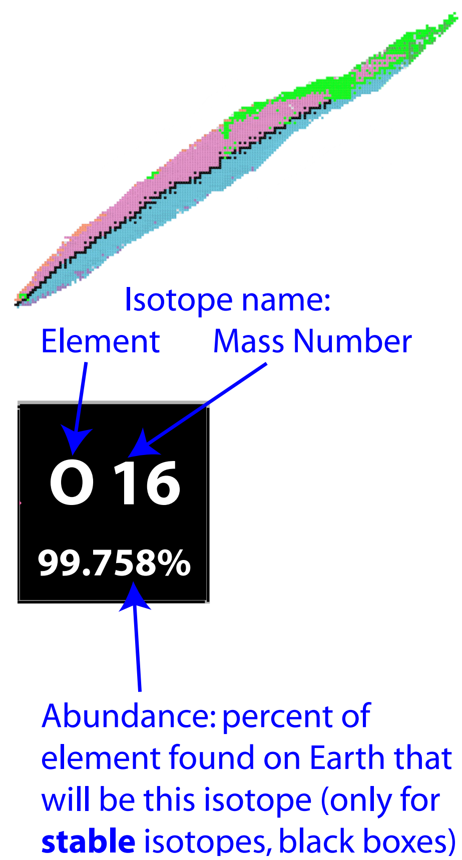


Figure 10. The full Chart and one box.

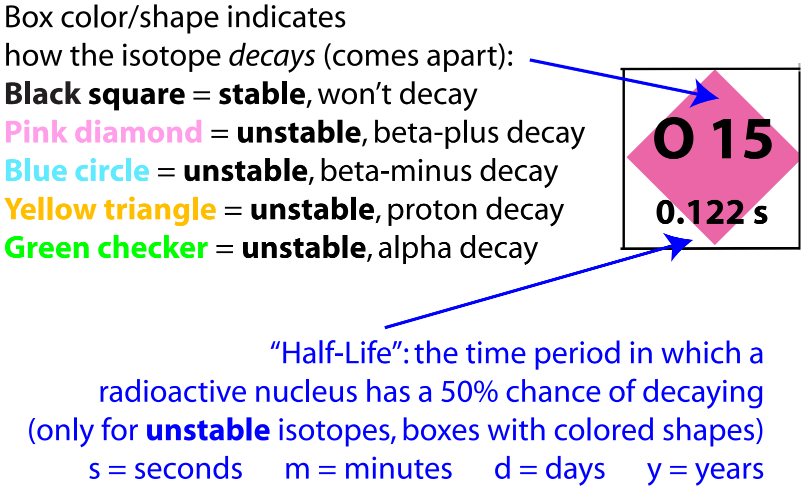


Figure 11: Legend for an unstable isotope box on the Chart.

The legends in figures 10 and 11 also appear on the Chart of Nuclides in this document, and should be all the students need to read the chart. Of course, the explanations of these facts are below.

This lesson doesn't go into detail about types of radioactive decay. The Marble Nuclei lesson (linked in the teacher notes on the first page) has a more thorough explanation.

What makes an isotope unstable?

Stable and low-energy nuclei form a line in the Chart of Nuclides called the "Valley of Stability." All other nuclei are higher-energy and radioactive; the process of decaying (releasing a particle) should lower their energy and eventually change them into a nucleus in the Valley.

You are surrounded by stable isotopes: **long-lasting, NOT radioactive, and so they are common**. The carbon-12 in your body is stable - *build one now*. You'll see that carbon-12 has a black square on the chart.

Now *take away one neutron to get carbon-11*. Its square has the pink diamond of an unstable isotope: **short-lived, radioactive, and rare**. Its half-life is about 20 minutes, so it doesn't last long before decaying.

Stable nuclei have a combination of protons and neutrons that is low energy, at least compared to nuclei around them on the Chart. Unstable nuclei are teetering at high energy.

The extra energy in unstable isotopes will eventually come out as a particle, possibly a whole proton or neutron. *Make a beryllium-8 on your plate and then shake it up and down a bit* - particles might fall off! Losing particles through radiation should lower the energy of the nucleus and make it more stable. *Did your nucleus change? What is it now?*

Figure 12: An unstable isotope with extra energy.

Making rare isotopes on Earth

On the campus of Michigan State University, there is a laboratory called the Facility for Rare Isotope Beams (FRIB) that studies rare isotopes not found on Earth. They are made on-site by accelerating stable/common nuclei to nearly half the speed of light and smashing them really hard!

Collect a carbon-12 nucleus in your hand and hold it about 12 inches over the plate. Drop it onto the plate - some of the protons or neutrons may have bounced away. What element/isotope is left on the plate?

This is how FRIB researchers create rare isotopes on demand! Otherwise, we would not have them available for study.

Figure 13: Before and after "smashing" a nucleus.

FRIB is a world-leading rare isotope research laboratory, enabling experiments that have never been done before and can't be done anywhere else on Earth!

That is one reason that MSU's nuclear science school is top-ranked in the United States.

Amazing Nuclei

Scientists at NSCL have learned much about some very rare and unusual nuclei - some are different shapes (flat as a pancake) or oblong like a football. *Make some interesting shapes with your pieces!*

Students are often interested in halo nuclei. For more resources, look up http://focus.aps.org/story/v17/st23

Researchers are very curious about the structure of lithium-11, which has two neutrons in a large "halo" around its other particles. *Build a lithium-11 nucleus with your pieces.*

This "halo" makes the lithium-11 nucleus as big as lead-208, a nucleus that contains almost 20 times as many particles! *Pull two neutrons off your nucleus and place them as far out as you think they'd have to be to make a nucleus the same size as one that contains 208 pieces.*

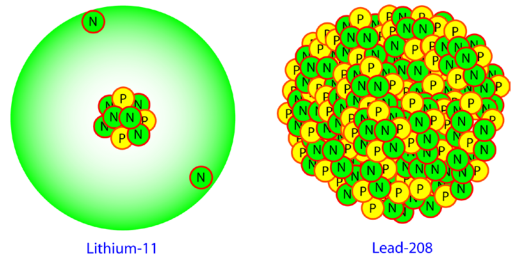


Figure 14. The "halo" nucleus lithium-11 compared to lead-208.

At least one current theory projects that there are over 8000 possible isotopes, meaning that we're only halfway through discovering them! The FRIB lab is predicted to discover over 1000 new isotopes.

Over 3000 isotopes have been discovered so far. We know a few isotopes can't exist (protons or neutrons fall off), but we're not sure how much "undiscovered territory" there is on the Chart of Nuclides. *Can you make an isotope that doesn't appear on your Chart?*

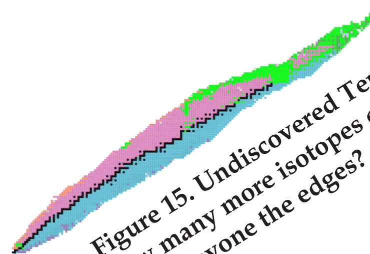


Figure 15. Undiscovered Territory - how many more isotopes can exist out here, beyond the edges?

Learning about how nuclei behave also helps us understand how stars work! The sun and other stars shine because they are "fusing" nuclei together - basically, fast nuclei run into each other and stick, making a bigger nucleus. This fusion makes new elements! *Build three helium-4 nuclei and combine them to create carbon-12.* If you've ever wondered where you came from, we know your carbon was made in a star just like that!

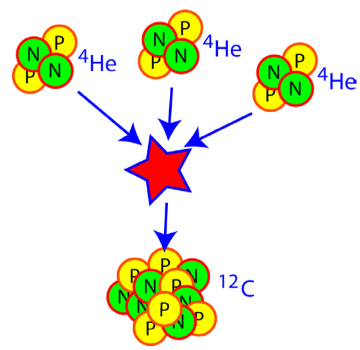
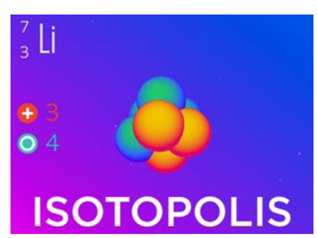


Figure 16. The carbon-12 nuclei in your body were made by a star fusing helium-4

Discover more

With your proton and neutron pieces, try the games on the next few pages to learn more about the Chart of Nuclides and how new nuclei are built in stars!



FRIB's nuclear video game, ISOTOPOLIS, is free on the App Store and Google Play: https://gamedev.msu.edu/isotopolis/

Lots of YouTube videos, a virtual lab tour, and much more about FRIB: https://nscl.msu.edu/public/education/learning.html

Periodic Table of the Elements

Atomic #
Element Symbol
Element Name

1 H Hydrogen																		2 He Helium
3 Li Lithium	4 Be Beryllium												5 B Boron	6 C Carbon	7 N Nitrogen	8 O Oxygen	9 F Fluorine	10 Ne Neon
11 Na Sodium	12 Mg Magnesium												13 Al Aluminum	14 Si Silicon	15 P Phosphorus	16 S Sulfur	17 Cl Chlorine	18 Ar Argon
19 K Potassium	20 Ca Calcium		21 Sc Scandium	22 Ti Titanium	23 V Vanadium	24 Cr Chromium	25 Mn Manganese	26 Fe Iron	27 Co Cobalt	28 Ni Nickel	29 Cu Copper	30 Zn Zinc	31 Ga Gallium	32 Ge Germanium	33 As Arsenic	34 Se Selenium	35 Br Bromine	36 Kr Krypton
37 Rb Rubidium	38 Sr Strontium		39 Y Yttrium	40 Zr Zirconium	41 Nb Niobium	42 Mo Molybdenum	43 Tc Technetium	44 Ru Ruthenium	45 Rh Rhodium	46 Pd Palladium	47 Ag Silver	48 Cd Cadmium	49 In Indium	50 Sn Tin	51 Sb Antimony	53 Te Tellurium	53 I Iodine	54 Xe Xenon
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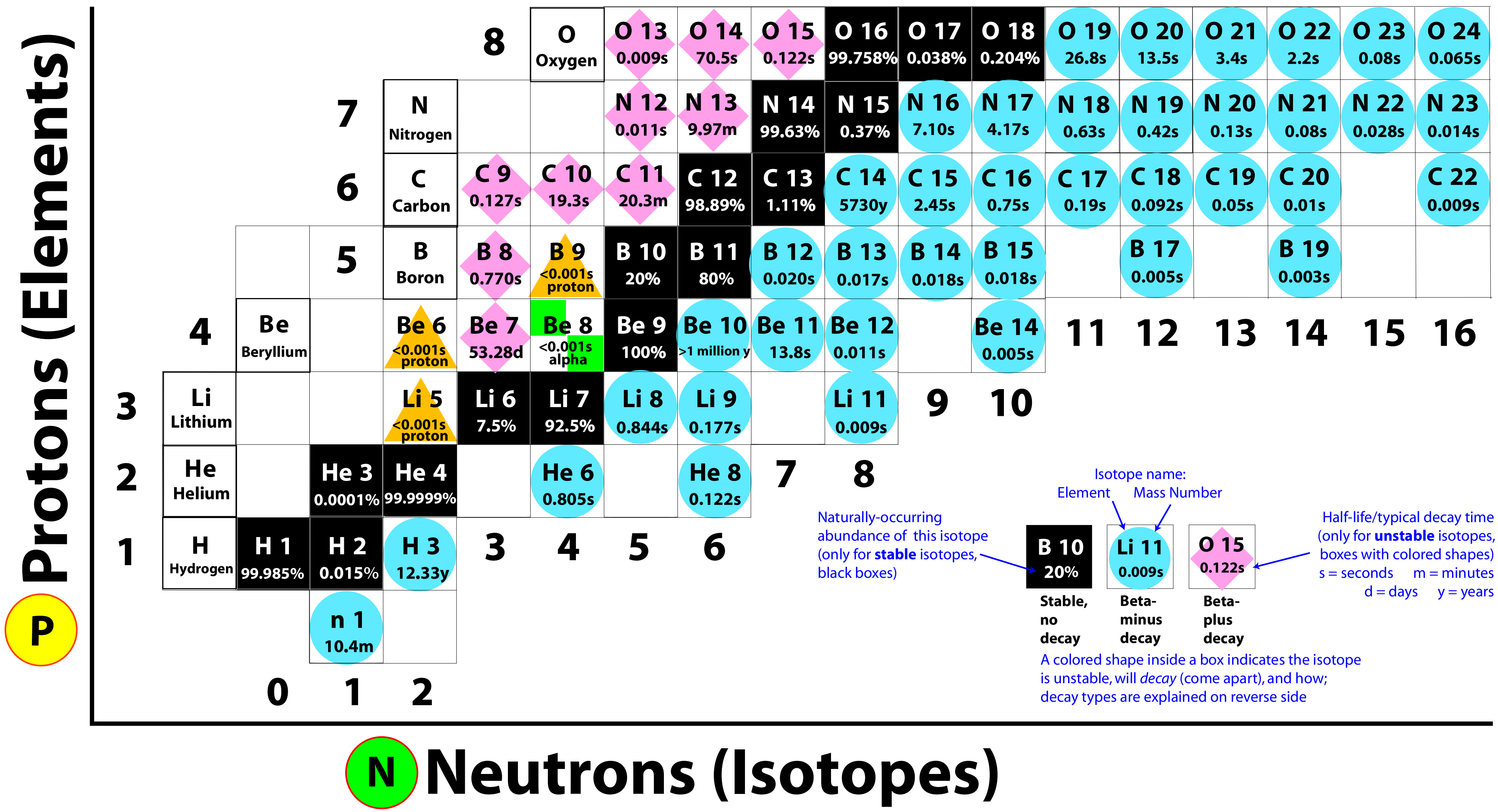
CHART of the NUCLIDES featuring the first eight elements

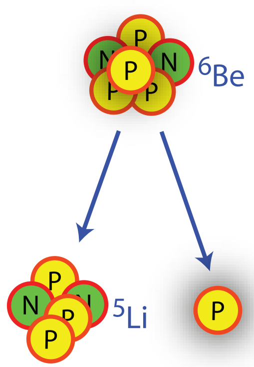


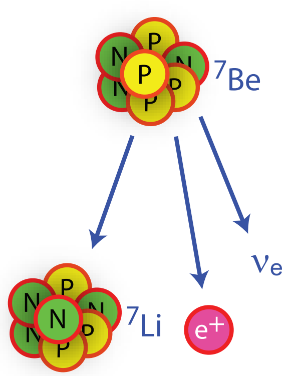
From "Learn Nuclear Science with Marbles" by JINA-CEE www.jinaweb.org/educational-outreach/marble-nuclei-lessons

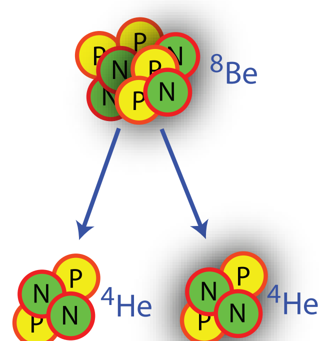
Types of radioactive decay

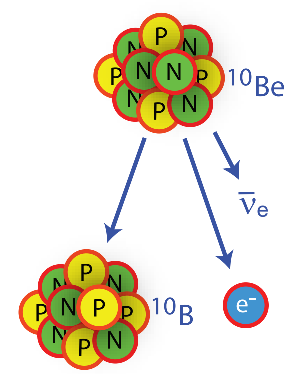
From "Learn Nuclear Science with Marbles" by JINA-CEE www.jinaweb.org/educational-outreach/marble-nuclei-lessons

Be 6 <0.001s proton	Be 7 53.28d	Be 8 <0.001s alpha	Be 9 100%	Be 10 >1 million y
Yellow triangle = **proton decay**	Pink diamond = **beta-plus decay**	Green checkerboard = **alpha decay**	Black square = **stable isotope, no decay**	Blue circle = **beta-minus decay**
Nucleus ejects one proton — P	Turns a proton into a neutron, emits a positron & a neutrino — P + N	Nucleus ejects an alpha particle (two protons & two neutrons) — P — N	% = abundance of this isotope found in nature	Turns a neutron into a proton, emits an electron & antineutrino — N + P
Isotope moves down one square on chart	Isotope moves down one square, right one square on chart	Isotope moves down 2 squares, left 2 squares on chart		Isotope moves left one square, up one square on chart









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 writing them out on slips of paper and picking from a hat, or some other method. It doesn't even have to be random!

"Choose one isotope that:"

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

The "BINGO card" on the next page can be printed separately. The use of shapes means the game can be played on black-and-white copies as well.

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 Chart of Nuclides is a great way to organize and describe the known isotopes, once you learn what all the shapes and numbers mean!

Each player needs:
- **A BINGO card (next page)**
- **Two types of small "game pieces" that serve as protons or neutrons, 8 of each. For example: pennies as protons and nickels as neutrons**
- **Some way to mark the squares (bits of paper, more coins, etc.)**

First, mark carbon-12 since it is a free space.

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**."

- *You must choose one and only one isotope on your BINGO card that matches that description* (in this example, any isotope in the lefthand column: Be-8, B-9, C-10, N-11, or O-12)
- *Use the legend on the BINGO card* to remind yourself what the symbols and numbers mean
- *Build that isotope* with your proton and neutron pieces (use the proton numbers for each row and neutron numbers for each column as guides)
- *Mark that isotope* (using a coin or a scrap of paper)

An example Be-9 "nucleus" made from 4 pennies representing protons and 5 nickels representing neutrons.

Note that each clue will have multiple possible answers, so you should choose isotopes that are most likely to give you a BINGO! Try to remember which isotope you chose for which clue (take notes if necessary) so you can show how you got BINGO at the end.

To win: mark off five isotopes in a row (vertically, horizontally, or diagonally, remembering that carbon-12 is a free space). NOTE: four corners does not win in Isotope BINGO!

When you have chosen and marked five isotopes in a row, *call "BINGO!"* 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 should be prepared to explain how your choices matched each of those clues!

Isotope BINGO!

(board made from Chart of the Nuclides)

Proton number (Elements) — P

Proton number	4	5	6	7	8	
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

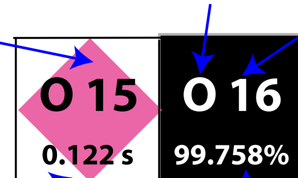
N Neutron number (Isotopes)

1. The BINGO leader will call out an isotope of a certain kind.
2. Use the Chart/game board above and legend to the right to **pick one isotope** of that kind.
3. Mark that isotope with a scrap of paper or other small object.
4. 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 checker = **unstable**, alpha decay

Isotope name: Element Mass Number



"Half-Life": the time period in which a radioactive nucleus 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

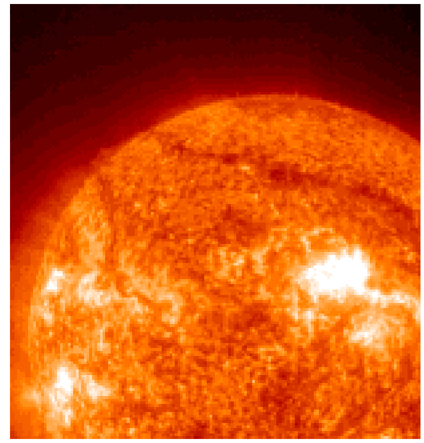
Important caveat: for simplicity, this game deviates significantly from what really happens as a star fuses lighter elements into heavier ones. We don't want your students to become confused. For more information, look up the "p-p chain" and the "CNO cycle": http://library.thinkquest.org/17940/texts/ppcno_cycles/ppcno_cycles.html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



The sun: a place for nucleosynthesis.

Note: this is also the way for stars to 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 the lightest element, hydrogen, 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.

An example Li-6 "nucleus" made from 3 pennies representing protons and 3 nickels representing neutrons.

You and your opponent(s) will need these items:

- **Two six-sided dice**
- **Two types of small "game pieces" that serve as protons or neutrons, 8 of each. For example: pennies as protons and nickels as neutrons.**
- **A paper or plastic plate**
- **The Chart of the Nuclides (attached to this file)**

The game is simple: each player starts with a hydrogen nucleus (1 proton). The first person 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 for help.

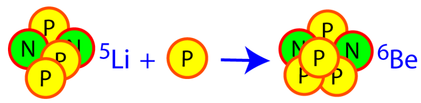
NOTE: this game is not intended to represent the actual process of stellar fusion, rather to familiarize you with some of the reactions involved. The rules on the next page include simplified versions of common nuclear processes (fusion, decay, etc.) and allow them to take place at all atomic numbers. 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

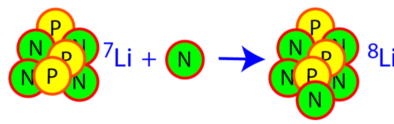
1. Each side *builds a hydrogen nucleus* (start with one proton piece). All player *roll the dice* **-** highest total goes first.
2. On your turn, *roll two dice and check the sum* in the right-hand column to see what happens to your nucleus, then *follow the appropriate directions* for your roll below.
3. Once you've changed your nucleus: *check your Chart of Nuclides* to see what isotope you made! (# of protons = element, protons + neutrons = isotope). ***If your nucleus doesn't appear on the Chart, it decays right away! Go back to your previous nucleus by undoing your last move***.
4. *Continue taking turns*, following the nuclear reactions below to build heavier and heavier nuclei (just like a star does).
5. The first side to *build oxygen or heavier* (8 or more protons) wins!

A penny "proton"

Hydrogen fusion
Add one proton piece to your nucleus.



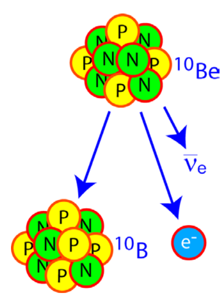
Absorb a neutron
Add one neutron piece to your nucleus.



Choose one: add a neutron piece OR do "Radioactive Decay" below.

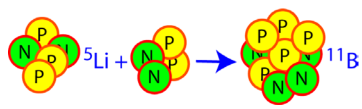
Radioactive Decay
Find your nucleus on the Chart of Nuclides and follow the instructions below based on the symbol in its box.

- *Black box*: do nothing
- *Pink diamond*: remove 1 proton piece, add 1 neutron piece (beta-plus decay)
- *Blue circle*: remove 1 neutron piece, add 1 proton piece (beta-minus decay)
- *Yellow triangle*: remove 1 proton piece
- *Green checkerboard*: remove 2 proton pieces and 2 neutron pieces (alpha decay)



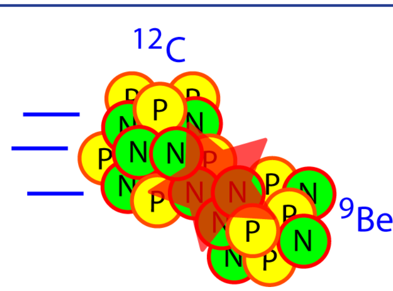
Choose one: add a proton piece OR two neutron pieces to your nucleus.

Helium fusion
Add two proton piecess and two neutron pieces to your nucleus.



Bombardment!
You ***may choose*** to "smash" your nucleus **AND** your opponents' nucleus, fragmenting one or both.

Hold your nucleus pieces about 12 inches over your plate while your opponent does the same. Drop your "nuclei" onto the plates. Any pieces that are not on the plate are removed from that nucleus.



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 electric repulsion between them.

Die Roll 5

This reaction depends on the density of free neutrons.

Die Roll 6

Die Roll 7-8

Students often get stuck on this, so you might demonstrate it once before starting. This step keeps students from making wildly unlikely isotopes - thus, it is the most likely die roll.

Also, many unstable isotopes have very short half-lives, so 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 electric 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 the type of pieces and plates.