Neutrino-less Double Beta Decay

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PHYS 730
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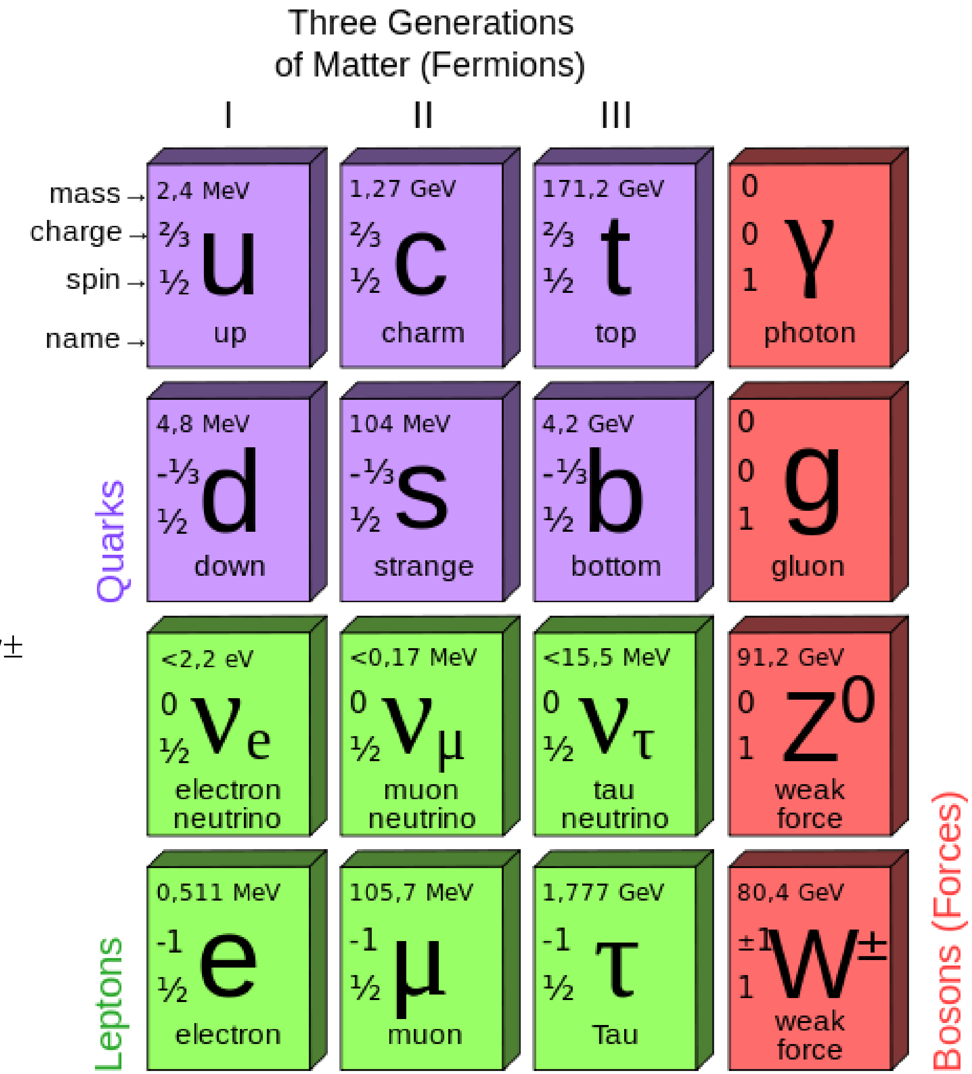
Outline

- The Standard Model
- What is Beta-Decay?
- Beta decay leads to ν discovery
- History of the Neutrino
- Why is 0νββ Important?
- ββ-Decay
- 2νββ vs. 0νββ
- Conclusion

The Standard Model

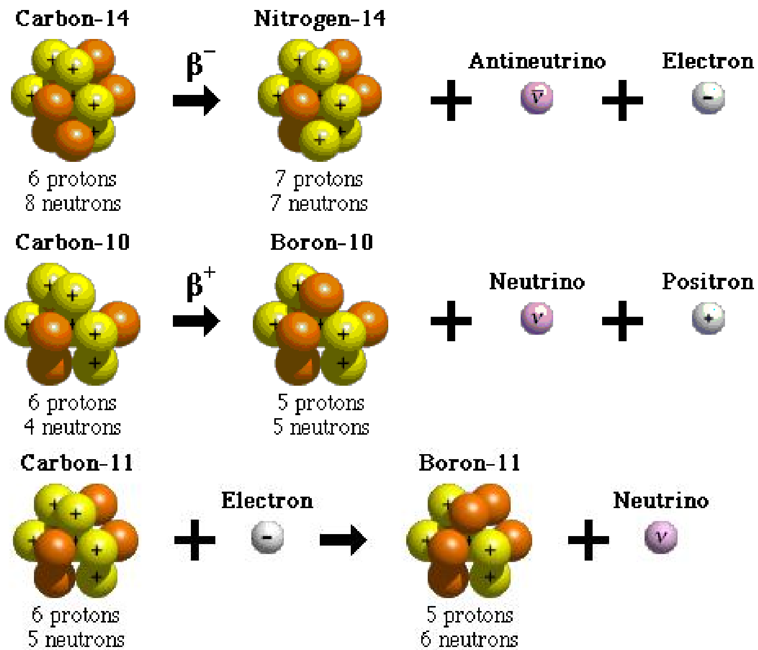
- 16 known particles
- 12 spin ½ fermions
- Quarks & Leptons = Normal Matter
- 4 spin 1 bosons
- Gauge Bosons = Interaction particles
- 3 generations: 2 quarks/2 leptons
- SM predicted 7/16 before discovery:

  Charm, top, bottom, ν_τ, gluon, Z^0 & $W^\pm$
- Theory is good but still has problems

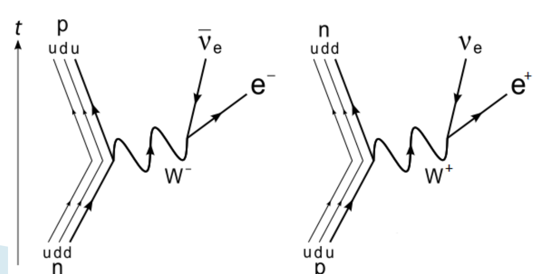


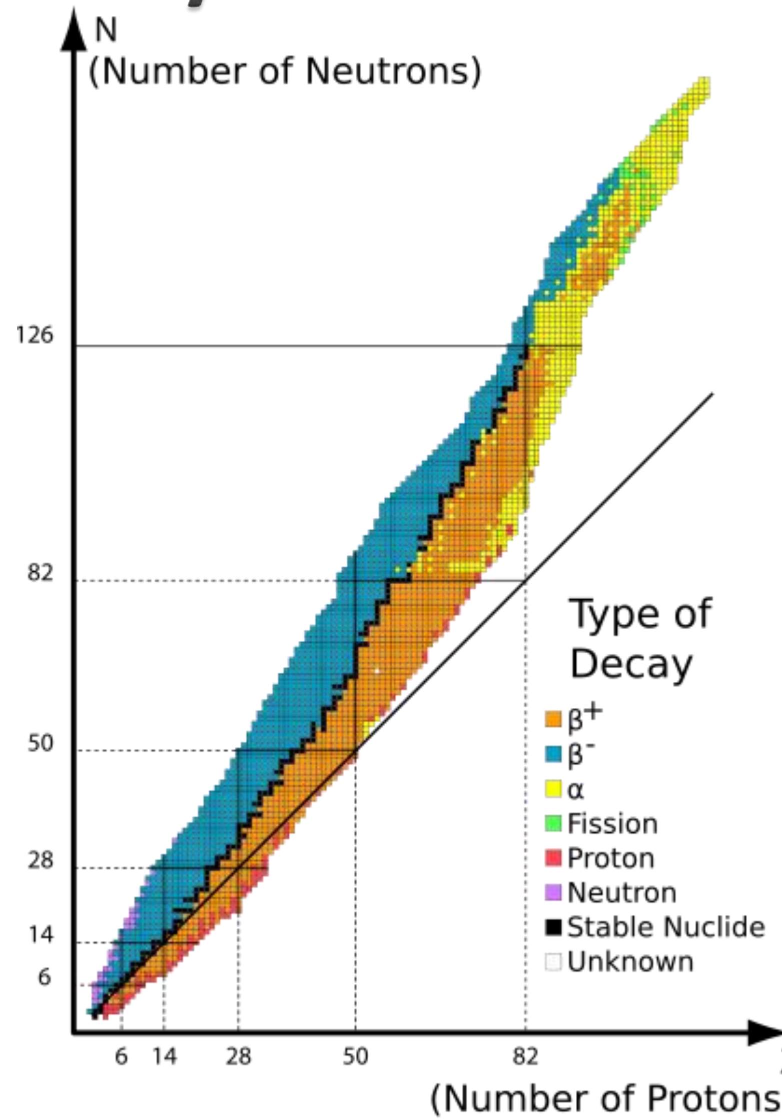
What is Beta-Decay?

- Most common form of radioactive decay
- Nucleon level:

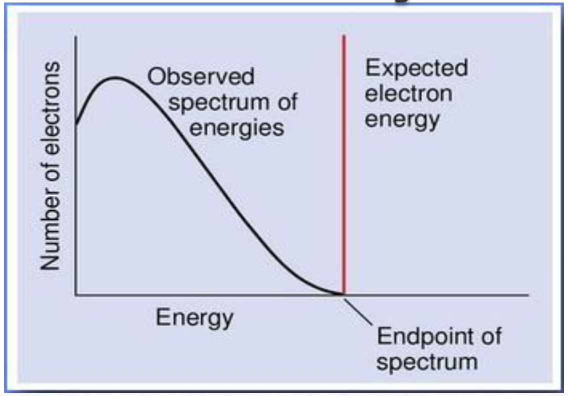


- Quark level:



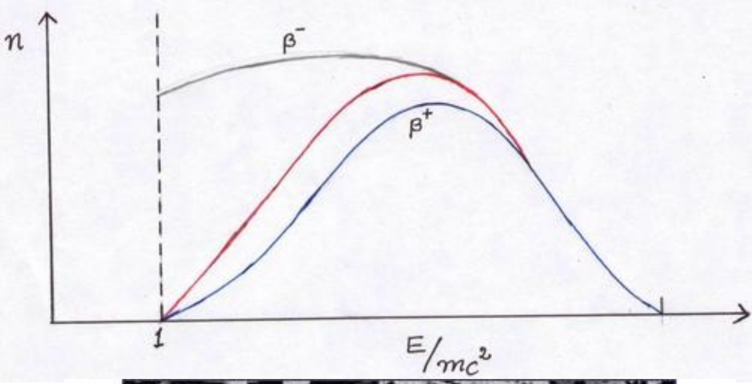


β-Decay leads to neutrino discovery



- Continuous energy spectrum of β-particles
- Exp. spin did not match theory
- 2-body decay: violates conservation of energy and momentum
- 1930: Pauli suggests 3-body decay
- Neutral, spin ½ with little to no mass
- "I have done a terrible thing. I have postulated a particle that cannot be detected."

  -W. Pauli

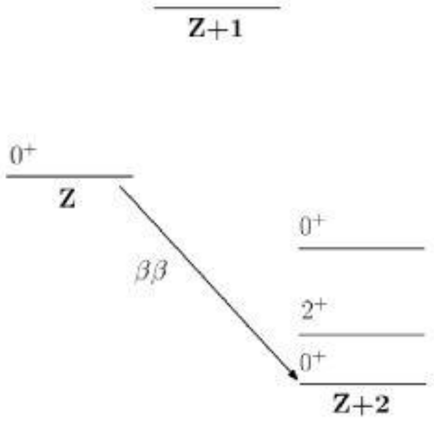


- 1956: Reines and Cowan confirm electron (anti-)neutrino existence $\bar{\nu}_e + p \rightarrow n + e^+$

History of the Neutrino

- 1930 – Pauli postulates the existence of the neutrino to solve beta decay energy and momentum crisis
- 1933 – Fermi's formal theory on beta decay
- 1935 – M. Goppert-Mayer published paper on "Double Beta-Disintegration"
- 1937 – E. Majorana suggests neutrino was indistinguishable from anti-neutrino
- 1937 – Rancah suggests using DBD to test Majorana's theory ($0\nu\beta\beta$)
- 1956 – Discovery of electron neutrino by Reines and Cowan
- 1962 – Discovery of muon neutrino at Brookhaven
- 1968 – Solar neutrino problem
- 1978 – Discovery of Tau lepton at SLAC, inferred existence of tau neutrino
- 1985 – First claim that neutrino are massive (unconfirmed)
- 1989 – Kamiokande confirms solar neutrino deficit
- 1998 – Super-Kamiokande announces evidence of non-zero neutrino mass
- 2000 – Discovery of tau neutrino at Fermi-lab
- 2001/2002 – SNO observes neutral currents for solar neutrinos along with charged currents and elastic scattering
- 2004 – Super-Kamiokande and KamLAND presents evidence for neutrino disappearance and reappearance, eliminating non-oscillation models

ββ-Decay



- Rare decay among isobaric nuclei ($\tau_{1/2}$ ~ 10^{18} - 10^{22} years)
- Simultaneously emits 2β particles via intermediate state
- Only when β-Decay forbidden by energy cons. and/or large change in L
- Situation occurs naturally b/c of "pairing" interaction of nuclei with even A
- Semi-empirical mass formula: $m = Zm_p + Nm_n - \frac{E_B}{c^2}$

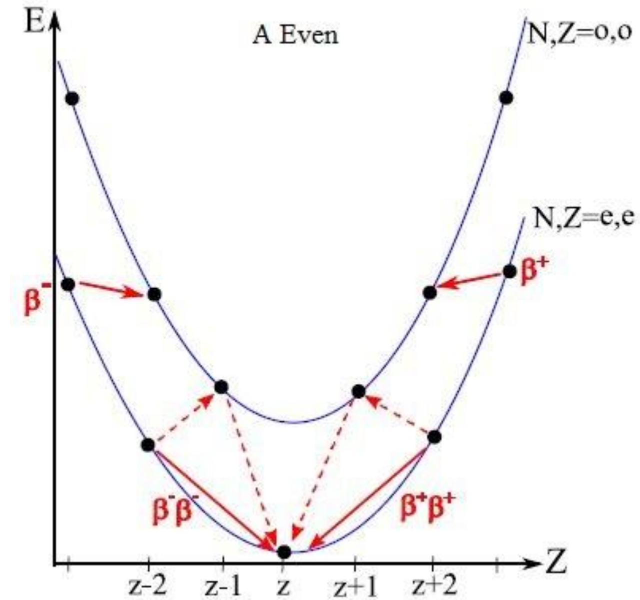
$$E_B = a_V A - a_S A^{2/3} - a_C \frac{Z(Z-1)}{A^{1/3}} - a_A \frac{(A-2Z)^2}{A} + \delta(A,Z)$$

Volume, Surface, Coulomb, Asymmetry, Pairing

$$\delta(A,Z) = \begin{cases} +\delta_0 & Z, N \text{ even } (A \text{ even}) \\ 0 & A \text{ odd} \\ -\delta_0 & Z, N \text{ odd } (A \text{ even}) \end{cases}$$

- Over 60 isotopes capable of DBD, 12 observed:

$$^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd,$$
$$^{128}Te, ^{130}Te, ^{130}Ba, ^{136}Xe, ^{150}Nd, ^{238}U$$



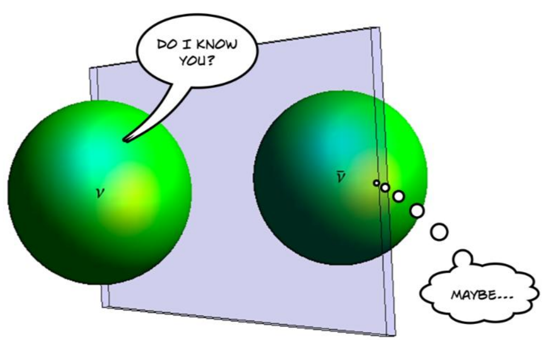
Why is 0νββ Important?

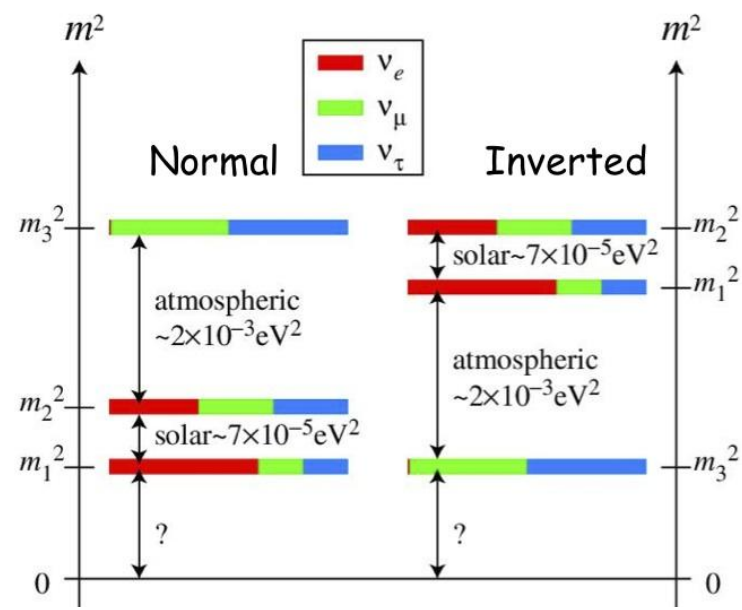
- From atmospheric, solar, and accelerator data, neutrinos oscillate; therefore, they must have mass: $|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle$
- This data yields mass differences and imply 3-mass eigenstates
- Only bounds on the lightest mass eigenstate; at least 0.04 eV
- Two important pieces of information missing about the neutrino
- Are they Majorana or Dirac particles? What is the absolute mass scale?
- 0νββ can be used as a tool to answer these fundamental questions
- Immediate implication of discovery:

Neutrino is a Majorana particle

Total Lepton number is not conserved

Neutrino mass can be determined





2νββ vs. 0νββ

2νββ

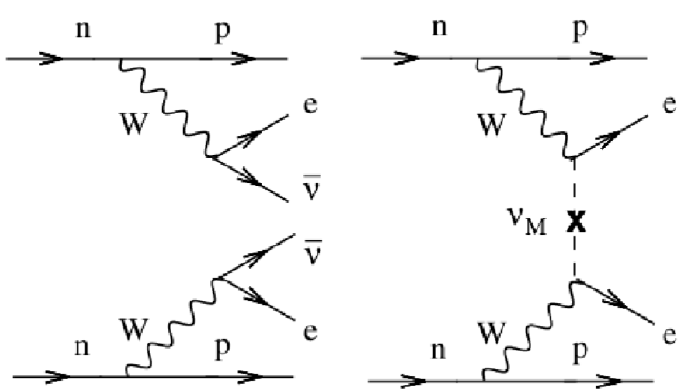
- Allowed by SM and observed exp.
- Imposes no requirements on neutrino properties
- Several decay modes possible:

$$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e \qquad (\beta\beta^-)$$

$$(A,Z) \rightarrow (A,Z-2) + 2e^+ + 2\nu_e \qquad (\beta\beta^+)$$

$$(A,Z) + 2e^- \rightarrow (A,Z-2) + 2\nu_e \qquad (ECEC)$$

$$(A,Z) + e^- \rightarrow (A,Z-2) + e^+ + 2\nu_e \qquad (EC\beta^+)$$



0νββ

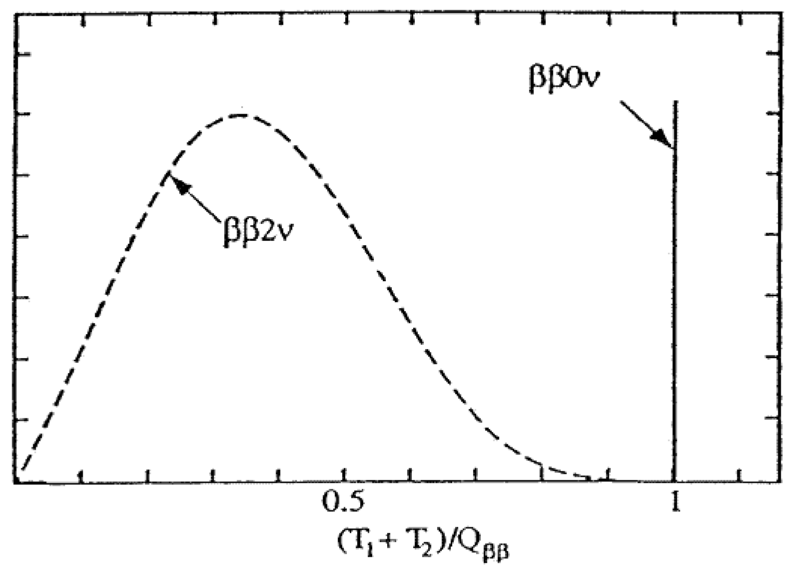
- Not allowed by SM ($\Delta L = 2$)
- Hypothetical/can only happen if:

Mass $\neq 0$, since helicity has to flip

(ν: LH Helicity; $\bar{\nu}$: RH Helicity)

Neutrino is its own anti-particle: $\bar{\nu} = \nu$

- Decay mode: $(A,Z) \rightarrow (A,Z+2) + 2e^-$



Conclusion

- Neutrino properties are important to fundamental questions in physics
- DBD used as a tool to look for currently unknown properties
- Majorana or Dirac particle
- Determine neutrino mass
- This information needed to further adapt understanding of the SM
- Many experimental challenges

- Thank you!
- Questions?