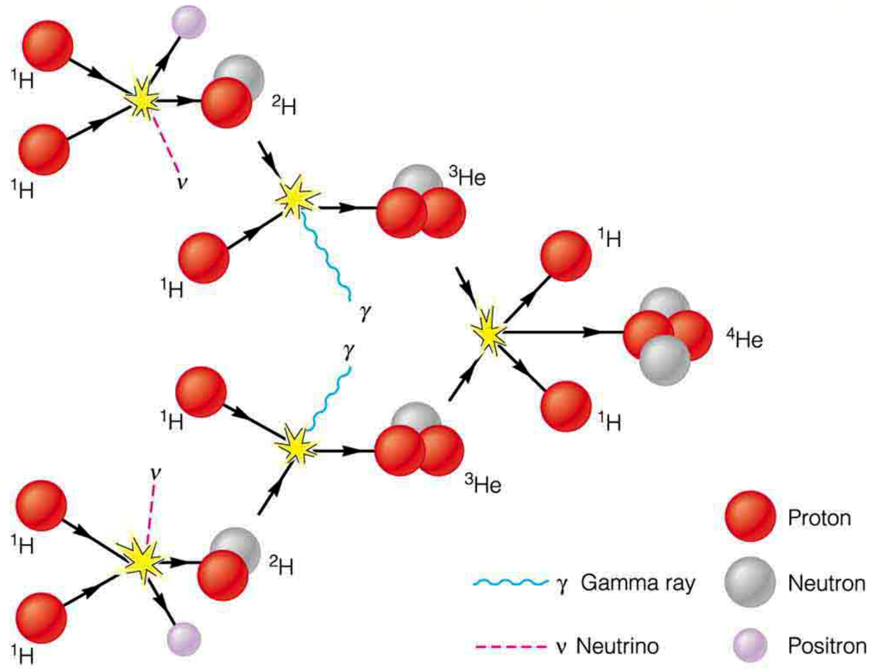
PHY20004 Nuclear Physics Class 6:
Nuclear fusion

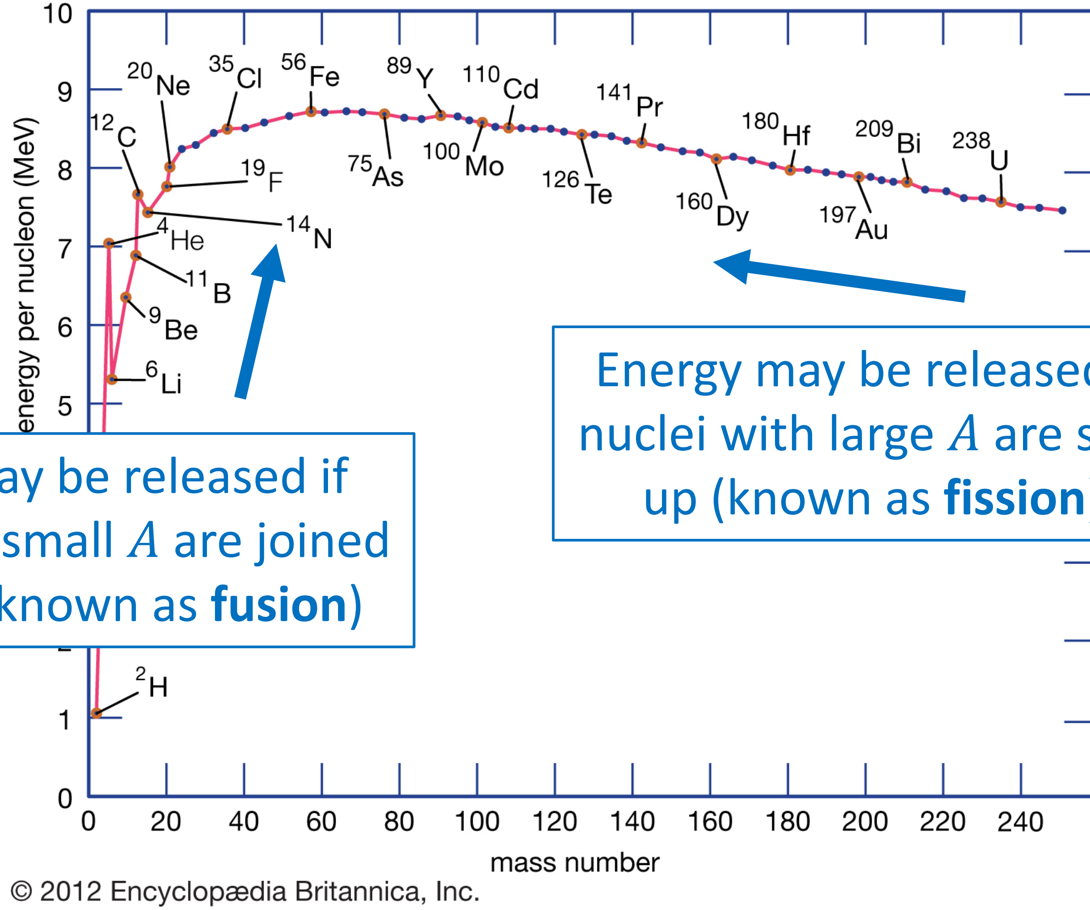
In this class we will describe how energy can be released through nuclear fusion, and its practical applications in the Sun and fusion reactors



Producing energy by fusion

- Recall again the plot of the variation of the **binding energy per nucleon**, B/A, with the **number of nucleons**, A:

Increasing binding energy is equivalent to **releasing** energy

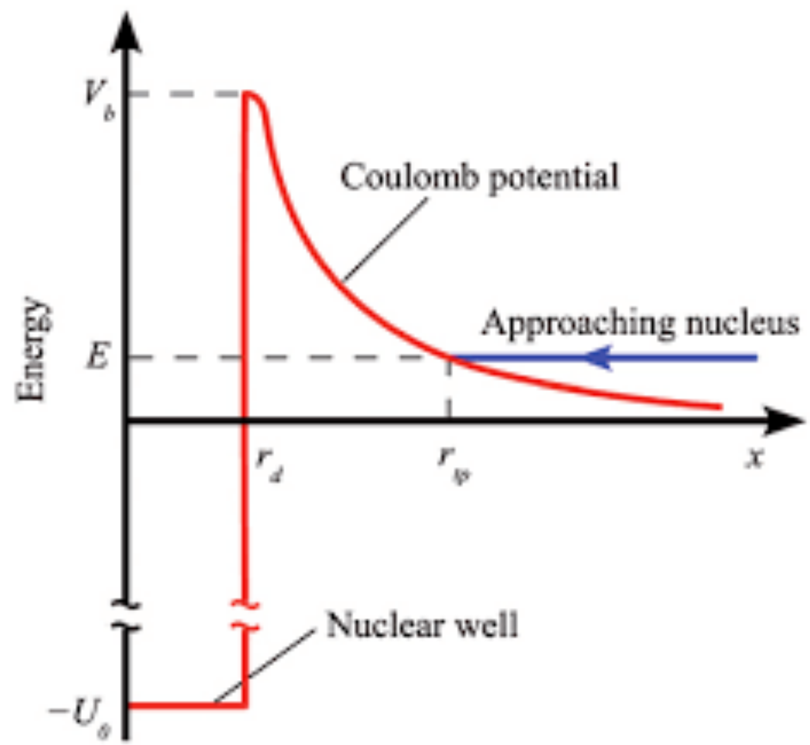


Energy may be released if nuclei with small A are joined together (known as **fusion**)

Energy may be released if nuclei with large A are split up (known as **fission**)

Producing energy by fusion

- **Nuclear fusion** is a process in which two light nuclei merge, releasing energy
- Since nuclei are positively charged, they need to overcome the **Coulomb repulsion barrier** before they can fuse
- Similar to α-decay, this is made possible by **quantum tunneling** – but requires extreme energies

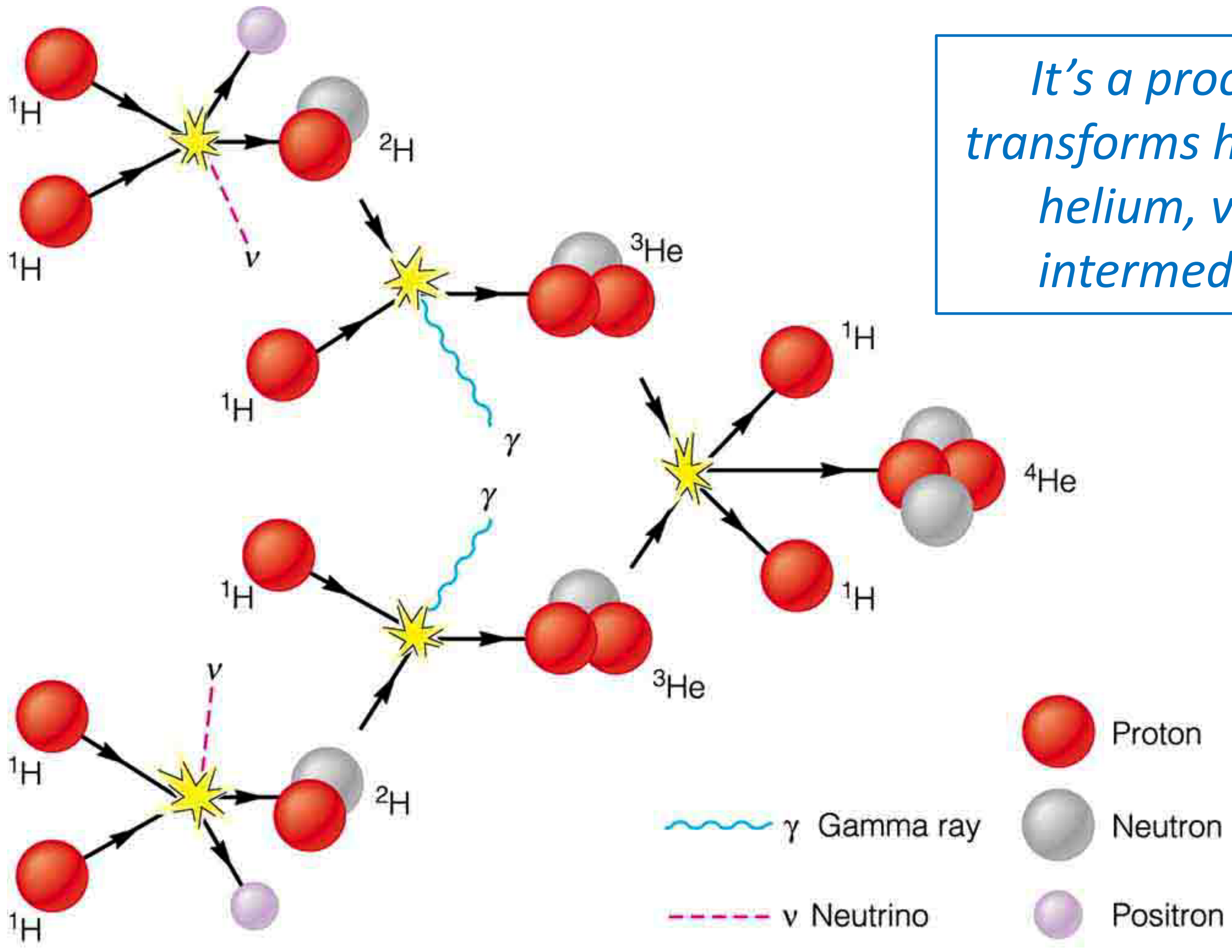


Credit: http://ursula.chem.yale.edu/~batista/

Nuclear fusion in the Sun

- The Sun produces energy through nuclear fusion by a set of reactions known as the **proton-proton chain**

It's a process which transforms hydrogen into helium, via several intermediate steps



Nuclear fusion in the Sun

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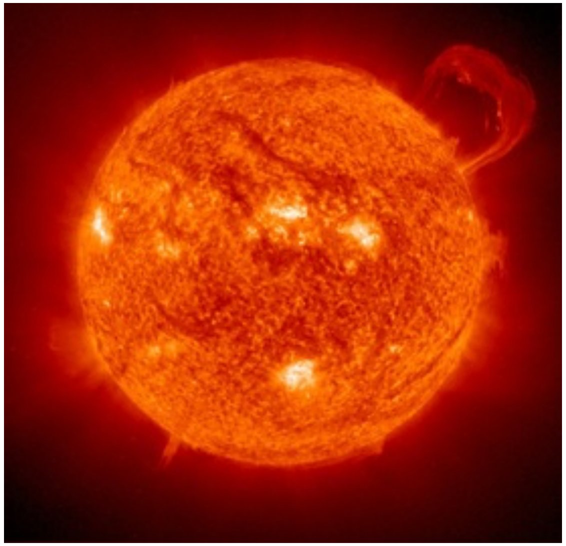
The reaction chain

$$^{1}\mathrm{H} + {}^{1}\mathrm{H} \rightarrow {}^{2}\mathrm{H} + e^{+} + \nu_e$$
$$e^{-} + e^{+} \rightarrow 2\gamma$$
$$^{1}\mathrm{H} + {}^{2}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \gamma$$
$$^{3}\mathrm{He} + {}^{3}\mathrm{He} \rightarrow {}^{4}\mathrm{He} + {}^{1}\mathrm{H} + {}^{1}\mathrm{H}$$



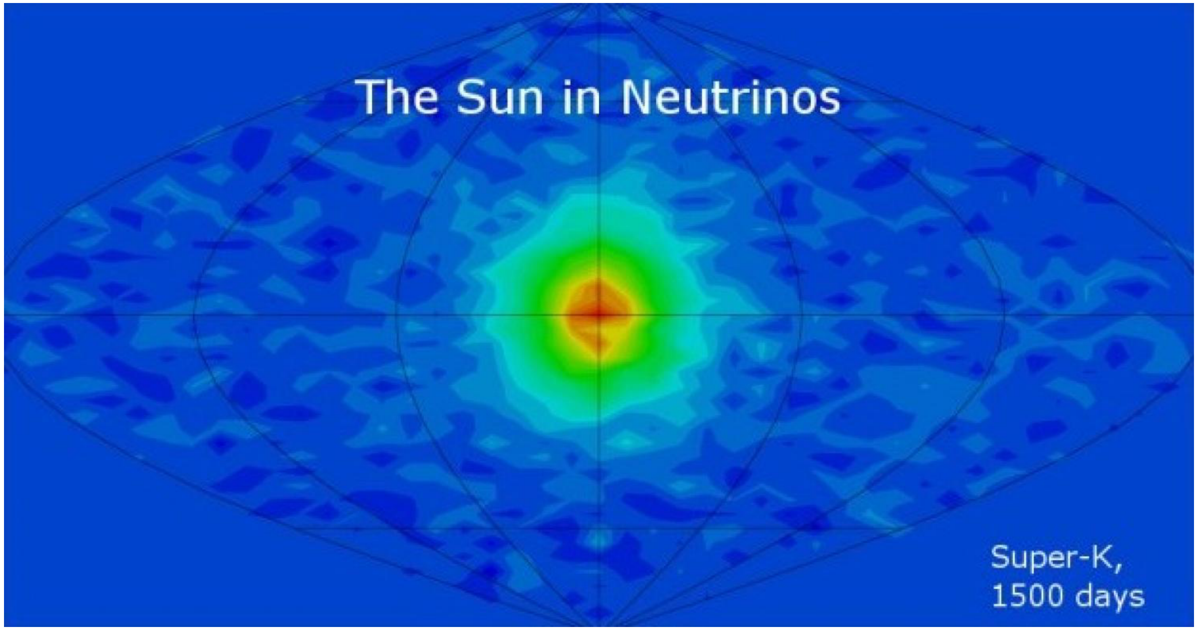
- The reaction fuses hydrogen nuclei into helium nuclei, with the release of **neutrinos** and **photons**

- Releases $\mathbf{26.7\ MeV}$ **of energy** per helium nucleus formed

Nuclear fusion in the Sun

- We are bathed in a sea of neutrinos from this reaction – *670 trillion per second per square metre* at the Earth!

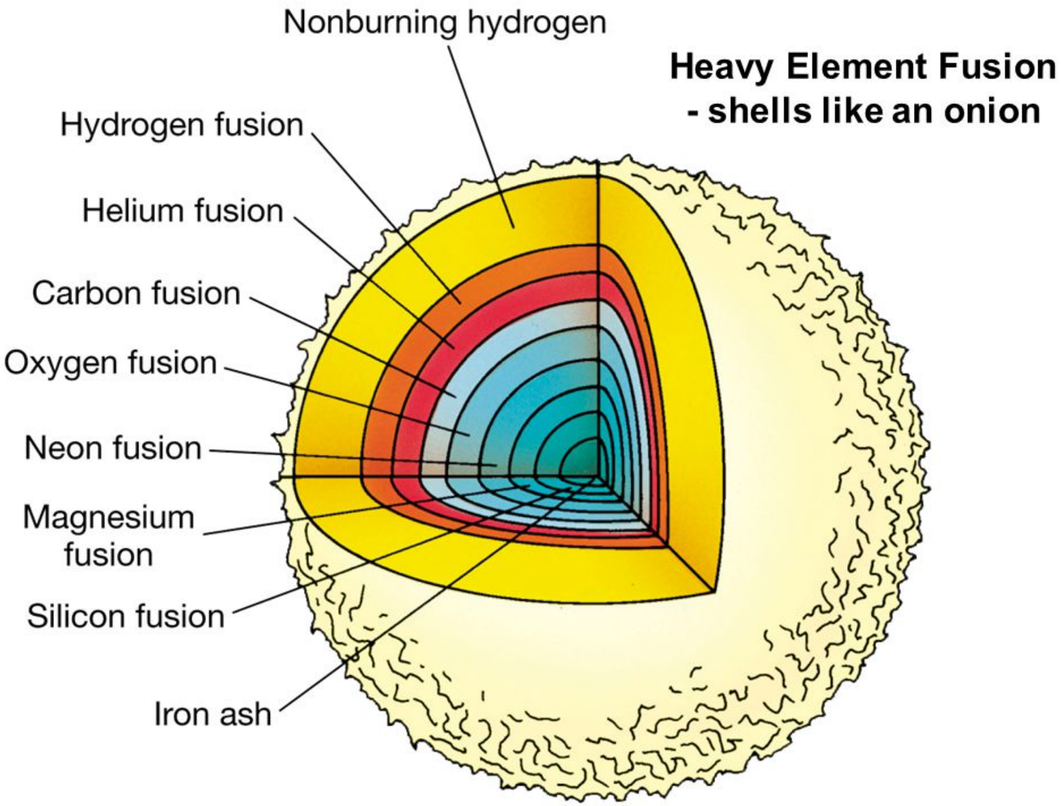
- We can even image the Sun in neutrino light … through the Earth!



Credit: https://www.colorado.edu/today/2020/04/15/neutrinos

Nuclear fusion in the Sun

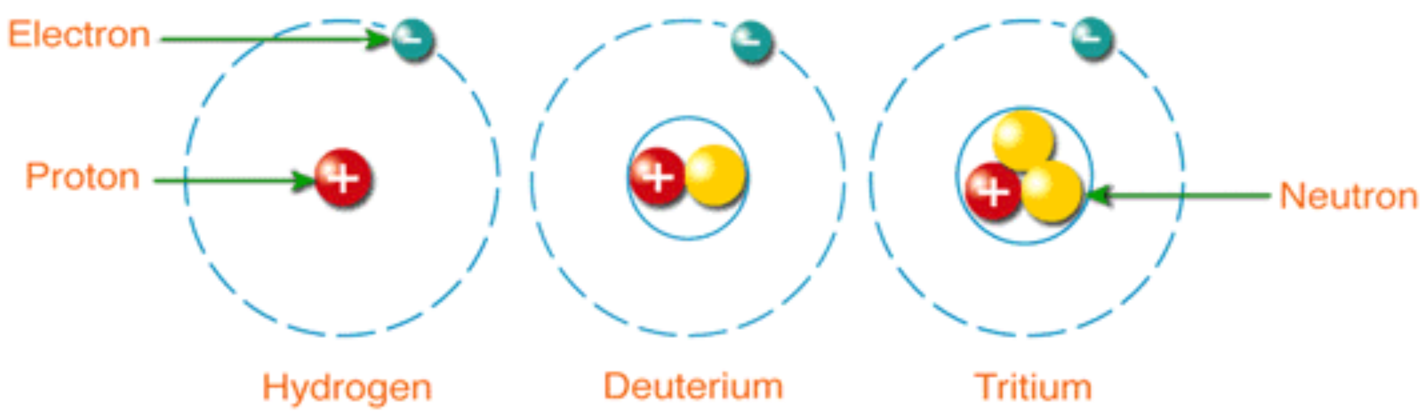
- When stars exhaust their hydrogen fuel, the resulting helium will start to fuse into heavier elements – creating a **series of shells** all the way up to the most stable element, iron!



This is a snapshot in the evolution of a massive star – the Sun will not be able to sustain the burning of heavier elements

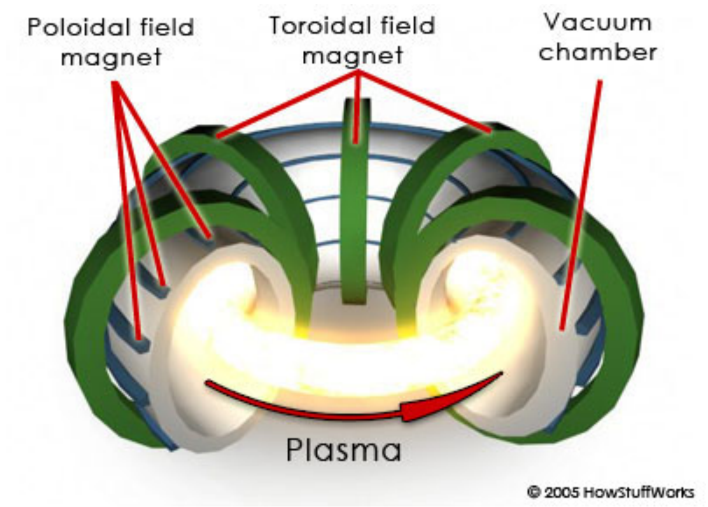
Nuclear fusion reactors on Earth

- *Will nuclear fusion solve our energy needs?*
- **Problem 1**: ${}^{1}H - {}^{1}H$ fusion is a reaction with a *very low probability* of occurring (since there is no state ${}^{2}He$ … we need some neutrons!) It's only feasible in the Sun due to the huge number of collisions occurring
- The solution is to instead fuse **deuterium** (${}^{2}H$) and/or **tritium** (${}^{3}H$), which have higher reaction cross-sections



Nuclear fusion reactors on Earth

- **Problem 2:** We need to create a necessary combination of *temperature* ($\sim 10^8$ K), *density* and *time* to enable *ignition* (that is, self-sustaining reactions)
- This has proved incredibly difficult to achieve in practice. The most promising techniques use **magnetic confinement** or **laser inertial confinement**



Credit: https://science.howstuffworks.com

Some exciting nuclear fusion experiments are currently in progress, such as ITER (https://www.iter.org) – but the breakthrough always feels like a few years away!

Key take-aways

- The fusion (amalgamation) of small nuclei **releases energy** by increasing the binding energy per nucleon
- This is the process by which the Sun generates energy, through the **proton-proton chain**
- The proton-proton chain also releases copious quantities of **neutrinos**
- Generating laboratory nuclear fusion requires other isotopes to be used – **deuterium** and **tritium**
- However, it is very challenging to achieve sufficient **confinement** (temperature, density, time)