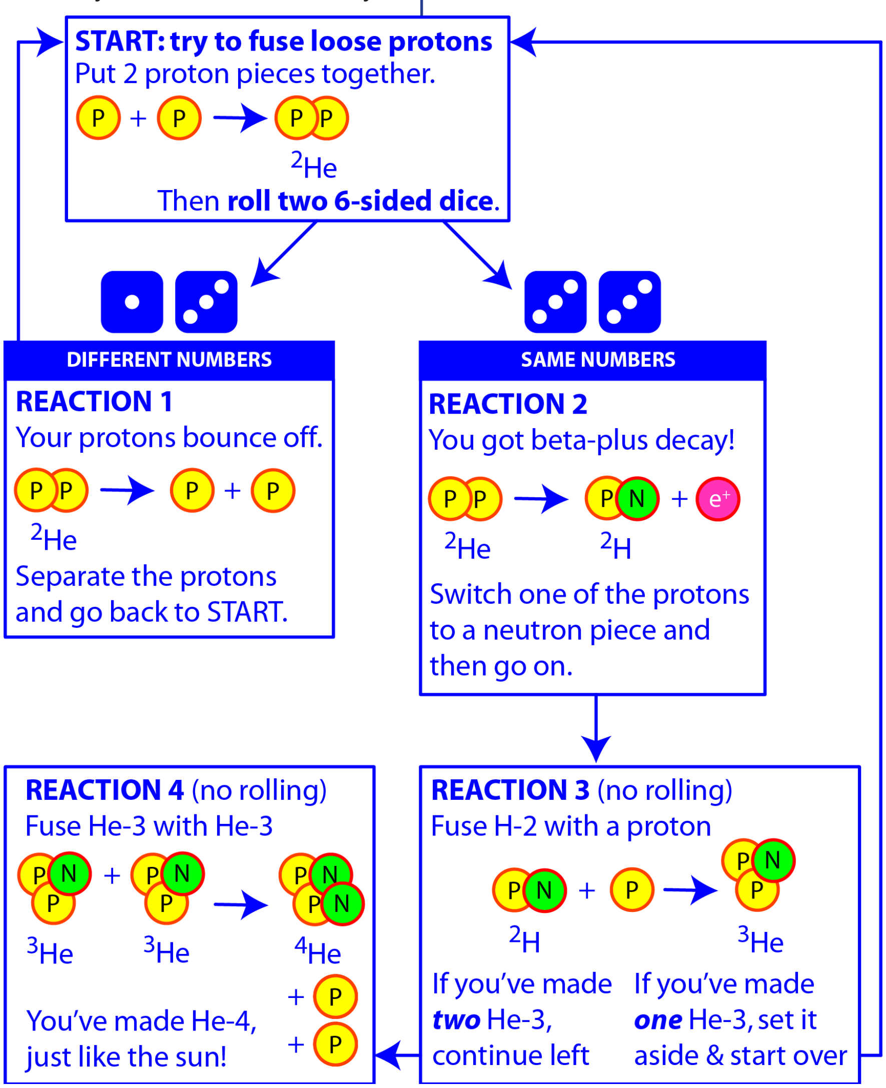
Stellar Fusion: the p-p chain

Stars produce energy through fusion - the combining of light nuclei to make heavier ones. The "ashes" left over after fusion "burning" are new elements! While the Big Bang produced a lot of hydrogen, helium and a bit of lithium, all the heavier elements were made by nuclear reactions. **Stars are nucleus factories.**

Our Sun is currently fusing hydrogen nuclei (protons) to make helium. You can recreate this "proton-proton chain" process using small objects (pennies & nickels, for example) to represent protons and neutrons.

Follow these rules to model how a star fuses nuclei to make energy!

1. *Start with 4 loose proton pieces to represent the hydrogen fuel in a star. You will also need two six-sided dice and two neutron pieces.*
2. *Perform the reactions below, following arrows from one to the next. If you make anything other than loose protons (H-2, He-3, He-4), keep it separate!*
3. Once you make Helium-4, you win!



Of the four possible reactions above (numbered 1-4),

- *Which reaction happened often?*
- *Which reactions were rare (difficult)?*
- *Why were those reactions rare (there are two different reasons)?*

Because those reactions are difficult, the sun fuses hydrogen slowly and hasn't used it all up - that's a good thing for us.

There are four p-p chains, but p-p I (used here) dominates at the core temperature of the sun, about 14 MK.

How to Play

Estimated time: ~10 minutes

Developed in collaboration with Dan Coupland

Note: keeping larger (created) nuclei separate from their starting protons is often students' biggest challenge, remind them that any new products they make should not be put in the pile of protons, but in a new place.

Because the helium-4 is tightly-bound and has slightly less total mass than the four protons this process started with, energy is released: 26.72 MeV.

You can vary the chances of a beta-plus decay by changing what rolls allow it - for a shorter game, try doubles and sevens. For a longer game, try ONLY double sixes! In reality, the chance of a beta-plus decay is almost zero, which is why the sun "burns" very slowly.

Often: two protons don't stick.
Rare: All the other reactions!
Reaction 2 (beta-plus decay of He-2) is rare because you have to roll low-probability numbers, while for reactions 3 & 4 there were rarely non-proton particles available to conduct them.

Big Bang Nucleosynthesis

This simple game lets the student discover for themselves that the low number of neutrons in the early universe makes nuclear reactions difficult!

Estimated time: ~10 minutes (developed by Dan Coupland)

How to Play

Don't hesitate to adjust the rules as necessary!

Note: keeping whatever nucleus they create separate from their other particle pieces is often students' biggest challenge, so remind them if things get mixed up.

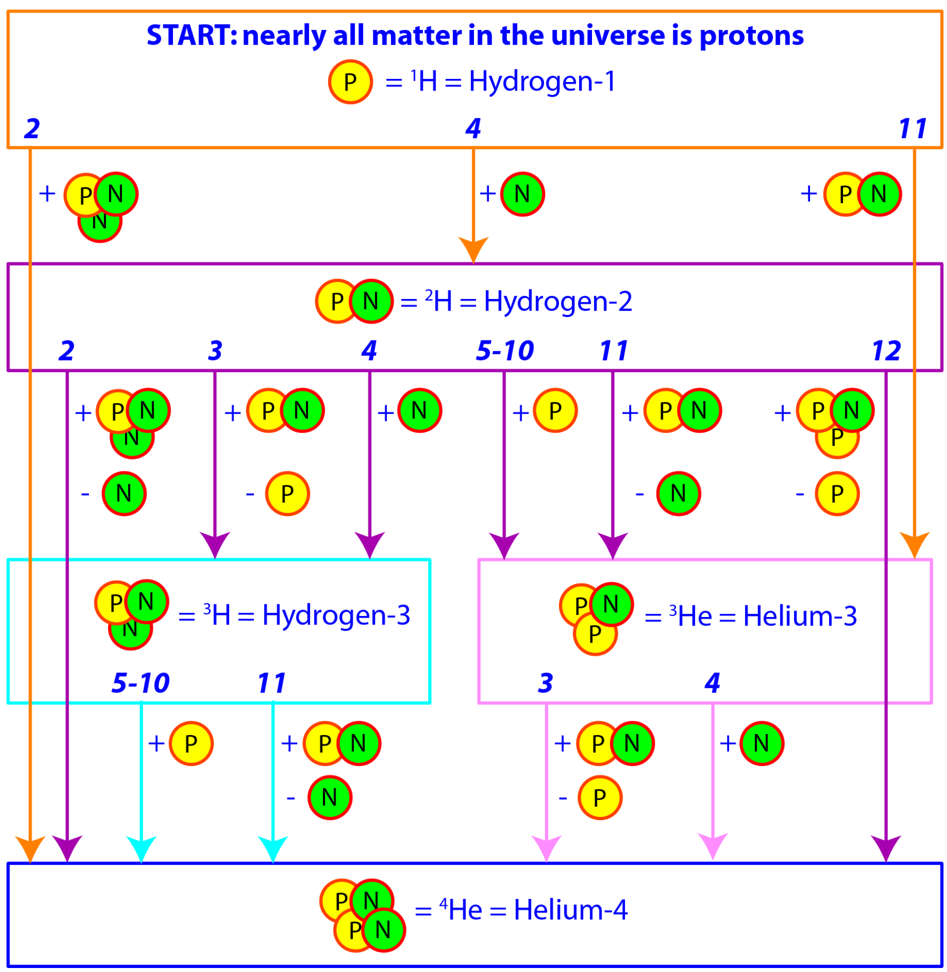
Note that the reactions featured to the right (adding or subtractin protons or neutrons) are the only ones allowed because this process happens too fast for beta decays to change a particle.

According to the Big Bang theory, about 14 billion years ago the universe was just a hot and dense soup of energy and particles (a plasma). As it expanded and cooled down, neutrons and protons were formed. After about 2 minutes the universe was cool enough so that protons and neutrons could combine to form nuclei without being disintegrated, and thus the process of Big Bang Nucleosynthesis (making elements) began!

At that time, most matter (87.5%) was hydrogen (1 proton) and there were few neutrons (12.5%). A series of nuclear reactions combined these neutrons and protons into ^{4}He nuclei (2 protons and 2 neutrons). Most of the helium that we see in the universe today was produced then.

For this activity, you will re-create the kind of reactions that occurred shortly after the Big Bang. Can you make helium-4?

1. *You'll need two proton pieces, two neutron pieces, and 2 six-sided dice.*
2. *Start with just one proton piece, a hydrogen-1, like in the top box below.*
3. *Roll dice to see what reaction happens to your particle and check the box:*
   - *If your number rolled appears above an allowed path down, follow that path to the next box and add the appropriate piece(s) to your nucleus.*
   - *If your number doesn't appear on a path, record the final nucleus.*
4. *Do this 10 times (each starting with a proton) trying to make helium-4!*



Count what's left: of the 10 protons (hydrogen) you started with, how many are still hydrogen? How many helium-4 did you successfully make? Is your "universe" still mostly hydrogen, but with a little bit of helium? Try it again if you like to see how the results change or stay the same!