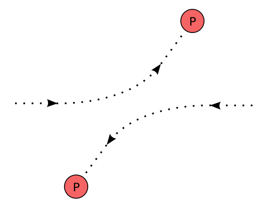
Ast 4 Lecture 12 Notes

1 Fusion in the core

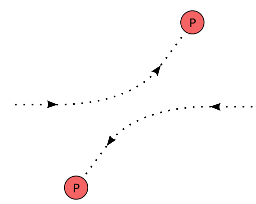
Inside the core

- Temperature $\sim 1.5 \times 10^7$ K
- Hydrogen and Helium in the form of **plasma**
- Plasma: positively charged ions and free electrons
- Due to the high temperatures electrons are no longer attached to nuclei

- Positively charged nuclei moving at high speeds
- Like charges repel
- The closer nuclei come together $\rightarrow$ stronger the repulsive force



- If the distance between nuclei $< 10^{-15}$m, the **strong nuclear force** overpowers the electromagnetic repulsion
- temperature and pressure in core allow fusion of hydrogen nuclei

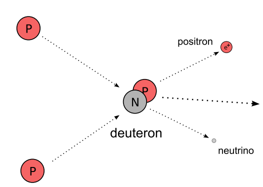


2 Proton-proton chain

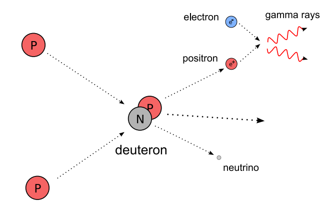
2.1 Step 1

Step 1

- Two protons fuse to form a **deuteron** releasing a **positron** and **neutrino**
- A deuteron is a nucleus of a isotope of hydrogen called *deuterium* (^{2}H)
- A deuteron consists of a proton and a neutron
- $^1\text{H} + {}^1\text{H} \rightarrow {}^2\text{H} + e^+ + \nu + \text{energy}$



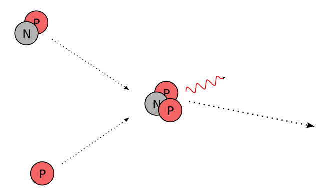
Step 1



- A positron is the *antiparticle* of an electron
- identical to electron except has a positive charge
- when a positron and an electron meet they annihilate each other producing gamma ray photons
- $e^+ + e^- \rightarrow 2\gamma$

2.2 Step 2

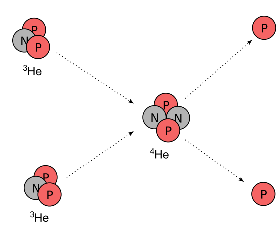
Step 2



- A proton interacts and fuses with a deuteron producing a helium-3 (^{3}He) nucleus
- Energy is emitted in the form of a gamma-ray photon
- $^1\text{H} + {}^2\text{H} \rightarrow {}^3\text{He} + \gamma + \text{energy}$

2.3 Step 3

Step 3



- Final step is the production of helium-4 nuclei
- two helium-3 nuclei fuse to form one helium-4 nucleus plus two protons
- $^3\text{He} + {}^3\text{He} \rightarrow {}^4\text{He} + {}^1\text{H} + {}^1\text{H} + \text{energy}$

2.4 Total Reaction

Total reaction

- $4\,{}^1\text{H} \rightarrow {}^4\text{He} + 2\,e^+ + 2\,\nu + 2\,\gamma + \text{energy}$
- *Where did the energy come from?*

2.5 Energy

Energy and Mass

- Mass of a proton is 1.6726×10^{-27} kg
- The mass of 4 protons is 6.6904×10^{-27} kg
- However the mass of a ^{4}He nucleus is 6.6447×10^{-27} kg
- Mass of ^{4}He $-$ mass of 4 protons $= -4.57 \times 10^{-29}$ kg
- *Where did the mass go?*

Einstein's famous equation

$$E = mc^2$$

or

$$\text{energy} = \text{mass} \times (\text{speed of light})^2$$

The missing mass was converted into energy

- mass of ^{4}He $-$ mass of 4 protons $= -4.57 \times 10^{-29}$ kg which is about 0.7% of the original mass
- Using $E = mc^2$ we can calculate the energy produced during the proton-proton chain

$$\begin{aligned} E &= mc^2 \\ &= (4.57 \times 10^{-29}\ \text{kg})(3 \times 10^{8}\ \text{m/s})^2 \\ &= 4.11 \times 10^{-12}\ \text{kg m/s} \\ &= 4.11 \times 10^{-12}\text{J} \end{aligned}$$

Fusion of 6.69×10^{-27} kg of hydrogen produces 4.11×10^{-12} J of energy

3 interior

3.1 Hydrostatic Equilibrium

Hydrostatic equilibrium

- **Hydrostatic Equilibrium**: outward pressure balances inward pull of gravity
- Sun is massive → gravitational pull is very strong → very high internal pressure needed
- High pressure requires very high central temperature

Hydrostatic equilibrium

Hydrostatic equilibrium keeps the fusion process at a constant rate (like a thermostat)

Scenario 1:

- If the fusion process where to speed up → more energy would be produced and pressure would increase
- This added pressure would cause the core to expand and cool, and the fusion rate would slow down to normal

Hydrostatic equilibrium

Hydrostatic equilibrium keeps the fusion process at a constant rate (like a thermostat)

Scenario 2:

- If the core temperature were to drop → decrease in fusion rate
- The pressure would decrease and the core would contract
- As the core shrank → temperature would increase → fusion rate would return to normal

Hydrostatic equilibrium

- Energy produced by fusion travels toward the surface at a steady rate
- The amount of energy leaving the top of a gas layer is equal to the energy entering the bottom