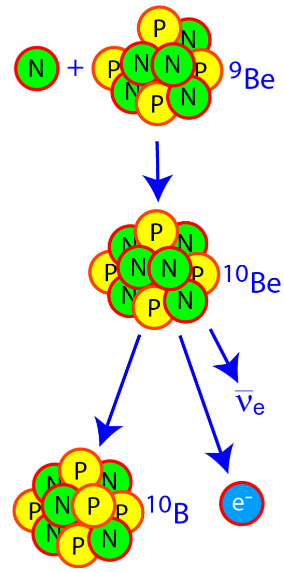
Building the heavy elements

This activity uses the "Neutron Capture Process Chart" so students can simulate neutron capture processes and perform their own theoretical calculations!

Estimated time: 20-30 minutes

Many elements are created by fusion in stars, but heavy elements can't be! Those elements may result from neutron capture processes:

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



Capture or decay first?

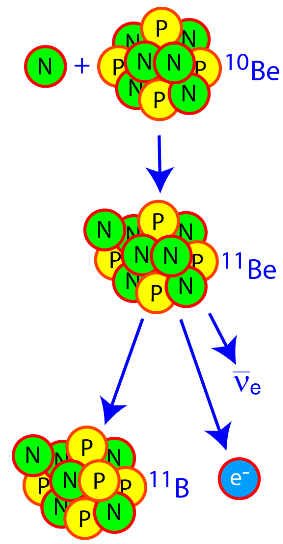
In a star with loose neutrons around, stable nuclei might absorb them every so often. Unstable nuclei might too, as long as they didn't decay first. Consider the Be-10 above... its half-life is over 1 million years. If neutrons were abundant enough that a nucleus would normally capture one every ten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

While radioactive, Be-10 is likely to exist at least ten years, long enough to capture a neutron

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

Be-11 will almost certainly decay long before the ten-year window is up

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



Creating a model

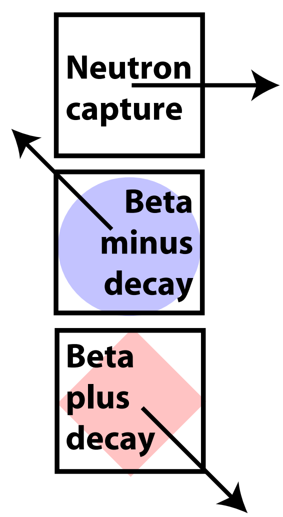
Students will perform so many beta-minus decays that they'll forget that beta-plus decay moves in the opposite direction, which can result in very incorrect paths!

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

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

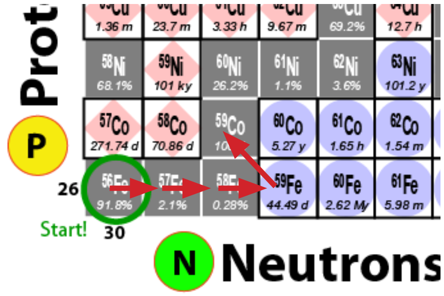
1. Neutrons capture every 10 yr
2. Isotopes with half-lives longer than 10 yr will capture, while isotopes with half-lives shorter than 10 yr will decay.

Using that model, you can make a prediction of the "s-process", a set of slow neutron capture reactions that may occur in a red giant star!



In the next part, you will draw on the "Neutron Capture Processes" Chart - either print it out or open the image file in a drawing program.

1. *Start at the Fe-56 nucleus, and assume that neutron capture in a red giant occurs **every 10 years**.*
2. *Decide whether Fe-56 will capture or decay first (hint: it's stable, so the half-life is forever) & draw an arrow to the resulting nucleus.*
3. *Decide whether the resulting nucleus will decay or capture first & draw an arrow; repeat!*
4. *Continue until you make the heaviest Sr (strontium) isotope you can.*

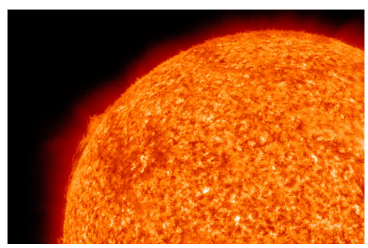


Did your s-process calculation create nuclei that were close to the line of stable (grey) isotopes, or far from it?

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

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

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



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

Use a new color to draw on your Chart (on paper or the computer):

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

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

Maybe the r-process can also create the heavy elements we see in nature. *Which stable isotopes could be made by the r-process or s-process? Which could only come from the r-process? Which were only made by the s-process? Are there any stable isotopes that neither process makes? What does that mean?*

S-process simulation

If you go through the first few steps with the students, maybe using the Neutron Capture Activity slides, they should be able to recognize the pattern and carry through.

Creating new isotopes

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

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

R-process simulation

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

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

The two processes overlap on many stable isotopes, but many more are just from the s-process, while a few outliers require the r-process. There are many other proposed capture processes to fill in the other stable isotopes