PHYS 3446 – Lecture #12

Tuesday, March 17, 2012

*Dr. **Brandt***

- Beta Decay
- Neutrinos

Nuclear Radiation: β-Decays

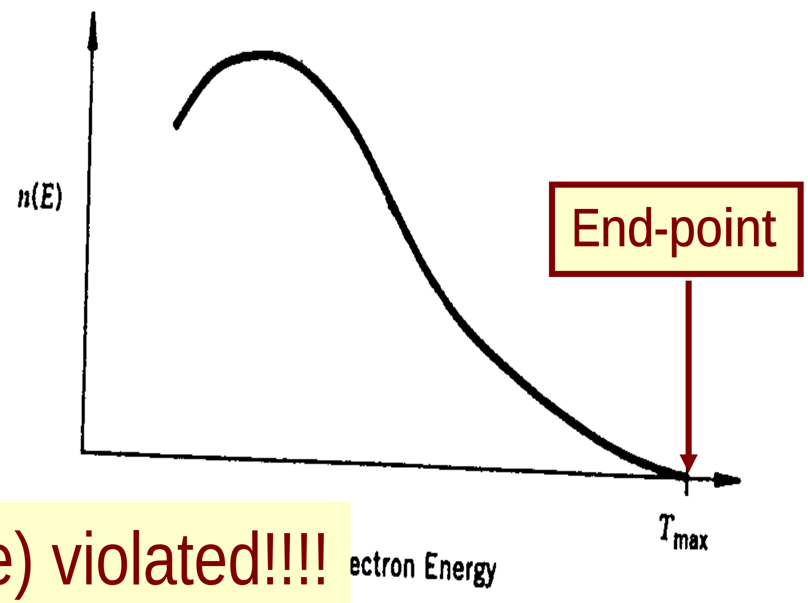
- Initially assumed to be 2-body decay $^{A}X^{Z} \rightarrow {^{A}Y^{Z+1}} + e^{-}$
- From energy conservation

$$E_X = E_Y + E_{e^-} = E_Y + T_e + m_e c^2$$

- Electron carries most of the KE since it is light (low mass)

$$T_e = \left(E_X - E_Y - m_e c^2\right) = \left(m_X - m_Y - m_e\right)c^2 - T_Y = Q - T_Y \approx Q$$

- This results in a prediction of a unique Q value as in α-decay.
- In reality, electrons emitted with continuous E spectrum with an end-point given by the formula above



Energy conservation is (seems to be) violated!!!!

Nuclear Radiation: β-Decays

- What about angular momentum?
- In β-decays total number of nucleons is conserved
  - Recall $|\Delta A|=0$ and $|\Delta Z|=1$ in β-decays
- Electrons are fermions with spin $\hbar/2$
- Independent of any changes of an integer orbital angular momentum, the total angular momentum cannot be conserved
  - How much will it always differ by? $\hbar/2$
- Angular momentum conservation is (seems to be) violated!!!

Nuclear Radiation: β-Decays

- In 1931 Pauli postulated an additional particle emitted in β-decays to "save" conservation of energy and angular momentum
  - Charge is conserved in β-decays
    - Electrically neutral
  - Maximum energy of electrons is the same as the Q value
    - Massless
  - Must conserve angular momentum
    - Must be a fermion with spin $\hbar/2$
- This particle was called neutrino (by Feynman) and expressed as ν
  - No one had observed this particle in experiments
    - Difficult to detect
    - First observation of ν_e in 1956, ν_μ in 1962 and ν_τ in 1977 (direct 2000)

Nuclear Radiation: Neutrinos

- Have anti-neutrinos $\bar{\nu}$ (all particles have anti's)
- Neutrinos and anti-neutrinos are distinguished through the spin projection on momentum
  - Helicity is used to distinguish them $H \propto \vec{p} \cdot \vec{s}$
    - Left-handed (spin and momentum opposite direction) anti-electron-neutrinos are produced in β-decays
    - Right-handed electron-neutrinos are produced in positron emission
  - e^- is a particle and e^+ is the anti-particle to e^-
  - ν_e is a particle and $\bar{\nu}_e$ is the anti-particle to ν_e

β–Decay Reaction Equations with Neutrinos

- Electron emission

$$^{A}X^{Z} \to {}^{A}Y^{Z+1} + e^{-} + \bar{\nu}_{e}$$

- Positron emission

$$^{A}X^{Z} \to {}^{A}Y^{Z-1} + e^{+} + \nu_{e}$$

- Electron capture

$$^{A}X^{Z} + e^{-} \to {}^{A}Y^{Z-1} + \nu_{e}$$

why no positron capture?

β-Decays with neutrinos

- If the parent nucleus decays from rest, from the conservation of energy

$$M_p c^2 = T_D + M_D c^2 + T_{e^-} + m_e c^2 + T_{\bar{\nu}_e} + m_{\bar{\nu}_e} c^2$$

- Thus the Q-value of a β-decay can be written

$$T_D + T_{e^-} + T_{\bar{\nu}_e} = \left(M_p - M_D - m_e - m_{\bar{\nu}_e}\right)c^2 = \Delta M c^2 = Q$$

- Electron emission can only occur if Q>0
- Neglecting all small atomic BE, e emission can occur if

$$Q = \left(M\left(A,Z\right) - M\left(A,Z+1\right) - m_e - m_{\bar{\nu}_e}\right)c^2$$

$$\approx \left(M\left(A,Z\right) - M\left(A,Z+1\right)\right)c^2 \geq 0$$

β-Decays with neutrinos

- Since the daughter nucleus is much heavier than e or ν, the small recoil energy of daughter can be ignored
  - Thus we can obtain $T_{e^-} + T_{\bar{\nu}_e} \approx Q$
- This means that the energy of the electron is not unique and can be any value in the range $0 \le T_{e^-} \le Q$
  - The maximum the electron K.E. can be is Q
  - This is the reason why the electron energy spectrum is continuous and has an end point (=Q)
- The same applies to the other two β-decays

Particle Numbers

- Baryon numbers: A quantum number assigned to baryons (protons, neutrons…) {proton decay??}
  - Mostly conserved in many interactions (sounds fuzzy, will return to this point later)
  - Baryons: +1
  - Anti-baryons: -1
  - Protons and neutrons are baryons with baryon number +1 each
- Hadrons are strongly interacting particles (all baryons are hadrons, but not vice-versa)
- Baryons consist of three quarks
- Mesons consist of a quark and an anti-quark

Particle Numbers

- Lepton numbers: A quantum number assigned to leptons (electrons, muons, taus and their corresponding neutrinos)
  - Leptons: +1
  - Anti-leptons: -1
  - Must be conserved at all times under SM in each species

Lepton Numbers

- Three charged leptons exist in nature with their own associated neutrinos

$$\begin{pmatrix} e^- \\ \nu_e \end{pmatrix} \quad \begin{pmatrix} \mu^- \\ \nu_\mu \end{pmatrix} \quad \begin{pmatrix} \tau^- \\ \nu_\tau \end{pmatrix}$$

- These three types of neutrinos are distinct from each other
  - muon neutrinos never produce other leptons than muons or anti-muons

$$\nu_\mu + {}^A X^Z \rightarrow {}^A Y^{Z+1} + \mu^-$$

$$\nu_\mu + {}^A X^Z \not\rightarrow {}^A Y^{Z+1} + e^-$$

$$\nu_\mu + {}^A X^Z \not\rightarrow {}^A Y^{Z+1} + \tau^-$$

Lepton Numbers

For electron neutrinos

$$\nu_e + {}^A X^Z \rightarrow {}^A Y^{Z+1} + e^-$$

$$\nu_e + {}^A X^Z \not\rightarrow {}^A Y^{Z+1} + \mu^-$$

$$\nu_e + {}^A X^Z \not\rightarrow {}^A Y^{Z+1} + \tau^-$$

For tau neutrinos

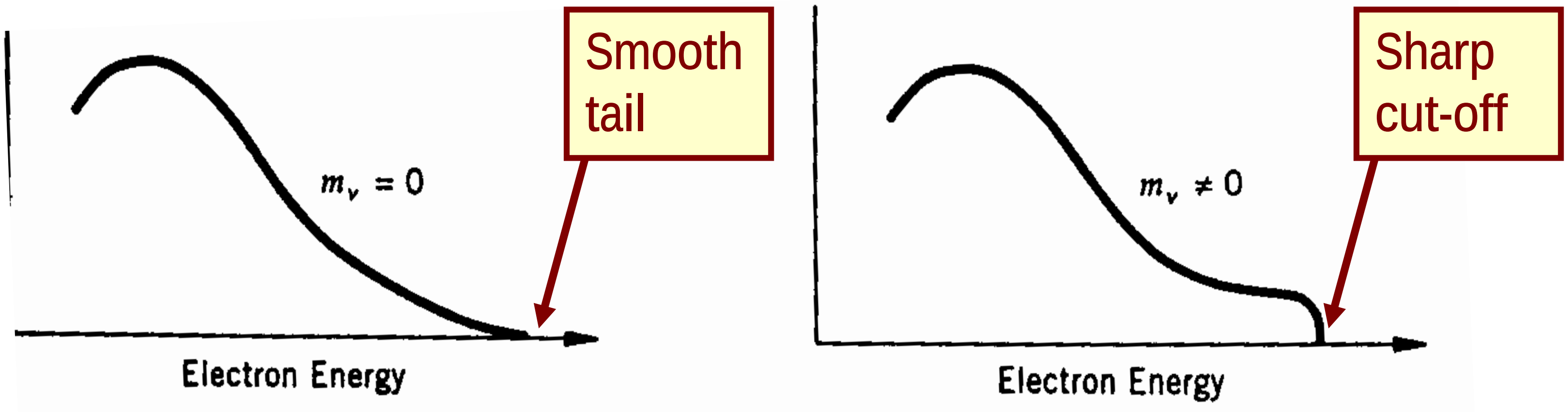
$$\nu_\tau + {}^A X^Z \rightarrow {}^A Y^{Z+1} + \tau^-$$

$$\nu_\tau + {}^A X^Z \not\rightarrow {}^A Y^{Z+1} + e^-$$

$$\nu_\tau + {}^A X^Z \not\rightarrow {}^A Y^{Z+1} + \mu^-$$

Neutrino Mass

- What does neutrino mass do to the β-spectrum?



- The higher end tail shape depends on the mass of the neutrino
  - β-spectrum could be used to measure the mass of neutrinos
    - Very sensitive to the resolution of the device
  - Most stringent direct limit is $m_\nu < 2 eV/c^2$
- Non-zero mass of the neutrino means
  - Neutrino Oscillation: Mixing of neutrino species

Weak Interactions

- β-decay can be written at the nucleon level as:

$$n \rightarrow p + e^- + \bar{\nu}_e \qquad p \rightarrow n + e^+ + \nu_e \qquad p + e^- \rightarrow n + \nu_e$$

- Since neutrons are heavier than protons, they can decay to a proton in a free space
  - On the other hand, protons are lighter than neutrons therefore they can only undergo a β-decay within a nucleus
  - Life time of a neutron is about 900sec
  - This life time is a lot longer than nuclear reaction time scale 10^{-23} s or EM scale 10^{-16} s.
- This means that a β-decay is a nuclear phenomenon that does not involve strong nuclear or EM forces
- Fermi postulated a new weak force responsible for β-decay

Weak Interactions

- Weak forces are short ranged
  - How do we know this?
    - Occurs in the nuclear domain
    - Weakness of the strength is responsible for long life time seen in β-decays
- Nucleus does not contain electrons
  - Electrons in β-decays must come from somewhere else
  - Electrons are emitted without time delay
    - The electron must come at the time of decay just like the alphas from a nuclear disintegration
  - β-decay can be considered to be induced by the weak force

Weak Interactions

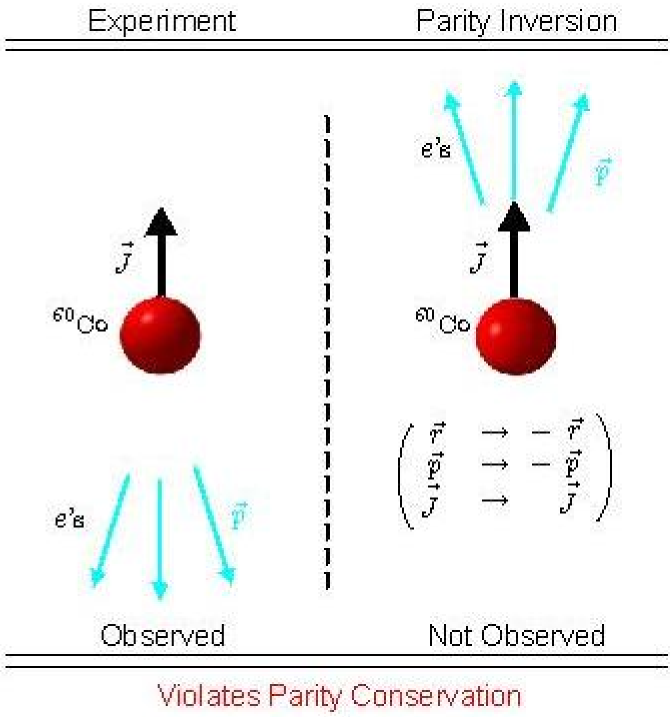
- β-decay can be written at the nucleon level as:

$$n \rightarrow p + e^- + \bar{\nu}_e \qquad p \rightarrow n + e^+ + \nu_e \qquad p + e^- \rightarrow n + \nu_e$$

- Fermi postulated a new weak force responsible for β-decay, due to long lifetimes. Strong:EM:Weak:Gravity 1:10^{-2}:10^{-5}:10^{-40}
- Weak force is relativistic and is also known as four fermion interaction
- Parity:
- A system is parity invariant if it does not change under inversion of spatial coordinates: $\psi(\vec{r}) = \psi(-\vec{r})$ (this was generally assumed to be true)
- The handedness, helicity s·p, should change upon spatial inversion (parity operation) since the direction of motion changes while the spin direction does not $\vec{r} \rightarrow -\vec{r}, \ \vec{p} \rightarrow -\vec{p} \ \Rightarrow \vec{L} = \vec{r} \times \vec{p} = (-\vec{r}) \times (-\vec{p}) = \vec{L}$
- Only left-handed neutrinos and right-handed anti-neutrinos are observed
- Since there are no right handed neutrinos, parity must be violated in weak interactions

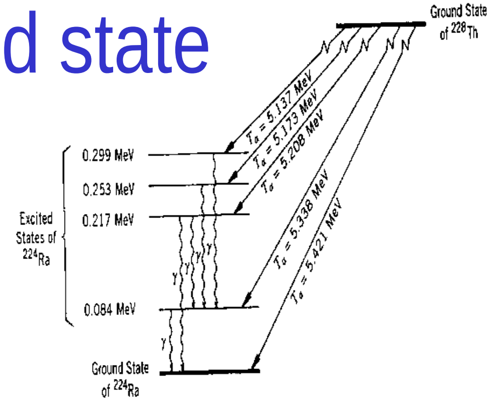
Parity Violation

- Lee+Yang, Wu et al
- observed which direction the electrons were emitted
- inverting coordinate gives same spin but now electrons would be emitted in opposite direction (not observed)



Gamma Decays

- When a heavy nuclei undergo alpha and beta decays, the daughter nuclei are often in an excited state
  - Must either break apart
  - Or emit another particle
  - To bring the daughter into its ground state



- Typical energies of photons in γ-decays are a few MeV's
  - These decays are EM interactions thus the life time is on the order of 10^{-16} sec.
- Photons carry one unit of angular momentum
  - Parity is conserved in this decay