Physics 2D Lecture Slides
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2D Quiz 1

Quiz Grade

# of people

0 2 4 6 8 10 12 14 16 18 20 More

Frequency
Nuclear Fusion: What Powers the Sun

Opposite of Fission
Mass of a Nucleus < mass of its component protons+Neutrons
Nuclei are stable, bound by an attractive "Strong Force"

Think of Nuclei as molecules and proton/neutron as atoms making it

Binding Energy: Work/Energy required to pull a bound system (M) apart leaving its components (m) free of the attractive force and at rest:

\[ Mc^2 + BE = \sum_{i=1}^{n} m_i c^2 \]

\[ ^4_2\text{He} + 23.9 \text{ MeV} = ^2_1\text{H} + ^2_1\text{H} \]
Helium Deuterium Deuterium

Think of energy released in Fusion as \textbf{Dissociation energy} in Chem

Sun's Power Output = \(4 \times 10^{26}\) Watts \(\Rightarrow 10^{38}\) Fusion/Second

No wonder Sun is considered a God in many cultures!
Nuclear Fusion: Wishing For The Star

• Fusion is eminently desirable because
  – More Energy/Nucleon
    • (3.52 MeV in fusion Vs 1 MeV in fission)
    • $^2\text{H} + ^3\text{H} \rightarrow ^4\text{He} + \text{n} + 17.6$ MeV
  – Relatively abundant fuel supply
  – No danger like nuclear reactor going supercritical

• Unfortunately technology not commercially available
  – What’s inside nuclei => protons and Neutrons
  – Need Large KE to overcome Coulomb repulsion between nuclei
    • About 1 MeV needed to bring nuclei close enough together for Strong Nuclear Attraction $\rightarrow$ fusion

• Need to
  – heat particle to high temp such that $kT \approx 10$keV $\rightarrow$ tunneling
  – High density plasma at high temp $T \approx 10^8$ K like in stars
  – Confine Plasma ($\pm$ ions) long enough for fusion
    » In stars, enormous gravitational field confines plasma
Pellet of frozen-solid Deuterium & tritium bombarded from all sides with intense pulsed laser beam with energy $\approx 10^6$ Joules lasting $10^{-8}$ S

Momentum imparted by laser beam compresses pellet by $1/10000$ of normal density, heats it to temp $T \approx 10^8$ K for $10^{-10}$ S

Burst of fusion energy transported away by liquid Li
Size of football field, 3 stories tall

Generates $1.0 \times 10^{14}$ watts (100 terawatts)

10 laser beams converge onto H pellet (0.5mm diam)

Fusion reaction is visible as a starlight lasting $10^{-10}$ S

Releasing $10^{13}$ neutrons
Dirac 1930: Combined relativity with Quantum Mechanics

- All negative energy states filled with electrons in a negative energy sea
- Rules prevent electron from jumping into negative energy states
- But if an electron from negative-energy sea is given \( E > 2mc^2 \)
  - Can jump out of sea and become an electron of positive energy
  - Leaves behind a positive charged HOLE which behaves like a particle of positive charge \( \Rightarrow \) POSITRON
- Positron is antiparticle of Electron,
- All particles must have anti-particles

\[
E^2 = p^2c^2 + (mc^2)^2
\]

\[\Rightarrow E = \pm \sqrt{p^2c^2 + (mc^2)^2}\]

We conveniently took the +E solution?
What does the -E solution imply?

In Nature if something is allowed is allowed, it must happen

Anti Matter!

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Tweeduldum and Tweedleddee
A positron from Outer space (Cosmic Ray) captured on photographic plate:

\[ E = \pm \sqrt{p^2 c^2 + (mc^2)^2} \]

Anderson 1931, Nobel Prize
Creating matter-antimatter:

\[ \gamma \rightarrow e^+ e^- \]

Annihilating matter-antimatter:

\[ e^+ + e^- \rightarrow \gamma \]

Making baby universes:

Go back to environment when the Universe was very young

Observe it
Large Electron-Positron Collider
Matter-Antimatter Collider Detector

Concentric Onion-like Shells of Precision "camera"
Measures Momentum & Energy of Particles

- Muon/Hadron Detector
- Magnet Coil
- Electron/Photon Detector
- Cherenkov Detector
- Tracking Chamber
- Support Tube
- Vertex Detector
ALEPH Detector At CERN
Very Fast Signal Readout (DAQ)
Reconstructing Decay of a $\pi^+$ Meson

The decay of a stationary $\pi^+ \rightarrow \mu^+ \nu$ happens quickly, $\nu$ is invisible, has $m \approx 0$; $\mu^+$ leaves a trace in a B field

$\mu^+$ mass=106 MeV/c$^2$, KE = 4.6 MeV

What was mass of the fleeting $\pi^+$?

Energy Conservation:

$$E_\pi = E_\mu + E_\nu \Rightarrow m_\pi c^2 = \sqrt{(m_\mu c^2)^2 + p_\mu^2 c^2} + p_\nu c$$

Momentum Conservation: $p_\mu = p_\nu$

$$\Rightarrow m_\pi c^2 = \sqrt{(m_\mu c^2)^2 + p_\mu^2 c^2} + p_\mu c$$

also $p_\mu^2 c^2 = E_\mu^2 - (m_\mu c^2)^2 = (K_\mu + m_\mu c^2)^2 - (m_\mu c^2)^2$

$$= K_\mu^2 + 2 K_\mu m_\mu c^2$$

Substituting for $p_\mu^2 c^2$ ⇒

$$m_\pi c^2 = \sqrt{m_\mu^2 c^4 + K_\mu^2 + 2 K_\mu m_\mu c^2} + \sqrt{K_\mu^2 + 2 K_\mu m_\mu c^2}$$

Put in all the known #s

$$\Rightarrow m_\pi c^2 = 111MeV + 31MeV = 141MeV$$

$$\Rightarrow m_\pi = 141MeV / c^2$$
THE SEQUENCE OF PARTICLE DECAY
FOLLOWING $e^+ e^-$ ANNIHILATION
My Discovery (1993): Beauty With Strangeness
Two Faced Particle: Matter & Antimatter

Sometimes Matter
Sometimes Antimatter

May help explain why antimatter in the Universe has disappeared

Why Universe is matter dominated