

# LESSON TEACHER GUIDE

# Learn Nuclear Science

## with Marbles



A JINA/NSCL outreach service by Zach Constan

Version 4.3 • January 2019

**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 “nucleus” of protons and neutrons surrounded by a “cloud” of electrons.

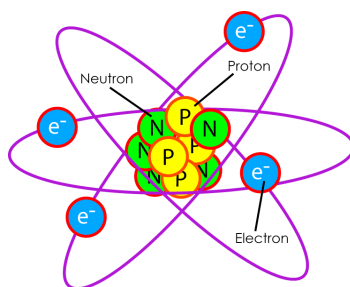


Figure 1. A schematic of the atom (Bohr model, not to scale).

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. To do so, they need advanced research facilities, such as the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University.

This project lets you picture what a nucleus is like by building a model with magnetic marbles. The marbles you’ll use to build nuclei come in many colors, to represent different particles. You should have **6 yellow and 6 green marbles** (and possibly others) that represent:



- Yellow (P)** Proton (heavy, positive charge)
- Green (N)** Neutron (heavy, no charge)
- Blue (e<sup>-</sup>)** Electron (light, negative charge)
- Pink (e<sup>+</sup>)** Positron (light, positive charge)

Figure 2. Sub-atomic particles and corresponding colored marbles for representation in the model.

**NOTE: this is a model, not a fully-accurate representation of a nucleus!**

The silver sphere in the photo is the super-strong magnet that holds your marble nuclei together. It doesn’t actually represent a particle. Be careful, this magnet is **strong** and can pinch your fingers! **Keep it away** from anything sensitive to magnetic fields (like phones and pacemakers)

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; you can write your answers in the outside margins or on a separate paper.* Also keep your Quick Reference Sheet handy.

## Introduction

### The Atom

*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 of those documents, “Marble nuclei guided lesson PPT”, may be useful with or in place of this lesson.*

*These lessons were featured in AAPT’s The Physics Teacher: <http://dx.doi.org/10.1119/1.3293660>*

*Before using this lesson, students should cover the atom in class. At the start, you might consider letting the students just play with the marbles for 2 minutes, it helps them focus later.*

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

*Marbles and magnets can be purchased from various internet sources- see accompanying document “Teacher Instructions”*

*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.*



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** you have, the number of **neutrons determines the isotope**.

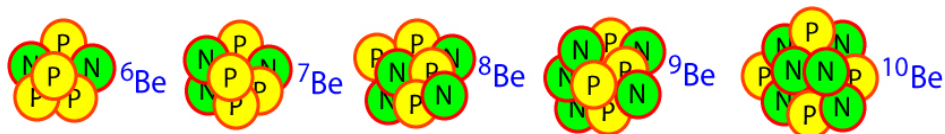


Figure 6. Several nuclei with a common number of protons (same element), but varying numbers of neutrons (different isotopes of that element).

You can name any isotope (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 the nucleus is.
2. Give it an element name or a “symbol” that’s an abbreviation of the element’s name. 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. Add the protons and neutrons to get a “mass number”, which is often called “A”.  $Z + N = A$
5. Write the isotope’s name using the element name/symbol and mass number as “Name-A”, “Symbol-A”, or “<sup>A</sup>Symbol”.

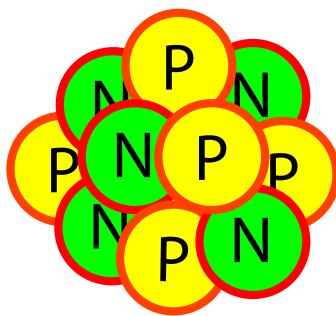


Figure 7. Name this isotope.

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

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

Answer: boron-10, B-10, <sup>10</sup>B

Try the opposite way: starting with the name of a nucleus, carbon-12 (also known as C-12 or <sup>12</sup>C), build the corresponding nucleus.

Every element has many possible isotopes, some elements more than others. You could imagine organizing all 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.

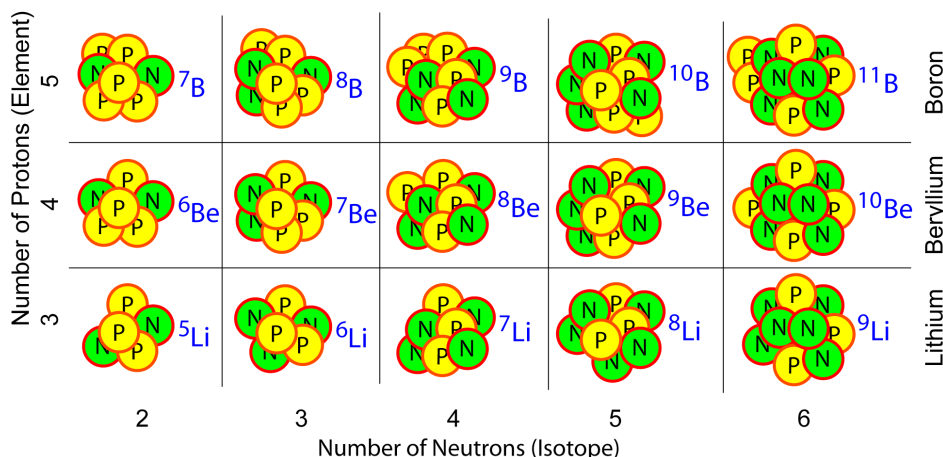


Figure 8. A chart of nuclei according to their numbers of neutrons and protons.

## Chart of the Nuclides

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

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

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

The Periodic Table omits isotope information, focussing instead on the number of valence (outer) electrons/chemical properties of the element.

Answer: lithium-9

## Part 2 How to read the Chart (and what it means)

Students will understand the various types of decay that the isotope undergoes during its lifetime: Proton decay, Beta-plus decay, Alpha decay, and Beta-minus decay.

Students will refer to the colored boxes on the chart of the nuclides, which identify the types of particular decay mode and radiation associated with that isotope.

Scientists who study the nucleus have done this: it's called the "chart of the nuclides". Your "Quick Reference Sheet" has a bigger version.

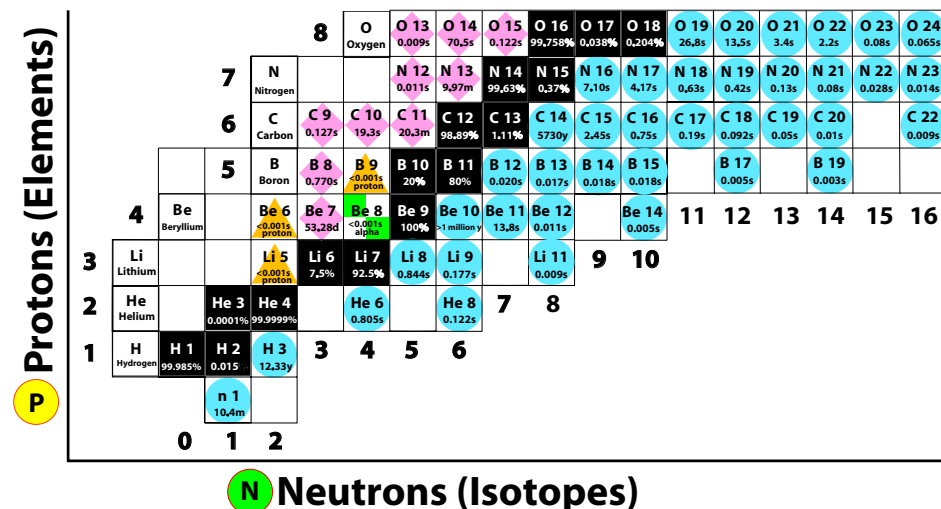


Figure 9. A portion of the Chart of the Nuclides

Each box on the Chart represents an isotope, naming its element and its mass. This is actually a very small part of the whole Chart (see below), which presents all known isotopes for each element and is very useful for nuclear scientists.

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

The whole Chart of the Nuclides (at right) contains plenty of information on over 3000 known isotopes... if you know what to look for. The simplified version on your Quick Reference Sheet only shows the tiny bottom left corner. Each box specifies the element and mass number, plus details depending on two types of isotopes:

**Stable isotopes** (e.g. O-16, at right) have black boxes. "Stable" means unchanging and permanent. They list an abundance, or the percent of that element on Earth that will be of that isotope.

**Unstable isotopes** (e.g. O-15, see next page) don't last forever. They list half-lives (with shorter time periods indicating greater instability) and colored shapes representing the type of radioactive decay that nucleus will likely undergo.

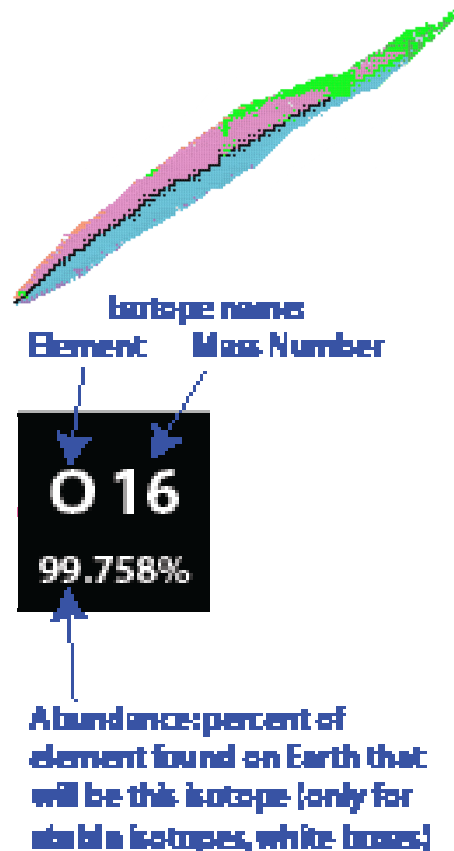


Figure 10. The full Chart and one box.

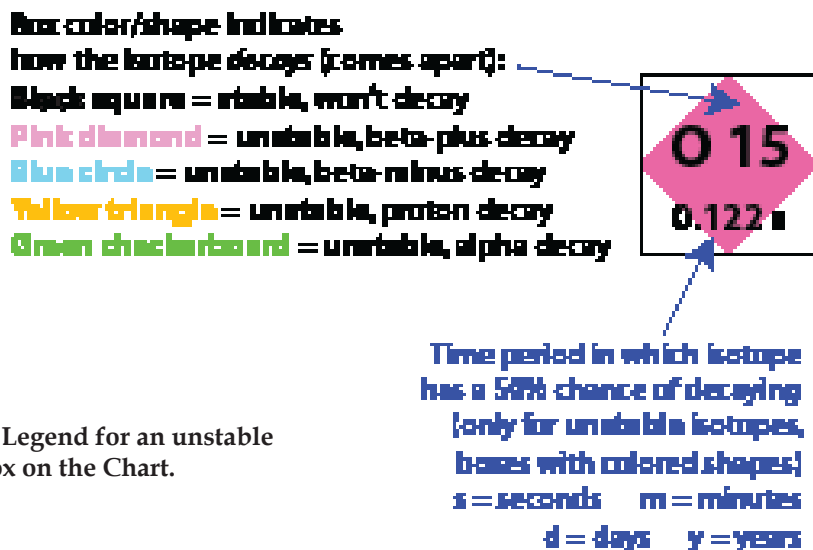


Figure 11: Legend for an unstable isotope box on the Chart.

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

Objects in our universe tend to move to the lowest possible energy state (a ball rolling down a hill is a good example), and so high-energy arrangements of protons and neutrons tend to be short-lived.

What this means is that 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 stable isotopes appear in a diagonal line on the chart, called the “valley of stability” which makes a lot of sense if you think of the stable, low-energy isotopes as a “valley” (low point), and the isotopes on either side with higher energies as “mountains.”

Unstable isotopes decay to reduce their energy, changing to a number of protons and neutrons that is more tightly bound.

- The amount of energy in a nucleus is decreased by:
- Balancing the number of protons and neutrons (paired sets of protons and neutrons have less energy than pairs of either one).
  - Decreasing the proportion of protons (like charges repel, adding energy) for very heavy nuclei, so there’s fewer protons than neutrons.
  - Having an even number of neutrons and/or protons (again, pairs are better than individuals) - VERY few stable nuclei have odd numbers of protons & neutrons!



Figure 12: Paired neutrons and protons.

The energy of a nucleus is determined by these and several other factors, all related to the “strong force” that binds the nucleus together. As its name suggests, the strong force between particles in a nucleus is the most powerful force in our universe, and yet only reaches to the closest particles (about a millionth of a billionth of a meter away). Researchers study this exotic force in the laboratory. *Build a carbon-12 nucleus. According to the rules above, should it be stable?* Radioactive decay allows a nucleus to change, moving from the high-energy “mountains” down to the low-energy “valley” of stability.

## What makes an isotope unstable?

## Why do unstable isotopes decay?

*Of course, this is a simplification of the rules for nuclear binding energy. These rules are still being studied, with several theories trying to approximate them and explain nuclear behavior.*

*The electric repulsion between protons is also called the “Coulomb barrier” between them; bringing protons together requires enough energy to overcome the barrier.*

*The strong force holds quarks together to form baryons (like protons and neutrons) and is transferred by gluons.*

*The force that holds baryons together to form a nucleus comes from “residual” strong force between quarks in adjacent baryons, which is transferred by pions (quark-antiquark pairs of up & down).*

## Beta-minus Decay

Now students will learn about a few varieties of radioactive decay, all of which will change the element and/or isotope of a nucleus.

Unstable isotopes will decay in the best way to directly reduce their energy, while obeying certain physical laws like conservation of energy.

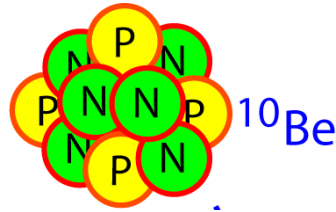


Figure 13. Beryllium-10.

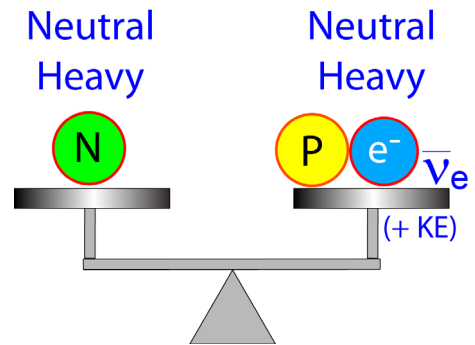
Make a Be-10. It's unstable because the number of protons and neutrons is imbalanced. How can it lower its energy?

Be-10 must lower its number of neutrons. But you can't just lose a neutron... it has to go somewhere! Conservation of charge and energy both limit how a nucleus can decay.

Neutron = heavy and neutral.  
Proton + electron = heavy and neutral.

Look at the chart of particles on page 1. What is the mass (heavy or light) and charge of a neutron? Now compare with a proton and electron together. What are their combined mass and charge?

Under the right conditions, a neutron can convert to a proton and electron (and antineutrino), since that doesn't alter charge or mass+energy. (To balance exactly, you need to count the kinetic energy of the electron and neutrino.)



Exchange one of the green neutrons in your Beryllium-10 for a yellow proton and blue electron, then let the electron "radiate" (speed away).

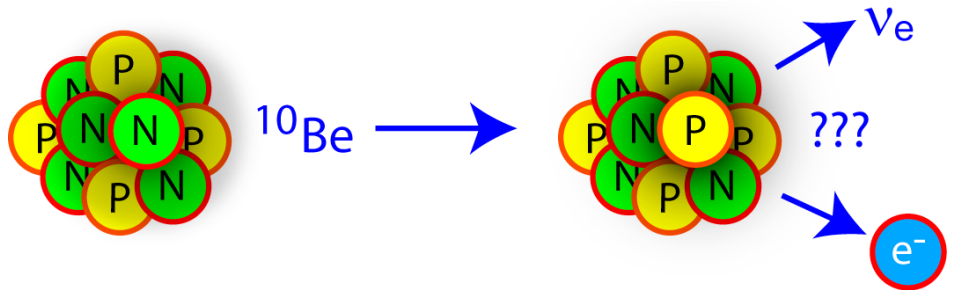


Figure 14. Equivalent charges and mass; Be-10 decay.

What has your nucleus become? Now, look at your Chart of the Nuclides. In moving from Be-10 to your final nucleus, which direction have you traveled on the Chart? Is the new nucleus a lower energy, and why? (hint: consider what is said about energy on the previous page)

This kind of radioactive decay is called "beta-minus" (the original name of the radiation before it was discovered to be an electron, which is the kind of particle emitted), and is represented on your Chart by a blue circle. Look on your Quick Reference Sheet for details.

Note where all the blue circles are on your Chart. Knowing which direction beta-minus decay moves your nucleus, towards what part of the chart will those decays always lead (hint, it was just named on the previous page)?

The neutrino is here for completeness - it is a particle lost by the nucleus in the decay, but isn't represented by a marble in this lesson. Mass+energy is conserved, and so is charge: the net charge is +4 both before and after the decay.

Beta-minus decay depends on the weak nuclear force, which is transferred by the exchange of W and Z bosons. The weak force essentially allows a quark to change flavors. In this case, the neutron with one up quark and two down quarks (udd) turns into a proton with two up quarks and one down quarks (uud); thus, a down quark changed to up. The process is relatively slow because the force is "weak", about a trillion times less powerful than the strong or electromagnetic forces, making these isotopes relatively long-lived (milliseconds or longer). This is a common form of decay among neutron-rich isotopes.

The final nucleus is a boron-10.

Direction of travel was up and to the left. This is lower energy because the number of protons and neutrons is balanced, so they can pair off. Of course, it also shows as stable on the Chart!

Beta-minus decays allow the nucleus to change and move closer to the valley of stability.

Beryllium-7 decays in a similar way; it has slightly more protons than neutrons, and would have less energy if the situation were reversed.

*Make a Be-7.* In this case, we need to swap out a proton for a neutron, plus something else to balance the charge and mass. In this case, it's a positron, or "beta-plus" particle.

Thus, as part of a nuclear decay, the proton essentially turns into a neutron and positron (plus neutrino), and the positron escapes as radiation. Again, charge and mass+energy are unchanged.

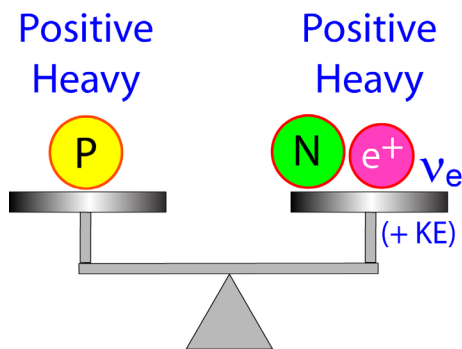


Figure 15. Equivalent charges & mass.

*Exchange one of the yellow protons in your Beryllium-7 for a green neutron and pink positron, then let the positron "radiate" (speed away). What is your new nucleus?*

Now, look at your Chart of the Nuclides. In moving from Be-7 to your final nucleus, which direction have you traveled on the Chart? Is the new nucleus a lower energy, and why?

Isotopes that undergo "beta-plus" decay are represented on your Chart by a pink diamond. Look on your Quick Reference Sheet for details.

Note where all the pink diamonds are on your Chart. Knowing which direction beta-plus decay moves your nucleus, towards what part of the chart will those decays always lead (you answered this for beta-minus decays)?

You can see that radioactive decay will always move nuclei towards more stable isotopes, since they have the lowest energies.

Green checkerboards (e.g. Be-8) represent alpha decay, while yellow triangles (e.g. Be-6) represent proton decay. These forms appear much less often than beta decays on your Chart, though alpha does occur often among extremely heavy elements.

Proton decay simply means that the nucleus ejects a proton.

Alpha decay indicates that the nucleus emits an alpha particle, also known as a helium nucleus (He-4): two protons & two neutrons.

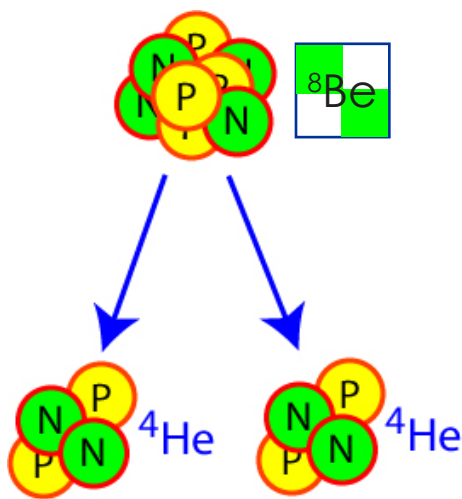


Figure 16. A schematic of alpha decay.

*Build a Be-8 and recreate this "alpha decay" with your marble nucleus. Again, charge and mass+energy is the same before and after decay (conserved).*

## Beta-plus Decay

*Beta-plus decay is also due to the weak force, and can take a relatively long time. This is a common form of decay among neutron-poor isotopes.*

**Important:** these decays occur because they lower the energy of the nucleus. Free neutrons and protons do not constantly decay back and forth!

*The final nucleus is a lithium-7.*

*Direction of travel was down and to the right. This is lower energy because there are now slightly more neutrons than protons. Of course, it also shows as stable on the Chart!*

*Again, beta-plus decays allow the nucleus to change and move closer to the valley of stability. Notice a pattern?*

## Alpha, proton decays

*Alpha decays are common among the elements near and beyond uranium.*

*These decays are very fast because they are due to the nuclear strong force, resulting in extremely short half-lives (microseconds or shorter).*

## Half-life or abundance

Oxygen-15 decays into nitrogen-15

You could have the class demonstrate this: have each student build a beryllium-10 nucleus, and all flip coins. Those who get heads decay into boron-10 (over 1.6 million years). Then repeat with those who still have boron-10, plotting the number of boron-10 and beryllium-10 isotopes over time.

Point out that the decays do not happen simultaneously at the 1.6-million-year mark, but distributed over that period!

Answer: 10 seconds

## Chart Practice

Answer: beta-plus decay

Answer: boron-9

Answer: helium-4

A famous decay chain would be the decays from uranium-238 to lead-206, which has 18 steps: ten alpha and eight beta-minus decays.

Half-life is a period of time over which a nucleus has a 50% chance of decaying. With a large number of nuclei, chances are that half of them will decay within one half-life.

All unstable isotopes on your Quick Reference Chart list a half-life, though some are much shorter than others. Oxygen-15, for instance, has a half-life of 0.122 seconds! Thus, given a sample of oxygen-15, in general, half of it will have decayed (*into what?*) within 0.122 seconds.

Note: for this reason, unstable isotopes are rare and generally do not exist on our planet. Consider long-lasting beryllium-10 (half-life: 1.6 million years): even if tons of it were present when Earth formed 4.5 billion years ago, their number has been cut in half so many times that by now almost none would remain... that's 2805 half-lives!

Stable nuclei don't decay, and thus have no half-life. Instead, the Chart lists an abundance, or how much of that isotope you would find in a naturally-occurring sample (e.g. over 99% of oxygen nuclei are oxygen-16, the most common oxygen isotope, while oxygen-17 and oxygen-18 make up the rest).

If you had 32 nuclei with a half-life of just 2 seconds, *how long would it be (on average) until only one was left?*

Build a carbon-9 nucleus: 6 yellow protons, 3 green neutrons. It's unstable, showing a pink diamond on the chart. What kind of decay is that?

What will the carbon-9 become after decay? Use your Quick Reference Sheet, and remember what direction those decays will move a nucleus on the Chart!

Draw an arrow on your Reference Sheet showing the decay from carbon-9 to the new isotope.

The newly-formed isotope is also unstable... use what you've learned about the different decays as shown by the box color/pattern, and *keep drawing arrows on your Reference Chart* to show how your nucleus decays until it reaches a stable isotope and stops. What stable isotope does it finally become?

This is called a "decay chain," a series of changes to an unstable nucleus that end in a stable one. It has reached the lowest energy it could.

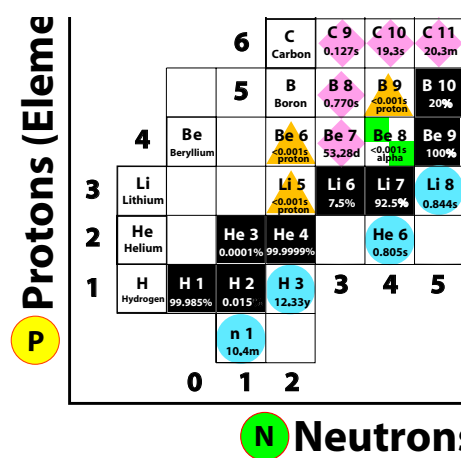


Figure 17. Part of Chart of the Nuclides.



Among all the decays listed in part 2, the common thread is that the nucleus emitted something to accomplish change. However, a nucleus can also be changed by an external particle coming in...

Example: some proton-rich nuclei do not undergo beta-plus decay as described above, because there is not enough energy available to produce a positron. There is another way to accomplish the same effect: capture an electron! Atoms have plenty of orbiting electrons available for this process.

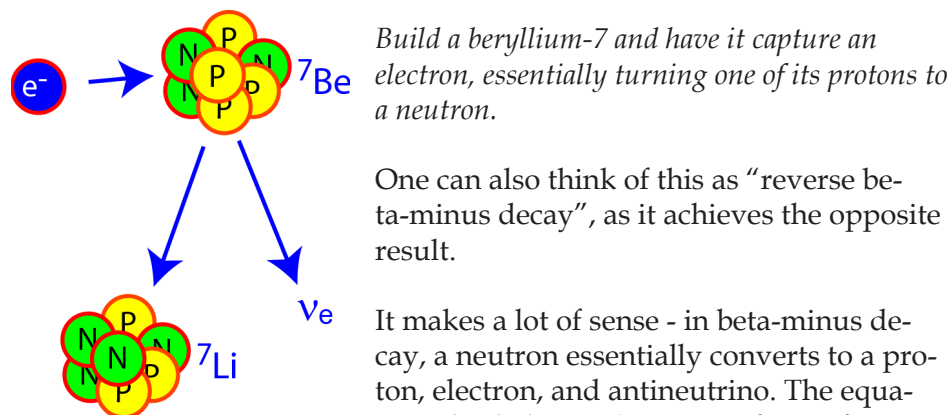
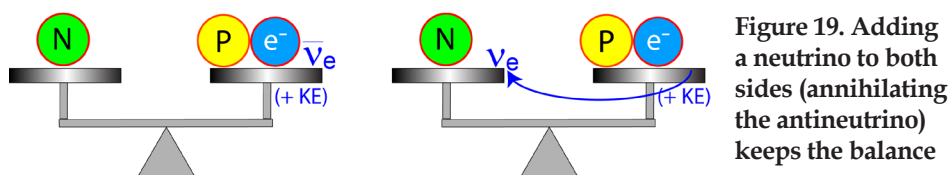


Figure 18. A Be-7 nucleus captures an electron.



Since neutrons are uncharged, there is no electric repulsion (often called the “Coulomb barrier”) to repel them from the nucleus, making it possible in environments with free neutrons (e.g. stars) for nuclei to absorb neutrons. Build a Li-7 and add a green neutron. What isotope have you produced?

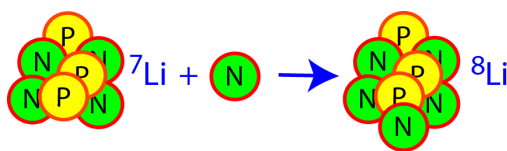


Figure 20. A Li-7 nucleus captures a neutron.

As this process occurs, it could produce neutron-rich unstable nuclei. What kind of decay will that nucleus undergo?

In very hot environments with lots of fast neutrons (e.g. a supernova), the nucleus can absorb many neutrons before decaying. It is possible that rapid neutron capture (the “r-process”) is responsible for forming many of the heavy elements!

Measuring capture rates is important research - and key to what we know about fusion and the formation of new elements, discussed in Part 3!

## Part 2a Capture reactions

This section is “optional” relative to the rest; it can be included or skipped

The absorbed electron is from one of the inner shells - afterwards, one of the electrons from an outer shell will drop down to fill the “hole” and emit a photon.

Answer: lithium-8

Answer: beta-minus decay, converting an excess neutron into a proton.

Students can learn more in the Fragmentation Box of “Marble Nuclei Activities” or the Neutron Capture Processes activity downloaded with this document. Read about the r-process here: <http://en.wikipedia.org/wiki/R-process>

## Part 3 Nuclear Reactions

Students will learn about a variety of nuclear reactions, including how and why they occur.

The “Marble Nuclei Project - Activities Student Worksheet” document has several activities related to the concepts in this section: “Nucleosynthesis Game”, “Stellar Fusion: the p-p chain”, and “Big Bang Nucleosynthesis”.

### Decay/Fission

Part 2 of this lesson has already gone over several kinds of decay.

Unstable isotopes have many uses:

- The decay of carbon-14 allows archaeologists to measure how long ago mummies (or other carbon-based life forms) lived.
- The radiation given off by americium-241 allows smoke detectors to detect minute smoke particles in the air.
- Iodine-131 is used to treat the thyroid gland for cancer.

Unstable isotopes don't generally exist on Earth. So where **do** they exist? The answer: where nuclear reactions can take place. Nuclear reactions are ways to change a nucleus from one isotope to another.

Nuclear reactions can occur on Earth, but are common and important in stars! Reactions between tiny nuclei determine:

- The lifetime of stars
- The elements in the universe
- The production of energy that supports life on Earth

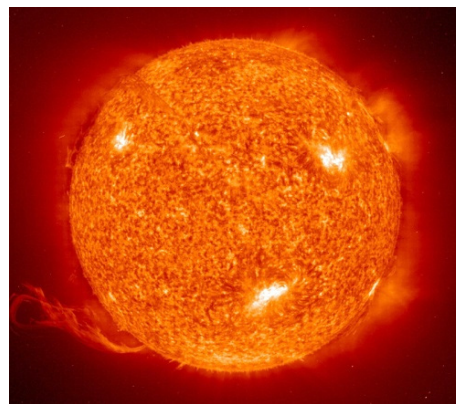


Figure 21. Nuclear reactions in the sun create the light we need. ©NASA/SOHO

That's why JINA scientists are busy studying nuclear reactions, including the following types that can make new isotopes.

You've already seen how decay allows the nucleus to release a particle or energy and become something else, so you know that some unstable isotopes can be made when another one decays. There are several other types of decay (e.g. “gamma”, releasing high-energy light) as well.

Sometimes a nucleus actually breaks apart into two whole nuclei. This splitting is called “fission”, and we use the fission of uranium-235 (92 protons, 143 neutrons) to generate nuclear power.

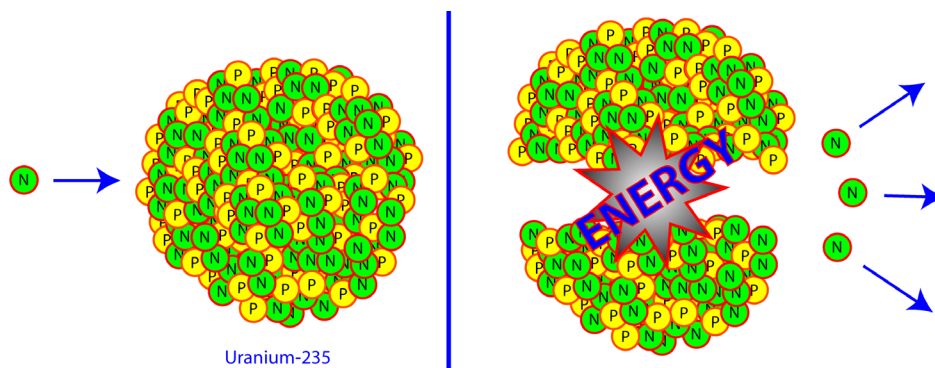


Figure 22. Before and after nuclear fission of U-235.

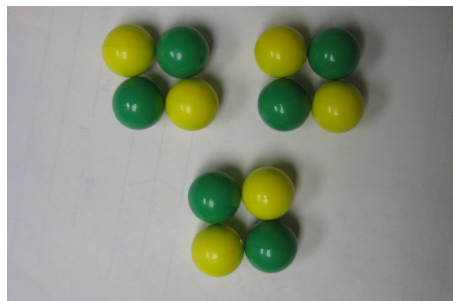
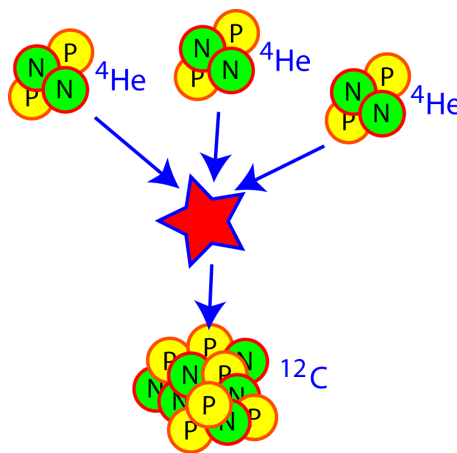
When a long-lived isotope decays or breaks apart, it could produce some short-lived isotopes that have long ago vanished from our planet. For example, uranium-238's half-life is 4.5 billion years, and it can currently be found on Earth... its decay chain produces a number of short-lived isotopes. This is one of the few naturally-occurring ways that new nuclei are made on Earth.

Build a carbon-12 nucleus, then randomly pull it into two pieces to simulate fission. What nuclei have you made (name them)? Put your carbon-12 back together, and simulate fission again. What nuclei have you made (name them)? Are they the same? Fission can result in various “daughter” nuclei.

What if two or more nuclei ran into each other and stuck together, becoming one nucleus? This kind of reaction is called fusion, and it's the process that produces energy in the sun and other stars!

In some stars, the fusion of three helium-4 nuclei forms a carbon-12, also known as the "triple-alpha process" (because helium nuclei are also called alpha particles).

*Make three groups of two yellow and two green marbles (like in the picture at right) and put them close together... these are your helium-4 nuclei. Then drop your silver marble in the middle of them to cause your own fusion reaction and create carbon-12!*



**Figure 23.** A schematic of "triple-alpha" fusion (top); arrangement of marbles to simulate fusion (bottom).

"Capture reactions" occur when a nucleus absorbs an incoming particle, such as an electron, neutron or (in extreme environments) a proton. *What would a beryllium-9 nucleus become after capturing an electron (hint: think of beta-minus decay, but done in reverse)?*

## Fusion/Capture

*The three helium-4 nuclei must fuse almost simultaneously. If just two fuse together, they form a beryllium-8 nucleus that will split back into two helium-4 in a millionth of a billionth of a second, leaving very little time for the third helium nucleus to join them!*

*Our best theory for the source of carbon-12 in our universe (essential to life!) is this reaction.*

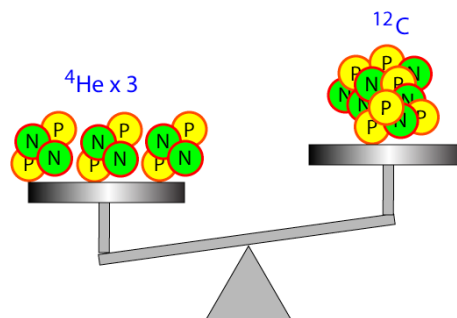
*Answer: a lithium-9 nucleus*

Nuclear reactions are the way stars produce energy and "shine". Specifically, light nuclei in the core of a star actually fuse to make a heavier nucleus.

Fusion releases energy because when multiple nuclei combine into something bigger, if that new nucleus is lower-energy/more tightly bound, 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!

Our sun is fusing an incredible number of hydrogen nuclei into helium every second to produce the solar energy we receive on earth. The mass lost in fusing four protons into one helium is  $4.8 \times 10^{-29}$  kg; *how much energy is that?* ( $c$  = speed of light =  $3 \times 10^8$  m/s; your answer will be in joules)

The converted mass ends up as the light we see: energy from the sun arrives in the form of infrared, visible, ultraviolet, and other wavelengths of light.



**Figure 24.** When three helium-4 nuclei combine to make one carbon-12 nucleus, it weighs less. The missing mass was converted into energy.

## Energy from Nuclear Reactions

*Note! the energy released in a nuclear reaction can come in the form of photons (light), but also goes into the kinetic energy of the resulting particle(s)!*

*Answer: Energy from one fusion reaction =  $mc^2 = 4 \times 10^{-12}$  joules*

*Protons (hydrogen nuclei) fused per second in the sun:  $3.6 \times 10^{38}$*

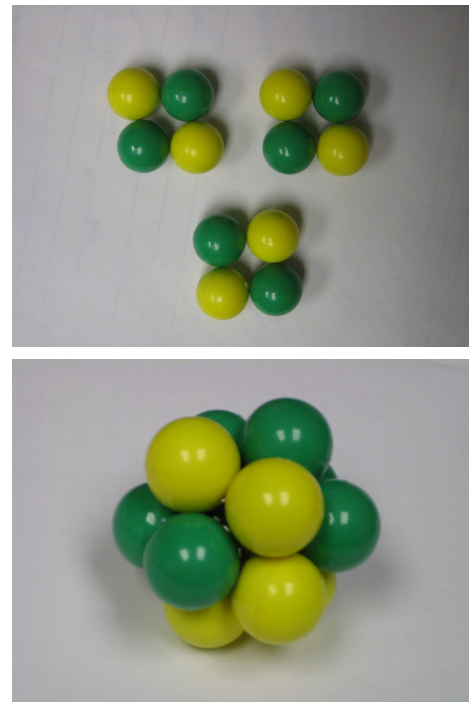
*Mass lost by the sun per second: 4 million tons*

*Energy produced by the sun per second:  $3.8 \times 10^{26}$  watts, equivalent to almost 100-billion megaton bombs*

To demonstrate the release of energy, simulate fusion again like you did above by *arranging three helium-4 nuclei and dropping your silver magnet in the center*, so all the marbles will “fuse” into a carbon-12 nucleus.

*Did energy come out when fusion occurred?* It’s not obvious, but it did. Think about what happened when you dropped the silver magnet: *did you hear a sound?* That was some energy escaping when the marbles combined. Of course, when real nuclei combine, they release light energy.

Now, “break” your carbon-12 nucleus back into three helium-4 nuclei. You have to spend energy getting them apart; you are putting energy into the marbles to separate them. This means that when you let them combine, the same amount of energy must be released.



**Figure 25.** Marble arrangements before and after simulated “triple-alpha reaction.”

*Energy is also released as heat, increasing the temperature of the marbles.*

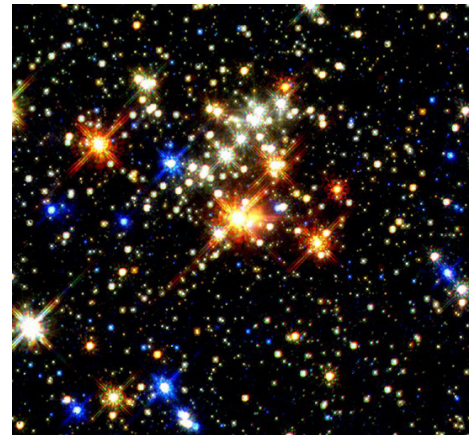
*This is due to Conservation of Energy.*

## Making New Elements

The only elements that existed after the Big Bang were the simplest ones: hydrogen and helium. Giant clouds of those gases condensed into hot balls of gas that we call stars. Stars are the “nucleus factories” that used fusion to make many of the heavier elements in our universe.

Our sun is making four hydrogen nuclei into helium-4. Try it: *put four protons together... what kind of decays must happen for that to change into helium-4?* Other stars can make even heavier elements like carbon, oxygen, iron, and more near the end of their lifetimes. This is called “nucleosynthesis”. There is an activity using the marble nuclei called “The Nucleosynthesis Game” that lets you try to build oxygen from hydrogen through a series of nuclear reactions.

We have good evidence to show that this is where the heavy elements in your body came from: you are carbon-based, using the iron in your blood to transport the oxygen you breathe. As astronomer and educator Carl Sagan would say: you are “star stuff”.



**Figure 26.** The “Jewel Box,” an open cluster of stars. ©NASA/STSC

*Stars actually convert hydrogen into helium through two processes: the proton-proton (“p-p”) chain and the CNO cycle. Stars heavier than 1.5 solar masses primarily use the latter.*

*Answer: Beta-plus decay*

*The “r-process” and “s-process” and more about how heavy elements could be made in stars are covered in the Neutron Capture Processes activity.*

If two nuclei smash into each other at high speed, one or both could “fragment”, breaking into different parts (individual protons, neutrons, and nuclei). The process of fragmentation can create a new (possibly unstable/rare) nucleus!

Build a carbon-12 nucleus, then drop it onto the floor from two feet up (fragmenting using gravity as the accelerator and substituting the floor for another nucleus). Is your nucleus still carbon-12? If not, what has it become, and is it stable or unstable? (check your Reference Chart) Try it three times; do you get different results?

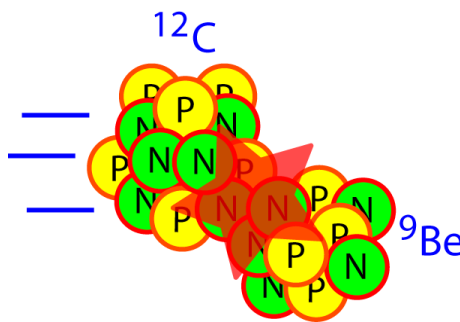


Figure 27. A fast carbon-12 nucleus fragments on a beryllium-9 nucleus.

If new isotopes can be made by nuclear reactions, then why are unstable isotopes so rare on Earth? Simple answer: nuclear reactions are hard to accomplish. While decay and fission do occur on earth, fragmentation and fusion/capture require two or more nuclei to get close enough to interact.

Because nuclei are SO small and they’re usually SO far apart, the chances of a reaction are VERY unlikely. Even “solid” objects have a lot of empty space between their nuclei (see picture at right)!

Estimate the diameter of your model carbon-12 nucleus. Multiply that distance by 10,000 to find out the size of an atom it would belong to. How many meters across is that?

In addition, the electric repulsion between nuclei (full of protons!) keeps them apart. Thus, nuclear reactions occur mostly in places that are dense (lots of nuclei) and hot (nuclei are moving fast).

Humans use particle accelerators to replicate these conditions, but there are a few natural ways on earth to force nuclear reactions. Cosmic rays, which are nuclei zooming through space, strike our atmosphere all the time and create fast-moving neutrons. A nitrogen-14 nucleus can capture one of those neutrons (what isotope does it become?), and the energy of impact can change it into carbon-14 (what particle must come out for that to happen?). Carbon-14 is commonly found in every lifeform on Earth.

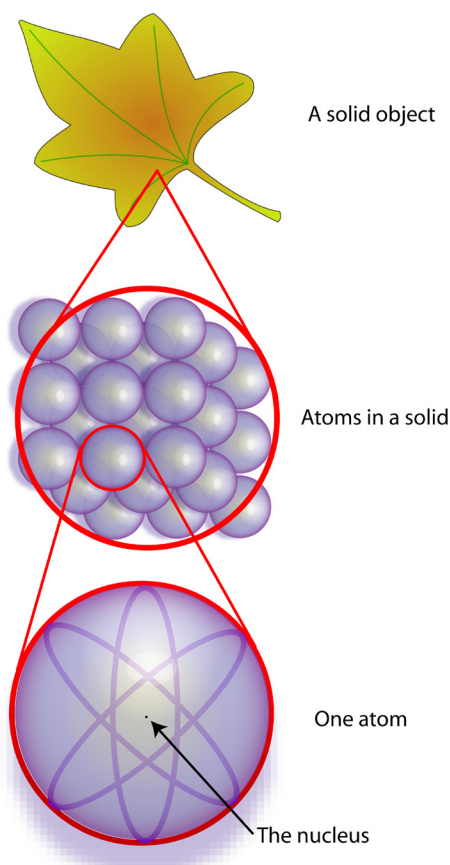


Figure 28. The nucleus as it relates to its place in a solid object.

## Fragmentation

The Fragmentation Box activity in “Marble Nuclei Activities” demonstrates this and the other varieties of nuclear reactions.

Depending on whether your classroom floor is carpet or tile, you might want to vary this activity. Students could drop nuclei into boxes to prevent marbles from rolling away!

Students should produce a variety of nuclei, hopefully some unstable ones.

## The difficulty of nuclear reactions

The electric repulsion between positively-charged nuclei makes it hard to get them that close.

Answer: For example, if the nucleus is 3 cm across, the whole atom would then be 30,000 cm across or 300 m (0.3 km)

Answers: N-14 becomes N-15 for a short period, but then releases a proton to become C-14.

## Part 3a Advanced binding energy

*This section is included for more advanced students, but can easily be skipped*

*One joule > 6 billion billion eV*

*Explained earlier in Part 3!*

*Another way to think about it: binding energy is a potential "well" for the nucleus, requiring kinetic energy for its component particles to escape.*

*Answer: B-10 because it has an equal number of protons and neutrons.*

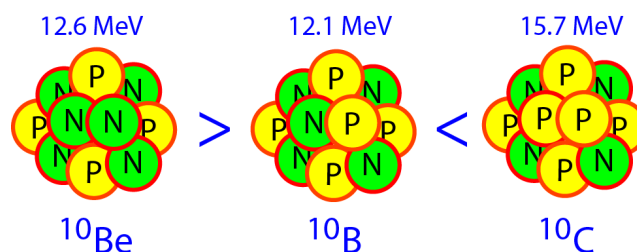
The previous sections mention energy a lot. Nuclear researchers spend a lot of effort measuring binding energy, which indicates how tightly bound a particular nucleus is. The **strong force** is what holds protons and neutrons together to form a nucleus. That means the **binding energy** is the amount of energy that you would need to break the nucleus back into individual particles. An **unbound** nucleus requires no energy, it will come apart naturally.

A good unit for measuring this amount of energy is an MeV (pronounced "em-ee-vee"), or mega electron-volt. An MeV is the amount of energy an electron would have if you accelerated it with a million volts. Sounds like a lot, but it's small compared with the energy you deal with every day, which is more like millions of MeV. *Toss one of your marbles in the air and catch it; you gave it about 10 quadrillion MeV, or a **billion** times more energy than the largest accelerator on Earth (Large Hadron Collider at CERN, Switzerland) can provide to a proton (about 10 million MeV).*

Binding energy can also be considered a measure of how much lower the energy of nucleus is compared to all its protons and neutrons separately. This is quite apparent if you measure the mass of a nucleus - it will be less than the total mass of its individual particles! The "lost mass" is equivalent to the binding energy. To sum up: nuclei have a lower overall energy due to the strong force, and some nuclei are especially low-energy, making them stable.

Get together with a friend: *one of you construct a B-10 (5 protons, 5 neutrons), while the other builds a Be-10 or a C-10. All three are similar aside from the balance of protons and neutrons. According to the "rules" given on page 5, which of these should be most stable/lowest-energy? Why?*

The stable nucleus in this example should have a lower energy compared to the other two. That energy (relative to a baseline) is listed in the figure below.



**Figure 29.** Three nuclei with the same number of particles (an "isomer" on the Chart of the Nuclides), each labeled with relative energy.

It appears that for 10-particle nuclei, B-10 should be the stable one (in the "valley") and Be-10 & C-10 should be unstable. Be-10 turns into B-10 by beta-minus decay, while C-10 does by beta-plus decay.

Note something else: changing from Be-10 to B-10 only lowers the energy by 0.5 MeV. Thus, it should be less likely to happen (and thus slower) than a process that results in a bigger energy drop. C-10, on the other hand, lowers its energy by 3.6 MeV in changing to B-10, which should make that decay more likely and quicker. *Look up their half-lives on your chart - is that correct?*

*Answer: It's true - C-10 has a half-life of only 19 seconds, while Be-10's half-life is over 1 million years!.*

Many factors contribute to the energy of the nucleus beyond the simple rules suggested on page 5. You may know that in chemistry, some special elements are called “noble gasses” (helium, neon, etc.) because they have the right number of electrons to “close a shell”, leaving none for interaction with other atoms.

Electrons form up in shells on an atom because of their quantum behavior - protons and neutrons do this as well! Because certain numbers of each have particularly low energy, it is favorable to make those nuclei.

## The Magic Numbers

of protons or neutrons to close a shell in a nucleus

2 8 20 28 50 82 126

Many charts of the nuclides mark these numbers so you can identify the “magic” nuclei - you’ll find several stable nuclei on those lines. He-4 is a good example: it is “doubly magic” because it has 2 protons and 2 neutrons. *What other elements have “magic” numbers of protons? They should be extra-stable because of their low energy - do they have many stable isotopes?*

One can measure the binding energies of all the common isotopes and plot them to get this graph, comparing how tightly-bound they are.

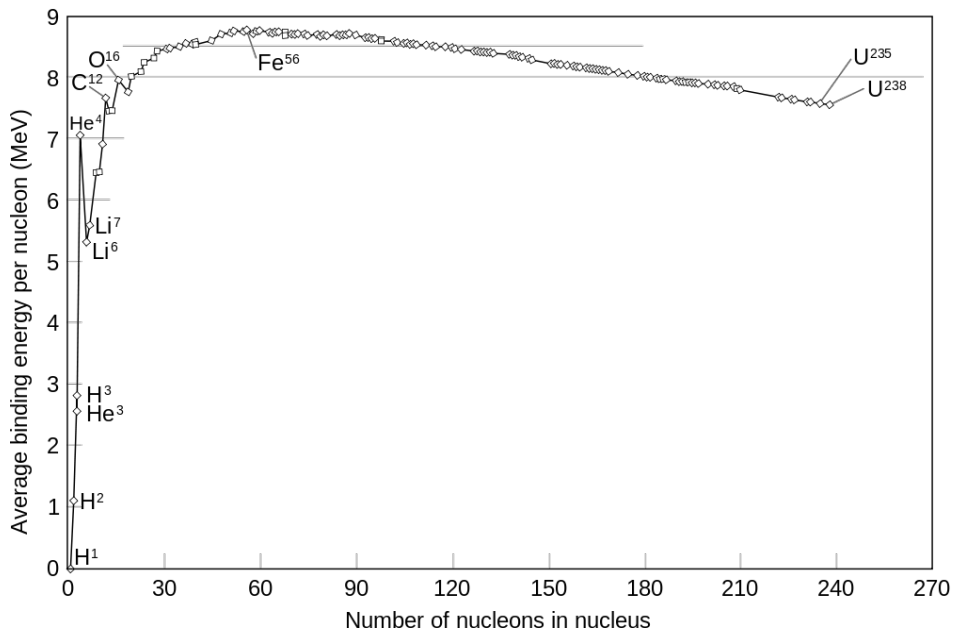


Figure 30 The Binding Energy curve, as a function of the number of nucleons. The most tightly bound nuclei are iron and nickel. (courtesy Wikipedia commons)

To change a nucleus to one that is less bound (moving down the graph) requires that you put energy in. Thus, changing a nucleus so that it moves up the graph means that energy comes out! Looking at the graph, *do the following reactions release or consume energy? Which reaction would release the most energy?*

- Four H-1 fuse (combine) to He-4
- Three He-4 fuse to C-12
- U fissions (breaks) into lighter elements
- Fe fuses or fissions

## Magic Numbers

*This project won't devote enough space for a thorough explanation: see the hyperphysics website!*  
<http://hyperphysics.phy-astr.gsu.edu/hbase/nuclear/shell.html>

*Answer: oxygen, calcium, nickel, tin, and lead are “magic” and feature a large proportion of stable isotopes for that reason!*

## Binding Energy per nucleon

*This project won't devote enough space for a thorough explanation: see the hyperphysics website!*  
<http://hyperphysics.phy-astr.gsu.edu/hbase/nucene/nucbin.html>

*Answer: H-> He goes way up the graph, releasing the most energy. He -> C releases energy, but not as much. U fission also releases energy, though much less. Fe is the most tightly bound, so changing in either direction will require consumption of energy.*

## Part 4 What Nuclear Scientists Study

Students will become aware of the goals of nuclear science. Scientists study the isotopes' size, shape, structure, and stability.

### Size of the Nucleus

Nuclei with full "shells" are more stable than average, and these "shell closures" occur at specific "magic" numbers of protons or neutrons: 2, 8, 20, 28, 50, 82, 126 (referred to in part 3a). This is analogous to the electron shell structure in the atom.

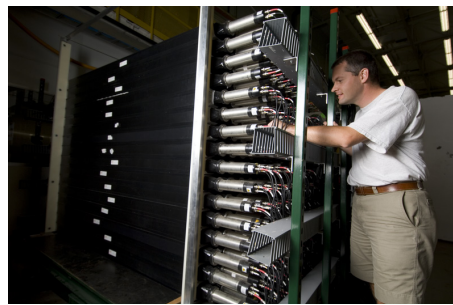
For example, a nucleus with 8 protons and 8 neutrons (oxygen-16) is energetically favorable and much more stable than neighboring nuclei on the Chart. Note, however, that many nuclei with full "shells" (and thus, "magic" numbers of particles) are still unstable!

### Mass of the Nucleus

Some elements have more than one stable isotope. In those cases, the element's accepted atomic mass (as listed on the Periodic Table) is an average of all stable forms, weighted by their relative abundance.

Answer: a carbon-10 nucleus

Nuclear science is dedicated to understanding why nuclei act the way they do. Researchers are very interested in unstable isotopes and how they will decay, or otherwise react with other particles. What we learn about the nucleus tells us about ourselves and everything made of matter in our universe.



As you add protons and neutrons to your nucleus, it changes size... sometimes in strange ways that researchers are investigating.

Cover your silver magnet with 6 protons (yellow marbles) and 6 neutrons (green marbles). Borrow extra marbles to create at least part of a second layer. Are the "protons" and "neutrons" in the outer layer (farther from the silver magnet) stuck as tightly to your nucleus?

Scientists theorize that nuclei ARE organized by layers called "shells" that are most tightly bound when they are full!

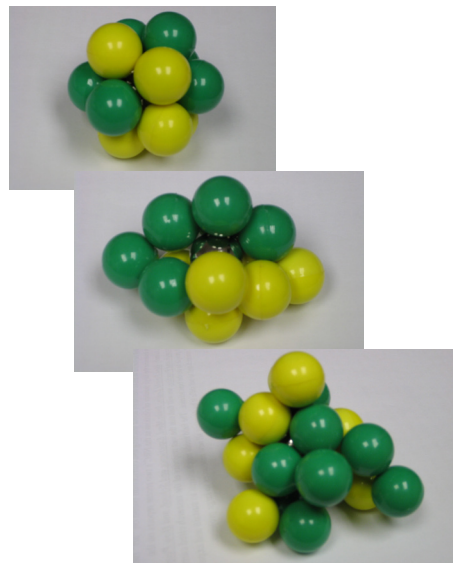


Figure 31. Varying sizes of nuclei, depending on number of particles.

Adding protons and neutrons also affects the mass. As you know, however, the mass of a nucleus is not just the sum of its parts - some of the mass is converted into the "binding energy" that holds it together.

Some nuclei are bound together more tightly than others, depending on how many particles they have, whether there's an even or odd number of them, and other factors. Measuring the mass of a nucleus, then comparing it with the total mass of its protons and neutrons, allows researchers to determine the amount of energy binding the nucleus.

For example, build a boron-10 nucleus. Its mass is known to be 10.012937 u ("u" is a standard nucleon mass). Now replace a neutron on your nucleus with a proton. What isotope do you have now? Its mass should be slightly **lower**... you have the same number of particles, and the proton you added has about 0.001388 u less mass than the neutron you took away.

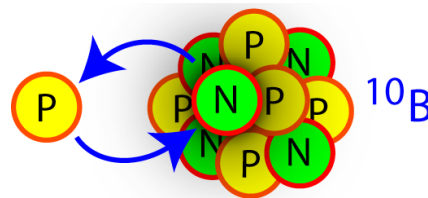


Figure 32. "Charge exchange" in boron-10 changes its mass.

However, the new isotope's mass has actually **increased** to 10.016853 u! This is due to the lesser binding energy of such an unstable nucleus (its half-life is only about 19 seconds).



Where does the Chart of the Nuclides end? Currently, no one can answer that question. For very light nuclei (e.g. helium, carbon, oxygen), researchers are fairly certain of the lightest (fewest neutrons) and heaviest (most neutrons) isotopes for each element. For heavier elements, the limits, especially on the heavy side, are unknown. Theories have predicted what those limits might be, but are occasionally proven wrong.

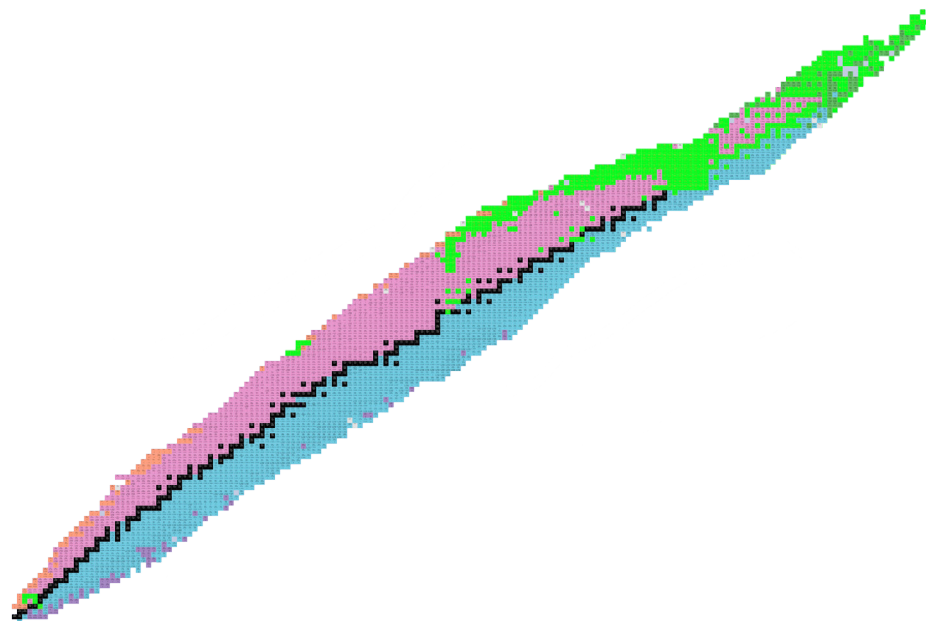
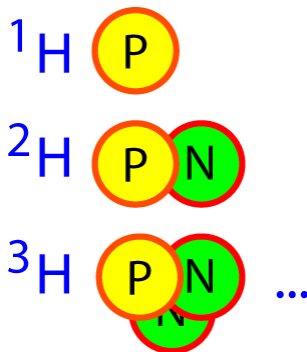


Figure 33. Full Chart of the Nuclides, >3000 known isotopes as of 2010.

Build a hydrogen-1 nucleus. Then add one neutron at a time, creating H-2 up through H-7. These are all the known hydrogen isotopes, and most of them are unbound, existing for almost no time at all. Can you imagine H-8? Do you think such a thing is possible?



Nuclei don't have to be round (spherical). Scientists have discovered nuclei that are:

- oblong like a football
- flying-saucer-shaped
- pear-shaped
- cigar-shaped
- and so on...

See what shapes you can make with your marble nucleus!

Although not all shapes of nuclei can exist, many oddly-shaped ones do. Draw your strangest-shaped nucleus.



Figure 34. Different arrangements of particles give varying shapes.

## Limits of Stability

The limits are called the "driplines;" for instance, if you try to add one more neutron to an isotope on the "dripline, that neutron will simply "drip" right back off since it is unbound.

New isotopes are often added to the Chart, so any printed information about it (including this lesson) is likely out of date.

## Shape of the Nucleus

The various shapes occur due to different amounts of energy in the nucleus, and whether or not it has a "magic" number of protons or neutrons.

There are a limited number of possible nuclear shapes due to the short-range nature of the strong force that binds the nucleus. For instance, "tails" are impossible.

## Amazing Nuclei

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

A lead-208 marble nucleus would have a volume of at least 208 times the volume of one marble ( $\frac{4}{3}\pi r^3$ ), where  $r$  = radius of one marble = 0.794 cm. Thus, the volume is  $436\text{ cm}^3$ , resulting in a radius of 4.7 cm. The actual radius would be larger because there is space between the marbles!

Scientists at NSCL have learned much about some very rare and unusual nuclei.

For instance, they are currently studying the structure of lithium-11, which has two neutrons in a large “halo” around its other particles. Borrow some extra neutrons and build a lithium-11 nucleus.

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 guess how far out they’d have to be to make a nucleus the same size as one that contains 208 marbles.

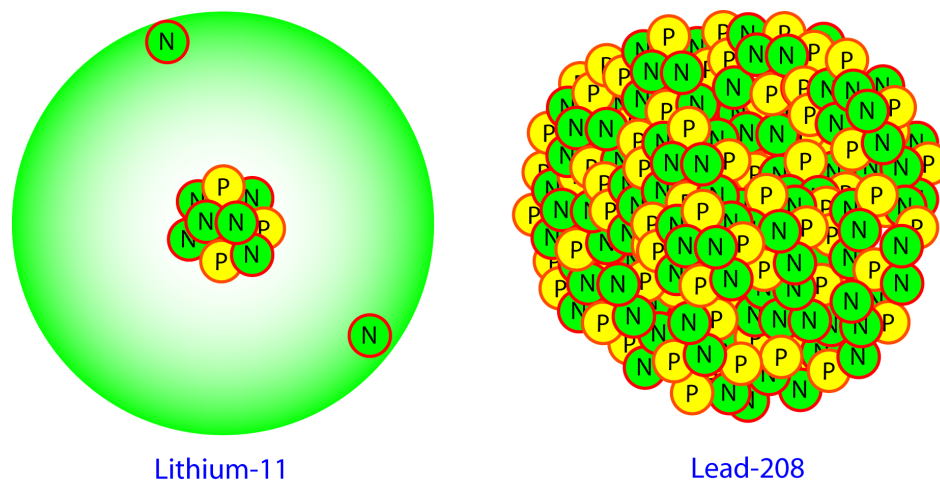


Figure 35. Size comparison of Lithium-11 and Lead-208 nuclei.

## How nuclear research is done

JINA and NSCL scientists who study nuclei, especially rare radioactive isotopes, need expensive and complex tools:

- \* Immense computing power to calculate such things as the temperature of a neutron star, the process of a supernova, or the orbits of ancient stars at the extreme edges of our Milky Way galaxy.
- \* Powerful particle accelerators (cyclotrons, for instance) that can push stable/common isotopes to half the speed of light before smashing them to create unstable fragments.
- \* Detectors of all shapes and sizes to measure invisible nuclei that don’t exist on Earth before they decay in less than a second and give off radiation.

## Exploring further

The “Teacher instructions” document that came with this lesson has links to other resources.

You can learn more about nuclear science by:

- Trying the “marble nuclei activities” that go with this lesson
- Visit NSCL’s “Nuclear Science Primer” website: <http://www.nsl.msu.edu/public/tour/primer.html>
- Touring NSCL (<http://www.nsl.msu.edu>) or another laboratory
- Reading JINA’s research highlights: <https://www.jinaweb.org/science-research>
- Seeking out more information on the above websites or elsewhere:
  - \* American Nuclear Society resources for educators & the public: <http://nuclearconnect.org/>
  - \* Jefferson Laboratory’s Education page: <http://education.jlab.org> (“The Shape of Things” explains detectors well!)