TUESDAY MAY 19
10:45 - 1:15

Formulas provided.
Similar to midterm, but longer.
Nucleosynthesis:
Environment: Big Bang, Stellar Fusion, Supernovae
Reactions: PP, CNO, 3α, s-process & r-process
Supernova in galaxy M51, 2005
Supernova in galaxy M51, 2005
And another in 2011!
A Supernova Remnant

The Crab Nebula
Neutron Stars

All stars more massive than 8 $M_{\text{Sun}}$ explode as supernovae. Their protons & electrons combine to give neutrons. A **neutron star**, is comparable to a giant atomic nucleus.

Mass: a few $M_{\text{Sun}}$
Density: $\rho \sim 10^{18} \text{ kg/m}^3$

$g_{\text{NS}} \sim 2 \times 10^{12} \text{ m/s}^2$

Don’t spill your coffee on a Neutron Star!! It will hit the floor with velocity: $v = 2 \times 10^6 \text{ m/s}$
K.E = $0.5 \times (0.25 \text{ kg}) (4 \times 10^{12}) \text{ J} = 500 \text{ billion Joules}$
$\sim 100 \text{ tons TNT}$
Neutron Stars: Theory

Only 2 years after the discovery of the neutron, W. Pauli (who proposed the neutrino) & W. Baade proposed that “neutron stars” should exist, resulting from supernovae.

They would be supported by Neutron Degeneracy Pressure.
Neutrinos react very rarely. Their signal is swamped by other reactions, e.g., cosmic rays...unless these contaminants are shielded out. So place your detector underground.

A neutrino from this PP reaction:

Might collide with a Chlorine atom:

You'll need a lot of Cl!
MSW Effect

Neutrinos react very rarely. Their signal is swamped by other reactions, e.g., cosmic rays...unless these contaminants are shielded out.

So place your detector underground.

A neutrino from this PP reaction:

Might collide with a Chlorine atom:

You'll need a lot of Cl!

---

**FUNDAMENTAL PARTICLES**

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory of weak and electromagnetic interactions (electroweak). Gravity is included on this page.

### FERMIONS

**Leptons**

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Mass GeV/c²</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e$ (electron neutrino)</td>
<td>$\leq 1 \times 10^{-8}$</td>
<td>0</td>
</tr>
<tr>
<td>$e^-$ (electron)</td>
<td>0.000511</td>
<td>-1</td>
</tr>
<tr>
<td>$\nu_\mu$ (muon neutrino)</td>
<td>$\leq 0.0002$</td>
<td>0</td>
</tr>
<tr>
<td>$\mu^-$ (muon)</td>
<td>0.106</td>
<td>-1</td>
</tr>
<tr>
<td>$\nu_\tau$ (tau neutrino)</td>
<td>$\leq 0.02$</td>
<td>0</td>
</tr>
<tr>
<td>$\tau^-$ (tau)</td>
<td>1.7771</td>
<td>-1</td>
</tr>
</tbody>
</table>

**Quarks**

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Approx. Mass GeV/c²</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u^+$ (up)</td>
<td>0.003</td>
<td>2/3</td>
</tr>
<tr>
<td>$d^-$ (down)</td>
<td>0.006</td>
<td>-1/3</td>
</tr>
<tr>
<td>$c^+$ (charm)</td>
<td>1.3</td>
<td>2/3</td>
</tr>
<tr>
<td>$s^-$ (strange)</td>
<td>0.1</td>
<td>-1/3</td>
</tr>
<tr>
<td>$t^+$ (top)</td>
<td>175</td>
<td>2/3</td>
</tr>
<tr>
<td>$b^-$ (bottom)</td>
<td>4.3</td>
<td>-1/3</td>
</tr>
</tbody>
</table>

**Spin** is the intrinsic angular momentum of particles. Spin is given in units of $\hbar$, which is the quantum unit of angular momentum, where $\hbar = \sqrt{\mu} = 6.58 \times 10^{-29}$ GeV s $= 1.05 \times 10^{-34}$ J s.
Extra-Terrestrial Mystery...

- In 1967, an astronomy graduate student named Jocelyn Bell operated a radio telescope in England.
- She found a source of radio waves pulsating every 1.33 seconds.

...a possible signal from extraterrestrials?

This **Pulsating Radio** source, called a “**Pulsar**”, was determined to be a neutron star.
One of the beams from the rotating neutron star is aimed toward Earth: We detect a pulse of radiation.
Model of a Pulsar
(a rotating Neutron Star)

b  Half a rotation later, neither beam is aimed toward Earth: We detect that the radiation is “off.”
The Lighthouse Model of Pulsars

A **pulsar** is a rotating neutron star. Like a lighthouse beacon, if the beam shines on Earth, then we see a **Pulse** of radio waves.

Neutron star’s magnetic field
Radio telescopes can record radio waves from pulsars.

Pulse periods range from a few seconds down to milliseconds.

The pulses repeat regularly, making them excellent clocks.
The Crab Pulsar

Inside the Crab Supernova Remnant, a **Pulsar** has been found
Pulsar in "off" state

Pulsar in "off" state

1 arcmin
After a supernova explosion, the core that remains is a neutron star.

However… J.R. Oppenhiemer & G. Volkoff (1939) showed that neutron degeneracy pressure cannot resist gravity if \( M_{\text{neutron star}} > 3 \, M_{\odot} \).

So, after a Supernova, if the remaining core exceeds this “Oppenheimer Limit”, it will collapse completely, getting smaller and smaller becoming......

a *BLACK HOLE* !