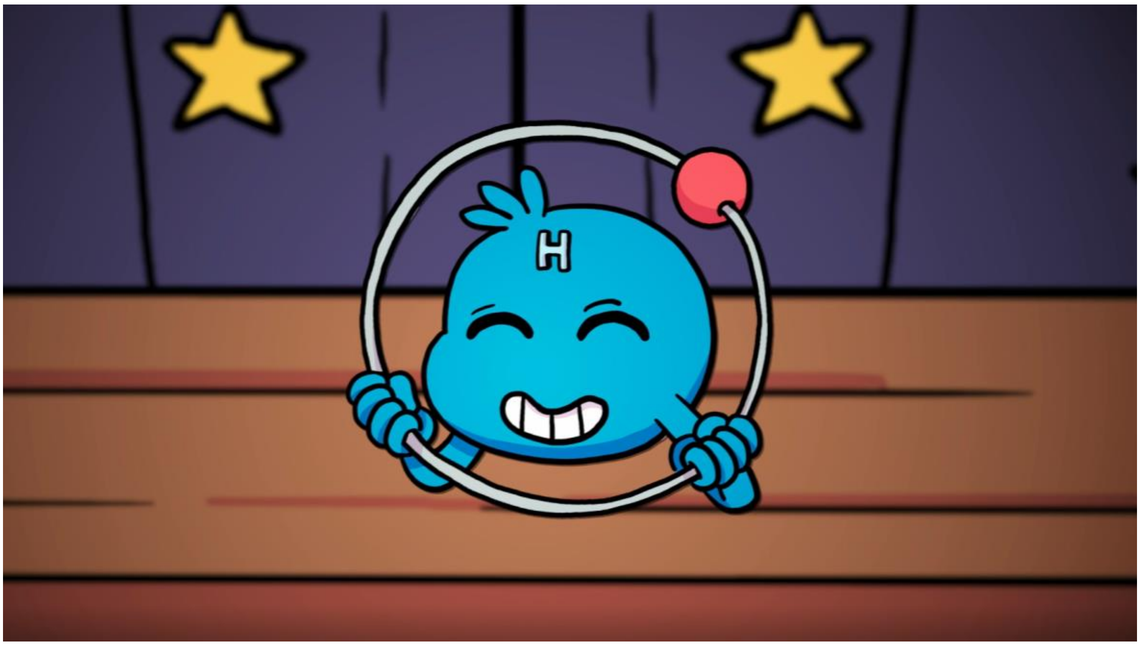
Nuclear Fusion in Stars

Post-16



Topics covered: Nuclear fusion, mathematical use of $E=mc^2$, stellar evolution, ideal gas law (pressure and temperature).

Introduction

Much of the energy production in our Universe comes from the process of nuclear fusion within stars. This process takes light elements like hydrogen and helium and builds them into heavier elements. However, this process in stars can only build elements up to Iron. Heavier elements are formed mostly in the intense explosions that occurs at the end of a star's life.

This activity starts by getting students to practice using the concept of energy-mass equivalence ($E=mc^2$) by considering the energy release of several nuclear reactions. Further questions then challenge students to use the information they have learned about nuclear reactions to determine:

- Why heavier elements require a higher temperature for the reaction to occur
- Why endothermic processes cannot occur at high rates in a stable star and what would happen to that star if they did
- The result of decreasing amounts of fuel and lower output energies on stellar lifetimes

This activity accompanies the Royal Observatory Greenwich animated video "The Origin of the Elements". It is available on our website (https://www.rmg.co.uk/discover/teacher-resources/origin-of-the-elements) and on our Vimeo page (https://vimeo.com/royalobservatory).

Equipment: scientific calculator

Questions to ask before the activity:

Question: *Why are stars made of atomic nuclei rather than atomic atoms?*
Answer: Stars are incredibly hot which means the electrons in an atom are given enough energy that they are stripped from the atoms. The atom becomes ionised and only the atomic nuclei remains (consisting of positively charged protons and neutrons).

Question: *Stars are extremely massive with intense self-gravity that is constantly trying to collapse the star in on itself. What stops this collapse from occurring?*
Answer: Stars are extremely hot in their cores. From the ideal gas laws, this extremely high temperature causes a very high pressure which balances out the force of gravity.
Note that stars are *not* typically held up by radiation pressure. It is degeneracy pressure – the pressure exerted by electrons, protons, neutrons or other fermionic particles when they are forced together as they are prevented from occupying the same 'space' or quantum state.

Question: *What process releases this energy within the Sun (and most other stars)?*
Answer: The nuclear fusion of hydrogen into helium.

Questions to ask after the activity:

Question: *Many of the elements larger than iron are made in supernovae. Why can their production happen there, but not in the cores of stars?*
Answer: Fusion of elements larger than iron is typically endothermic. If this occurred in stars, it would decrease the temperature of the core, stopping nuclear fusion from occurring and causing the star to collapse. However, in the ensuing supernova explosion, vast amounts of energy are released. This energy can be used by nuclei to fuse into larger elements. With no fine balance between gravity and pressure to maintain, what would be an unstable process in a star can occur unabated in the supernova.

Activity: Nuclear Fusion in Stars

Nuclear fusion is a process that takes small atomic nuclei and combines them together to make a larger one. Through this process, hydrogen and helium, the simplest elements in the Universe, were built into heavier elements. Much of this process occurs in the cores of stars where elements up to Iron can be formed in the largest of stars. However, elements heavier than this can only be formed in large quantities in powerful explosions called supernovae. In this activity you will learn why this is the case.

1) In 1905, Albert Einstein showed that mass and energy are equivalent. This means that energy and mass are in effect the same thing. A stationary object with a certain mass has an amount of energy equivalent to that mass, known as the rest mass energy. In any reaction where the products are less massive than the ingredients, there is a resulting release of energy, given by the equation:

$$\Delta E = \Delta m \times c^2 \quad (1)$$

where ΔE is the change in energy in Joules, Δm is the change in mass in kg and c is the speed of light (299,792,458 ms^{-1}).

The following is a list of nuclear reactions. In each case, determine the mass of the inputs and outputs, and determine the amount of energy released in a single instance of each reaction.

a) $$4({}^{1}_{1}H) \rightarrow {}^{4}_{2}He + 2e^{+} \quad (2)$$

b) $$3({}^{4}_{2}He) \rightarrow {}^{12}_{6}C \quad (3)$$

c) $${}^{12}_{6}C + {}^{12}_{6}C \rightarrow {}^{20}_{10}Ne + {}^{4}_{2}He \quad (4)$$

d) $${}^{206}_{82}Pb + {}^{4}_{2}He \rightarrow {}^{210}_{84}Po \quad (5)$$

Note that atomic weights are given in amu (atomic mass units), where 1 amu = 1.66054×10^{-27}kg.

Element/Particle	Symbol	Atomic Weight (amu)
Hydrogen	${}^{1}_{1}H$	1.007825
Helium-4	${}^{4}_{2}He$	4.002603
Carbon-12	${}^{12}_{6}C$	12.000000
Neon-20	${}^{20}_{10}Ne$	19.992439
Lead-206	${}^{206}_{82}Pb$	205.974465
Polonium-210	${}^{210}_{84}Po$	209.98287
Positron	e^{+}	0.000549

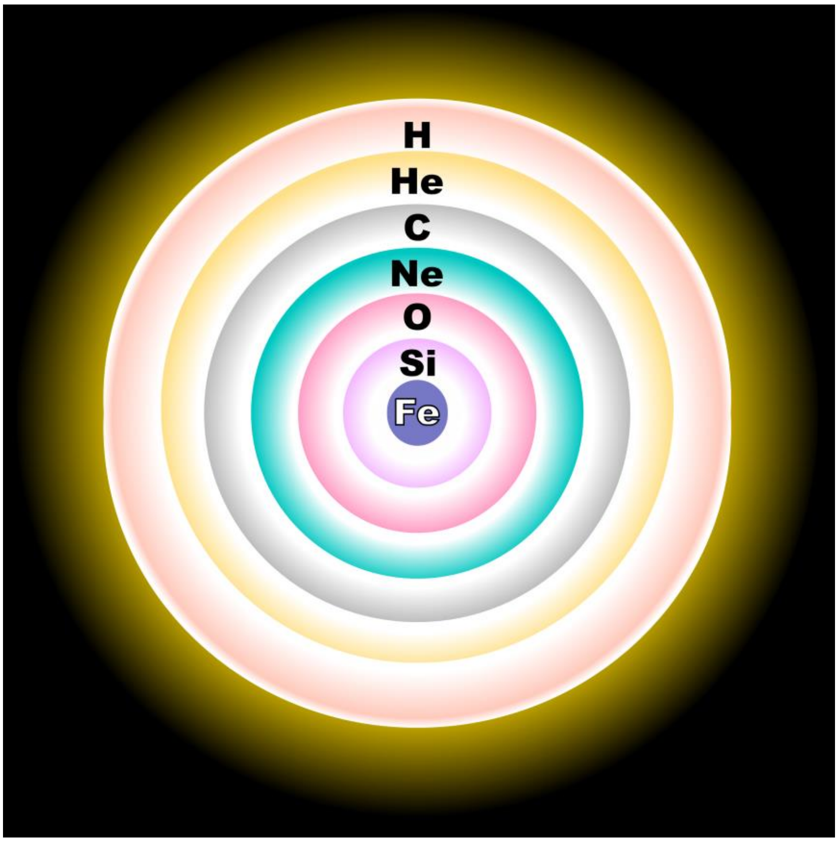
2) Assume reaction a) is the dominant form of energy production in the Sun. How many reactions must occur per second to sustain the Sun's luminosity (3.828×10^{26}W)?

3) Reaction a) is the shortened version of a process known as the proton-proton chain. It occurs in stars whose cores reach at least 10 million Kelvin.

Reaction b) is known as the triple-alpha process. It converts helium into carbon in stars later in their lives, when their cores are 100 million Kelvin or higher.

Reaction c) is one of the next stages in nuclear fusion. It only occurs in stars much larger than our Sun in the even later stages of their lives with cores at 500 million Kelvin.

Why do the later reactions require much higher temperatures to occur? (Hint: Consider what the inputs must overcome in order to combine themselves)



4) Stars are carefully balanced with the force of gravity attempting to collapse them and the pressure generated by the heat of star pushing outwards.

Reaction d) does not occur in stars. Thinking about your answers to question 1), what might have suggested this fact? If the reaction did occur in great quantities, what would happen to the core of the star?

(Hint: What is the name given to reactions that produce energies like that seen in a) iv)? What do these types of reactions do to their environment?)

5) Consider a single star. At each new stage of its life it will fuse a different, heavier element to the one before. As 4 hydrogen nuclei are required for reaction a), 12 hydrogen nuclei (3 helium nuclei) are required for reaction b), and 24 hydrogen nuclei (2 carbon nuclei) are required for reaction c), this means there is less fuel available at each stage for the star to fuse.

Stars late in their lives also produce far more light than stars during their main sequence. This requires more energy.

Thinking about the above, and your answers to question 1), what will this mean for the duration of each stage of a star's life?

Nuclear Fusion in Stars: ANSWERS

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1) a) Mass of inputs $= 4 \times 1.007825 = 4.0313$ amu

Mass of outputs $= 4.002603 + 2 \times 0.000549 = 4.003701$ amu

$\Delta m = 4.0313 - 4.003701 = 0.027599$ amu
$= 4.5829 \times 10^{-29}$kg

$\Delta E = 4.589 \times 10^{-29} \times (299792458)^2 = 4.12 \times 10^{-12}$J
$= 25.7$ MeV

(If you want students to convert to MeV, simply add in the conversion factor 1 Joule = 6.242×10^{12} MeV)

b) Mass of inputs $= 3 \times 4.002603 = 12.007809$ amu

Mass of outputs $= 12.0$ amu

$\Delta m = 12.007809 - 12.0 = 0.007809$ amu
$= 1.2967 \times 10^{-29}$kg

$\Delta E = 1.2967 \times 10^{-29} \times (299792458)^2 = 1.17 \times 10^{-12}$J
$= 7.27$ MeV

c) Mass of inputs $= 2 \times 12.0 = 24.0$ amu

Mass of outputs $= 19.992439 + 4.002603 = 23.995042$ amu

$\Delta m = 24.0 - 23.995042 = 0.004958$ amu
$= 8.23296 \times 10^{-30}$kg

$\Delta E = 8.23296 \times 10^{-30} \times (299792458)^2 = 7.40 \times 10^{-13}$J
$= 4.62$ MeV

d) Mass of inputs $= 205.974465 + 4.002603 = 209.977068$ amu

Mass of outputs $= 209.98287$ amu

$\Delta m = 209.977068 - 209.98287 = -0.005802$ amu
$= -9.6345 \times 10^{-30}$kg

$\Delta E = -9.6345 \times 10^{-30} \times (299792458)^2 = -8.66 \times 10^{-13}$J
$= -5.40$ MeV

2) Reaction rate = $\frac{3.828\times10^{26}}{4.12\times10^{-12}} = 9.3 \times 10^{37}$ reactions per second

3) The nuclei of atoms have a positive charge. Larger nuclei with more protons have a stronger positive charge which repels other nuclei more strongly. The particles in higher temperature gases have more energy and so can collide with enough energy to overcome the repelling force.

4) Reaction d) produces products of greater mass than the combination of the inputs. As a result, it absorbs energy rather than releasing it. This is called an endothermic reaction and causes the surroundings to decrease in temperature.

Were this to occur at high enough rates, it would stop the production of heat energy that supports the star. Gravity would overcome radiation pressure and the star would collapse. This process actually occurs in large stars and is the trigger for a supernova.

5) If in each stage of its life the star has less fuel to use, produces less energy per reaction and yet emits more light than in the stage before, then the star must be using its fuel quicker to produce the energy required to shine brighter / emit more light. Therefore, each stage's duration will be much shorter than the one that came before.

As an example, our Sun has a main sequence lifetime (dominated by reaction a) in Q1 – hydrogen burning) of 10 billion years, but will spend less than a billion years in the next stage (dominated by reaction b) in Q1 – helium burning).