Mathematics, Science, and Technology (MST) program 2009

Nuclear Astrophysics Course

Michigan State University

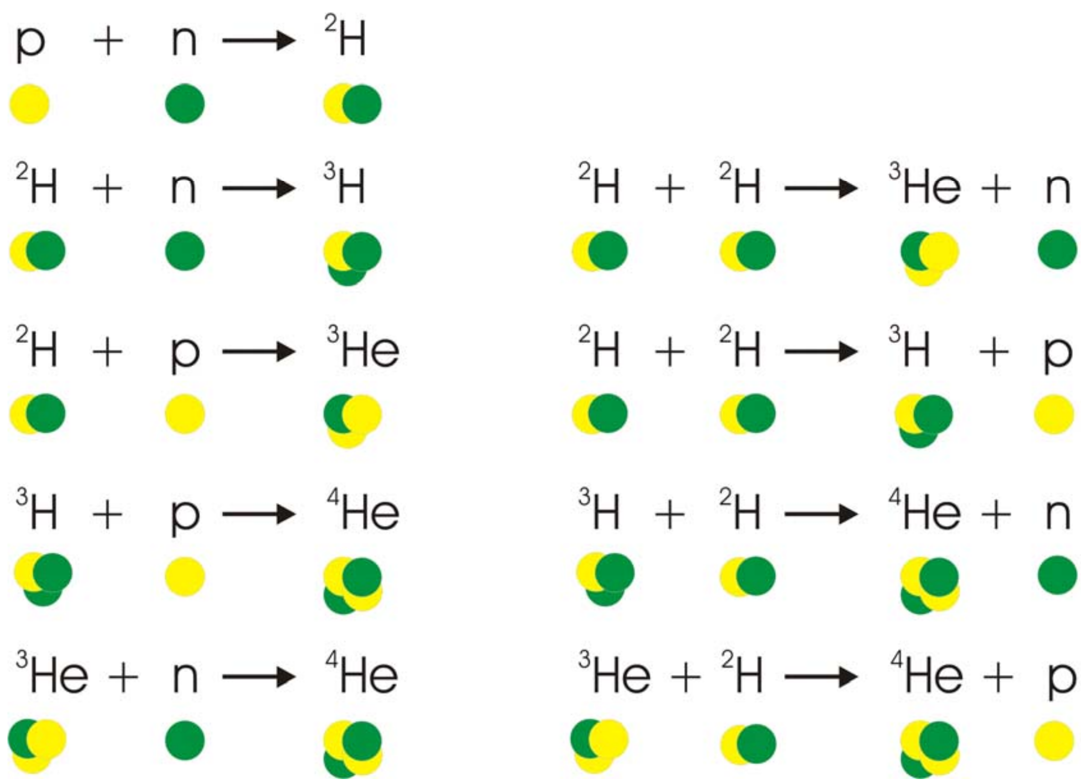
Lesson #5: Nucleosynthesis

How stars create the elements

1 - Big Bang Nucleosynthesis: making ^{4}He.

According to the Big Bang theory, about 15 billion years ago the universe went through a huge explosion and started expanding. In this stage the universe was made up of a hot and dense soup of energy and particles (a plasma). As the universe expanded and cooled down, neutrons and protons were formed. After about 2 minutes the universe was cool enough so that protons and neutrons could combine to form nuclei without being disintegrated, and thus the process of Big Bang Nucleosynthesis began. At this point there was one neutron for every 7 protons. Then a series of nuclear reactions combined these neutrons and protons into ^{4}He nuclei (2 protons and 2 neutrons)[1]. Most of the He that we see today in the universe was produced in this time. Also traces of other light isotopes were made (^{2}H,^{3}He, ^{7}Li).

EXERCISE! You'll begin with the same ratio of protons to neutrons found in the early universe (7 protons to 1 neutron), and following the list of possible nuclear reactions make as much ^{4}He as you can.



isotope	100 seconds after Big Bang	15 minutes after Big Bang
n	12.5 %	
p (^{1}H)	87.5 %	
^{2}H		
^{3}He		
^{4}He		
^{7}Li		

[1] The nuclear force that binds the protons and neutrons together in the nucleus likes to arrange them in pairs. Because ^{4}He has both a pair of protons and one of neutrons it is one of the most stable light isotopes.

2 - Nuclear Reactions in Stars

After ^{4}He is formed in the early universe all nucleosynthesis stops, and it only resumes once galaxies and stars are formed. In this section you'll understand why the synthesis of the heavy elements happens in the interior of stars

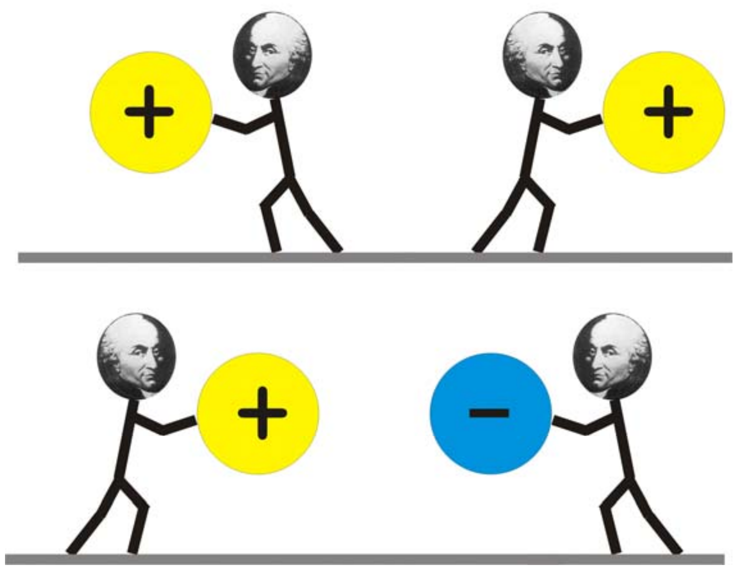
May the (electric) force be with you!

Many of the nuclear reactions that make the elements involve particles with positive electric charge (for example protons and all heavy nuclei), so the electric force between them is important to decide if the reaction is possible or not.

The following are two important properties of the electric force (described by Coulomb's Law , due to Charles Augustine de Coulomb, 1780s):

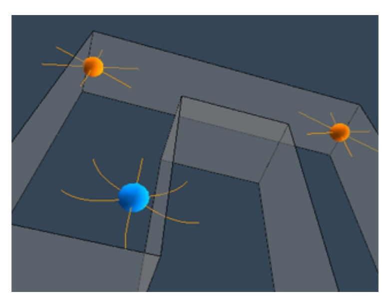
1. Opposite charges attract and like charges repel each other.

$$F = k_e \frac{q_1 q_2}{r^2}$$



Since two nuclei have positive charges (for example, 2H+ and 4He++) the electric force might prevent them from getting close enough to react with each other.

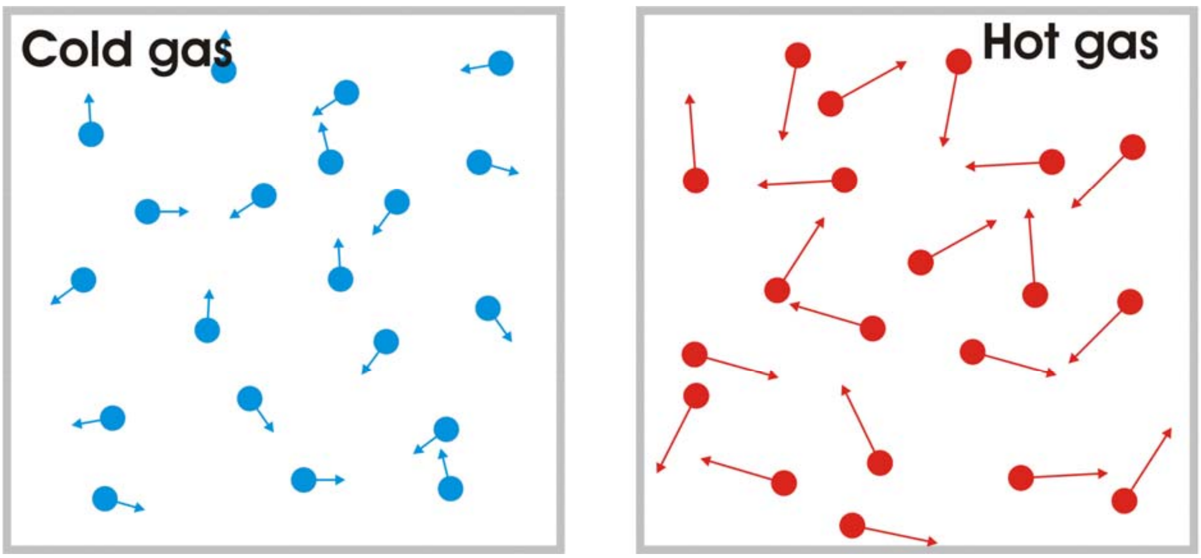
2. The attraction (or repulsion) is larger if the particles have a larger electric charge. Try it by yourself with The Electrostatic Videogame! http://web.mit.edu/8.02t/www/802TEAL3D/visualizations/electrostatics/videogame/videogame.htm
Heavy nuclei have a large electric charge (equal to the number of protons), so the electric repulsion between them can be very large.



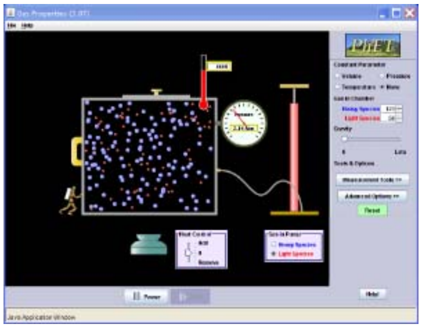
The kinetic energy of particles in a gas.

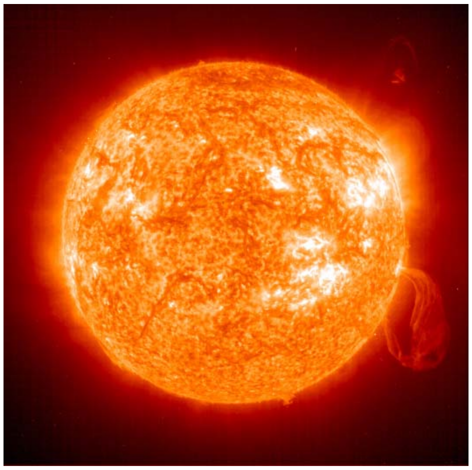
Nuclei will only be able to get close enough to go through a nuclear reaction if they can overcome the repulsion of the electric force between them. How can they do it?... if they are moving fast enough (in the physicist's slang: if they have enough *kinetic energy*).

How fast particles are moving in a gas is described but what we call the Ideal Gas Law (the relevant astrophysical scenarios, like stars, are gaseous). From this physics law we know that in a gas with a large temperature particles move faster, and will have a better chance to go through nuclear reactions:



DEMOS! Ballon in liquid nitrogen and the ideal gas simulation: http://phet.colorado.edu/simulations/sims.php?sim=Gas_Properties





So that solves the problem of the electric force repulsion! We just need a very hot environment where the reactions that synthesize the heavy elements are possible: the interior of a star!!

3 – ^{12}C and the triple alpha process.

Galaxies and stars were formed from the material left over from the Big Bang. The heavy elements in the universe were then produced by different stellar processes. Making carbon is the next important step in the process to synthesize all the other elements. Carbon is also the 4th most abundant in solar system, and it's an essential component of the molecules that make up such things as bacteria and human beings.

EXERCISE! Starting from the leftovers from the Big Bang Nucleosynthesis exercise find a path of nuclear reactions that would make ^{12}C (6 protons and 6 neutrons). Initially you should have one ^{4}He every 12 protons (and traces of other light isotopes). Use the chart in the following page to decide which reactions are possible.

In the following space write down a nucleosynthesis path that makes ^{12}C. Hint: look at the title from this section for the name of the reaction you're looking for (^{4}He is also called an alpha particle).

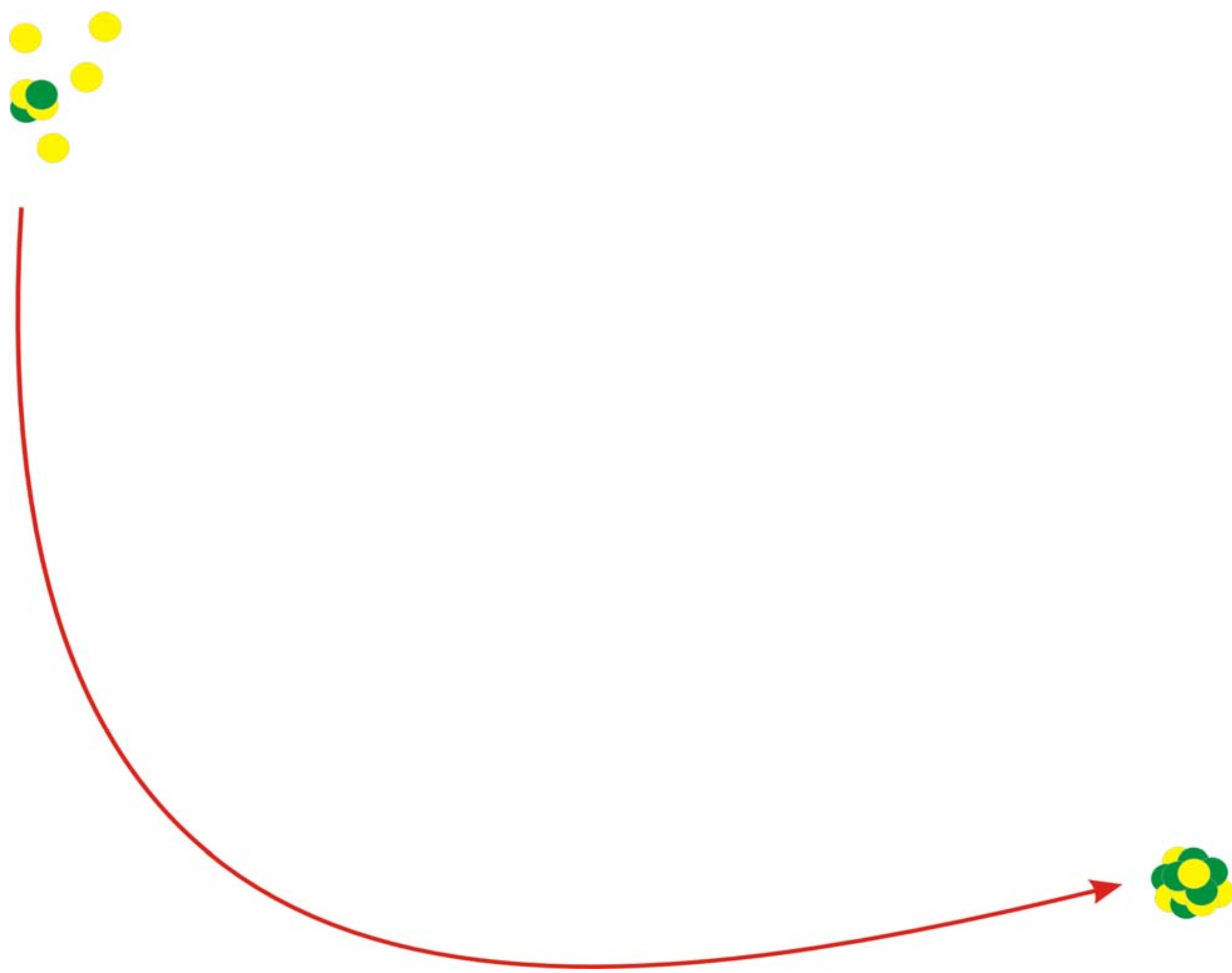
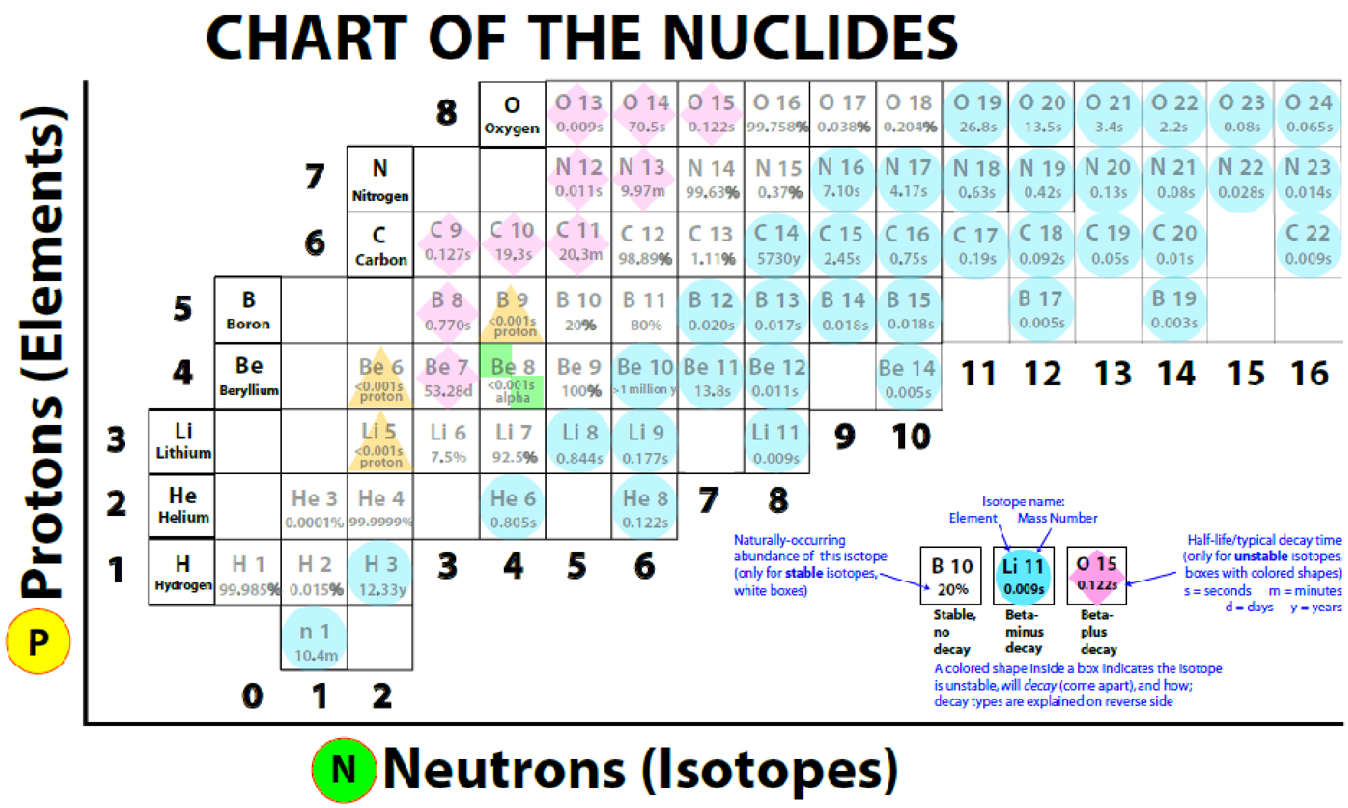
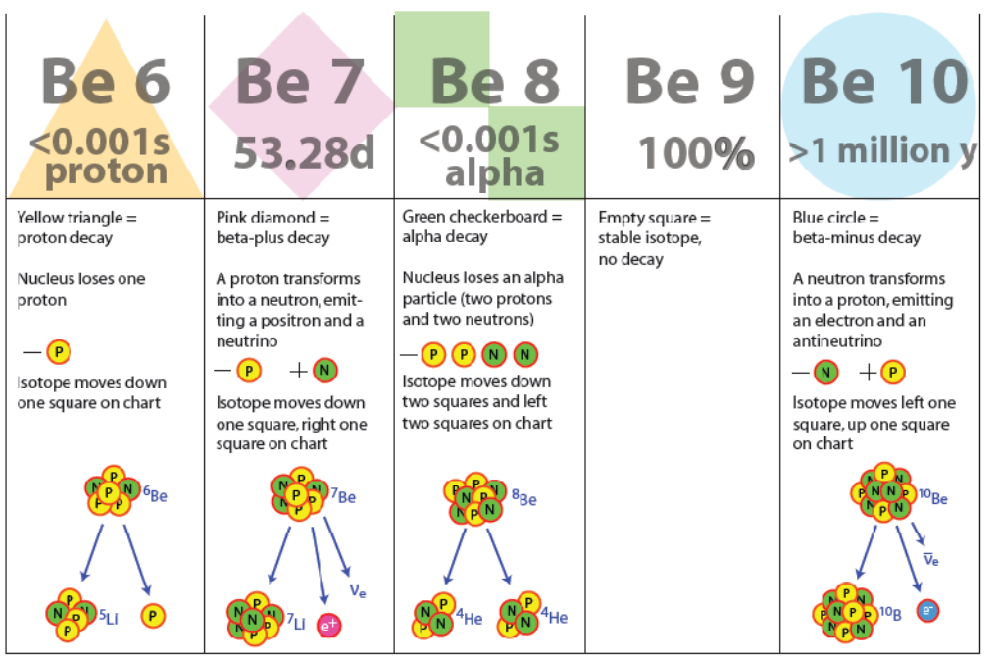


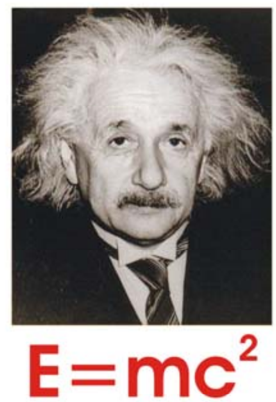
Chart of the nuclides indicating the decay mode of unstable isotopes.





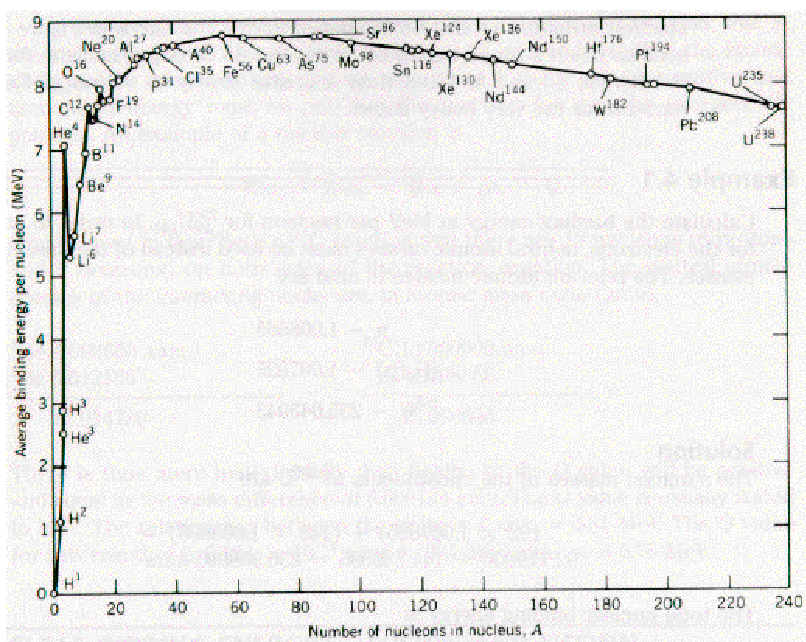
4 - Advanced burning stages.

After ^{12}C is made nucleosynthesis continues via the fusion of nuclei into heavier elements. For example, the figure shows the case of the fusion of two ^{12}C nuclei to produce ^{20}Ne and a ^{4}He nuclei. This, as well as other fusion reactions, produce energy because the combined mass of the two ^{12}C nuclei is larger than that of ^{20}Ne and ^{4}He. The “missing mass” is released as energy into the star (think Einstein and $E=mc^2$!).



$$^{12}C + ^{12}C \longrightarrow ^{20}Ne + ^{4}He + 4.6 \text{ MeV}$$

However, stars run into a significant obstacle once they reach the isotopes in the region of iron (Fe, with 26 protons). Because of the properties of the strong nuclear force that keeps neutrons and protons together forming the nucleus, isotopes in the iron region have the smallest mass per nucleus of all the isotopes. Then it is impossible to release any nuclear energy by fusing them into heavier isotopes. The graph shows the binding energy per nucleon for several isotopes; a larger binding energy is equal to a smaller nuclear mass.

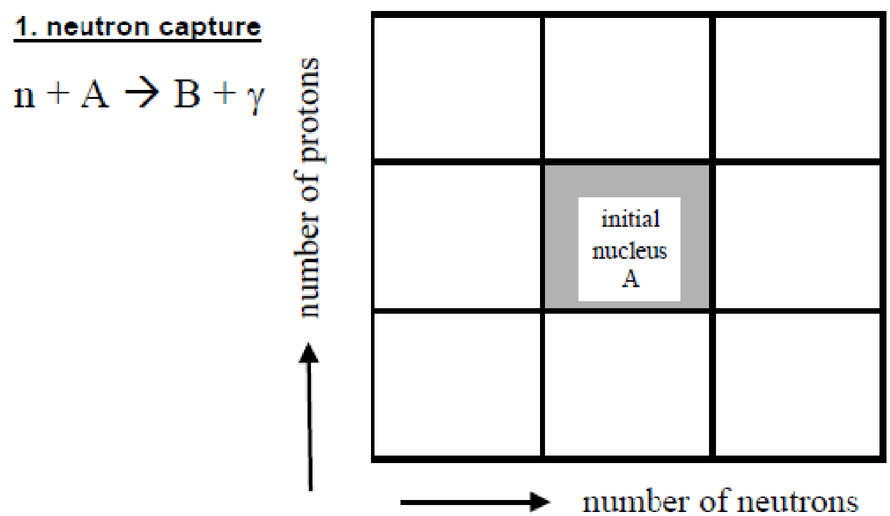


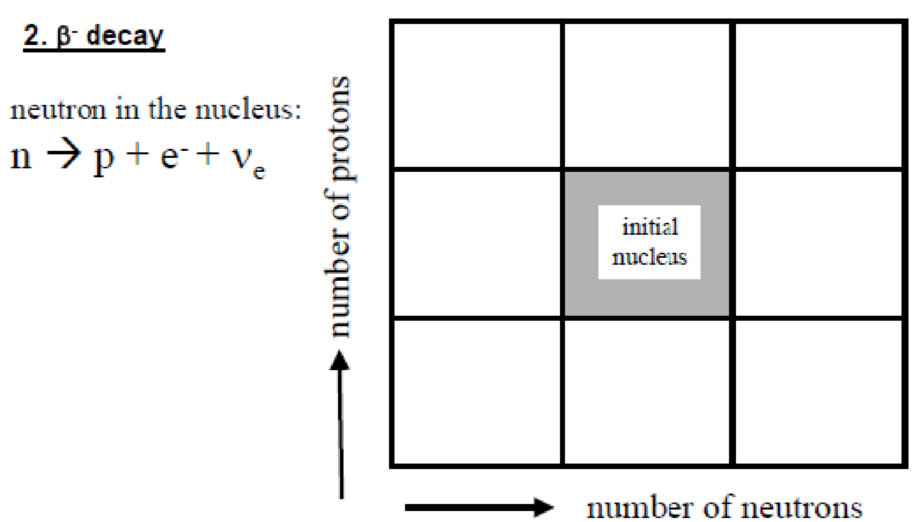
The fusion mechanism doesn’t work anymore! That is why nucleosynthesis by fusion reaction only makes the heavy elements up to iron.

5 - Neutron capture processes and nucleosynthesis of the most heavy elements.

The nucleosynthesis of the elements heavier than iron happens by neutron capture processes. As we learned in section 2, the electric force only affects charged particles. Since neutrons have no electric charge there will be no repulsion due to the electric force in a nuclear reaction where a heavy isotope captures a neutron, and there is no need for a hot environment to make the reactions possible. There are not many stellar environments with a lot of free neutrons lying around, but in this section we will study the two cases that account for the production of almost all isotopes heavier than iron: the **s-process** in red giant stars (more precisely thermally pulsing AGB stars), and the **r-process** during core collapse supernovae (or collisions between neutron stars?… the site of the r-process is still a matter of scientific debate).

EXERCISE! There are two types of nuclear reactions that drive the neutron capture processes: neutron captures and β^- decays. Draw a line from the initial to the final nucleus for each reaction in the following charts:





EXERCISE A: Draw the path of the s-process. Starting at ^{56}Fe, draw the path of the s-process assuming that it takes on average 10 years to capture a neutron.

Step 1: Find the starting point, ^{56}Fe on your chart and mark it with a dot.

Step 2: Compare the typical time for this nucleus to β^- decay (if its stable that time is infinitely long) with the typical time it takes to capture a neutron (given above) and decide which one happens first. If both times are close assume both happen.

This creates a new nucleus.

Step 3: Draw a line from your original nucleus to the new nucleus for the reaction chosen. If both reactions happen draw a line for both and follow the two paths separately.

Step 4: Go to Step 2 using your new nucleus and continue until you reach the end of the chart and you created Strontium (Sr).

Careful! The nuclei marked with arrows do not decay by β^- decay but by β^+ decay (a proton is converted into a neutron) so when for those nuclei the decay occurs before the neutron capture, they decay in the direction indicated by the arrow (opposite to β^- decay)

Questions:

- What isotopes of Strontium did you produce?

- Estimate how long does it take to make them:

  count the number of neutron capture steps: …………………………………………..
  multiply by the average time to capture a neutron: x 10 years

  the total time to make Sr is: ………………………………………………

  (doing this estimate we ignore the time of the β^- decay, but they are in general shorter than the neutron capture times).

- What do you think '*s*' stands for in the name of the *s-process*?

EXERCISE B: Draw the path of the r-process. Starting at ^{56}Fe, draw the path of the r-process assuming that it takes on average just 100 ms (100 mili seconds = 0.1 seconds) to capture a neutron.

Step 1: Find the starting point, ^{56}Fe on your chart and mark it with a dot.

Step 2: Compare the typical time for this nucleus to β^- decay (if its stable that time is infinitely long) with the typical time it takes to capture a neutron (given above) and decide which one happens first. If both times are close assume both happen.

This creates a new nucleus.

Step 3: Draw a line from your original nucleus to the new nucleus for the reaction chosen. If both reactions happen draw a line for both and follow the two paths separately.

Step 4: Go to Step 2 using your new nucleus and continue until you reach the end of the chart and you created Strontium (Sr).

Questions:

- what isotopes of Strontium did you produce?

- Estimate how long does it take to make them:

  count the number of neutron capture steps: ……………………………………………….
  multiply by the average time to capture a neutron: x 0.1 seconds

  the total time to make Sr is: ……………………………………….…………

  (doing this estimate we ignore the time of the β^- decay, but they are in general shorter than the neutron capture times).

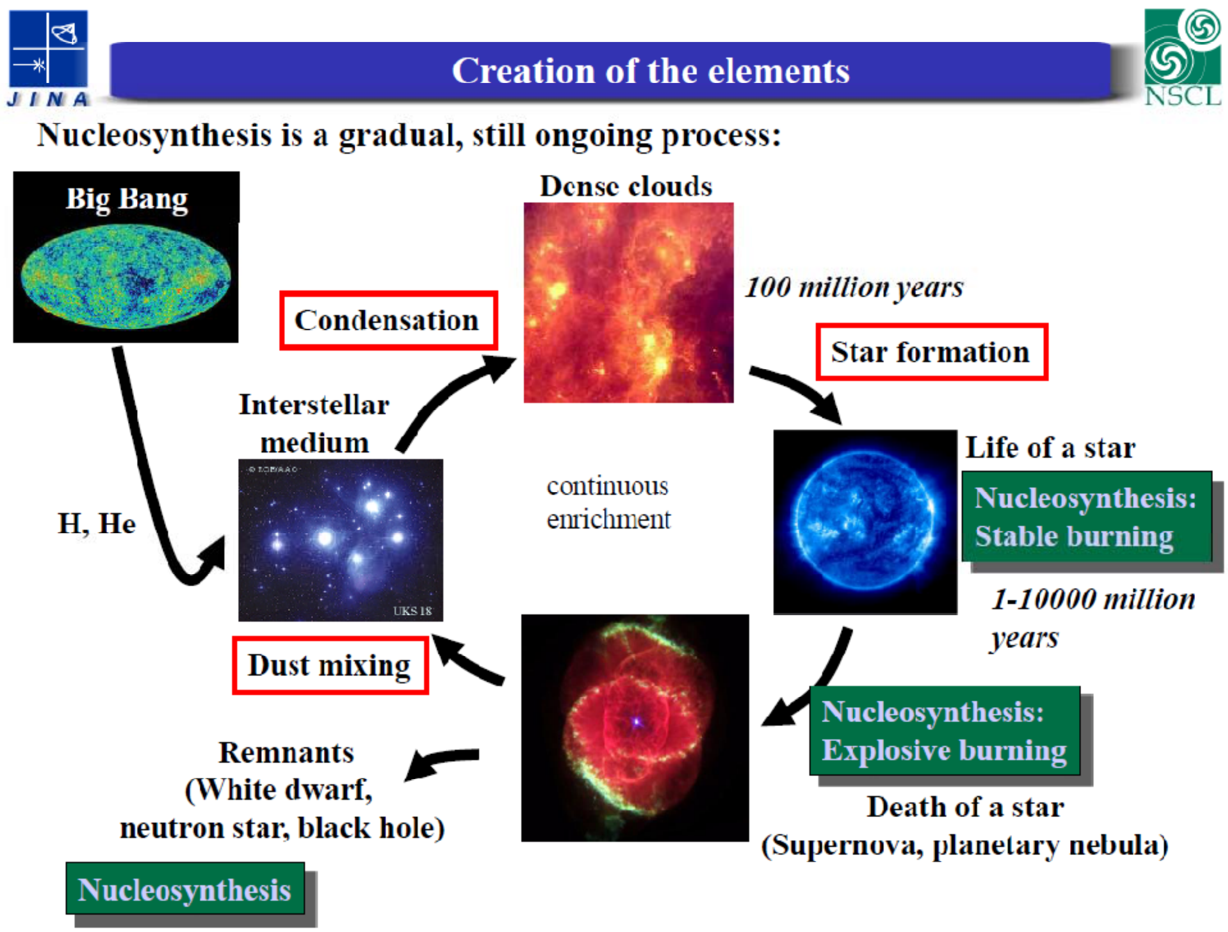
- What do you think '*r*' stands for in the name of the *r-process*?

CHART OF NUCLIDES FOR EXERCISE

(from Hendrik Schatz)

5 – How does all these nucleosynthesis processes fit together?

The products of the nucleosynthetic processes we discussed are ejected from the stars back into the interstellar medium by different mechanisms, such as a supernovae explosion or stellar winds from AGB stars. This material in turn condenses into dense clouds that form new stars (for example our own solar system!) where nucleosynthesis continues. Nucleosynthesis is still a very active process in our galaxy!



SUMMARY EXERCISE: Locate the following processes in the chart of the nuclides.