One and the Same? Majorana vs. Dirac

Examining the Difference Between Dirac and Majorana Particles in the Neutrino Sector

Scott Davis

University of Washington

Agenda

- Theory
  - Dirac Equation and Representations
  - Massless Neutrinos
  - Particle/Anti-particle Operator
  - Massive Fermions
- Experimental Searches
  - Beta Decay/Weak Interactions
  - Double Beta Decay

Dirac Representation

$$H\phi = (\alpha \bullet \mathbf{P} + \beta m)\phi$$

$$\phi = \begin{pmatrix} \chi \\ \psi \end{pmatrix}$$

$$\alpha = \begin{pmatrix} 0 & \sigma \\ \sigma & 0 \end{pmatrix}$$

$$\beta = \begin{pmatrix} \mathbf{I} & 0 \\ 0 & -\mathbf{I} \end{pmatrix}$$

$$\alpha = \begin{pmatrix} -\sigma & \mathbf{0} \\ \mathbf{0} & \sigma \end{pmatrix}$$

$$\beta = \begin{pmatrix} \mathbf{0} & \mathbf{I} \\ \mathbf{I} & \mathbf{0} \end{pmatrix}$$

- General Dirac equation has several representations but physics is still the same.
- Dirac-Pauli is most general representation.
- Another representation is the Weyl representation. Useful for helicity.

Massless Neutrinos

$$E\chi = -\sigma \bullet \mathbf{p}\chi$$

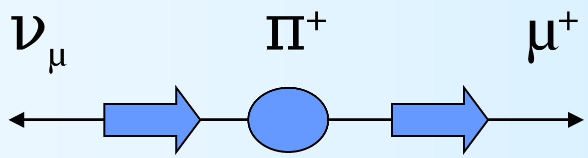
$$E\psi = +\sigma \bullet \mathbf{p}\psi$$

$$J^{\mu} \propto \bar{\phi}_e \gamma^{\mu}(1-\gamma^5)\phi_{\nu}$$

$$(1-\gamma^5)\phi_{\nu} \propto \begin{pmatrix} \mathbf{I} & 0 \\ 0 & 0 \end{pmatrix}\begin{pmatrix} \chi \\ \psi \end{pmatrix} \propto \begin{pmatrix} \chi \\ 0 \end{pmatrix}$$

- For a massless fermion, Dirac equation simplifies into two independent equations using the Weyl representation.
- χ shows that positive E solution has negative helicity (L chirality) and negative E (anti-particle) has positive helicity (R chirality). ψ has the opposite terms.
- For example, charged current weak interaction will only allow χ so only certain helicity is allowed.
- A massive particle is not longer an eigenstate of chirality and helicity can also change with a proper boost.

Charged Pion Decay



- Charged pion decays weakly into an anti-neutrino and an electron or muon.
- Expect dominant decay will be to electron due to the lower mass with higher allowed phase space.
- With massless particles, pion must decay into an anti-particle with positive helicity and a particle with negative-helicity.
- Pion is spin 0, so violates angular momentum. But the particle is massive so it can be in a positive helicity state with a probabilty based on its mass.
- This means the dominant decay is to a muon, not an electron.

Particle-Antiparticle Operator

$$\phi^C = i\gamma^2\gamma^0\bar{\phi}^T = C\bar{\phi}^T$$

$$(\phi_L)^C = (\phi^C)_R$$

- There exists an operator which will transform a particle to the equivalent anti-particle.
- Solve Dirac Equation for anti-particle to find structure of the operator.
- Different from charge conjugation as it flips chirality (using γ matrices). Hence why the weak force violates charge conjugation.

Massive Neutrinos (Fermions)

$$m\bar{\phi}\,\phi = m(\bar{\phi}_L \phi_R + \bar{\phi}_R \phi_L)$$

$$\phi_L = (\phi_R)^C$$

$$\bar{\phi}_R \phi_L = (\phi_R^C)^T C \phi_L = \phi_L^T C \phi_L$$

$$\phi \rightarrow e^{i\alpha}\phi, \bar{\phi} \rightarrow \bar{\phi} e^{-i\alpha}$$

- Mass term in Largangian has both chirality states.
- Dirac particle has each state independent of the other.
- Also, can use particle-antiparticle conjugation to have only one massive state – Majorana spinors. Therefore a particle corresponds to its own anti-particle and must be electrically neutral.
- Note that a Majorana spinor is not invarient under U(1) transformation. Therefore it will not conserve lepton number while a Dirac spinor will.

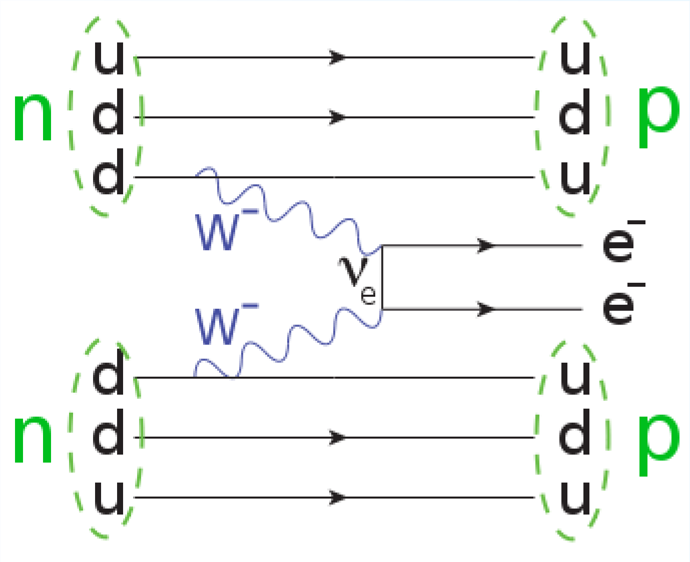
Experimentally, can we find if neutrinos are their own anti-particle?

$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$ - *allowed*

$\bar{\nu}_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$ - *not*

- From experiment, anti-neutrinos from beta decay cannot be absorbed.
- But from weak will not allow this unless the neutrino is negative helicity.
- Helicity (aka angular momentum) selects these reactions so if neutrinos are massless, cannot tell if there are 2 particles with 4 helicities (since only 2 are coupled) or a single particle with 2 helicities.
- Mass mixing is on the order of $(M_\nu/E)^2$ so it is a small effect, but allows for helicity to change due to a boost. Try looking for deviations due to a non-zero mass.

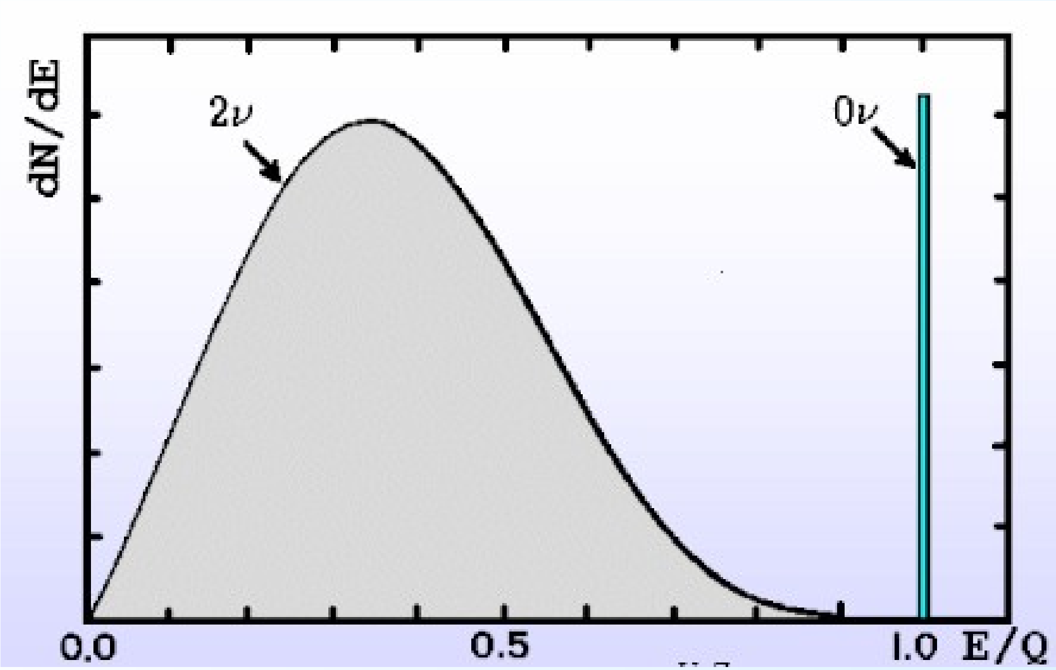
Neutrino-less double beta decay



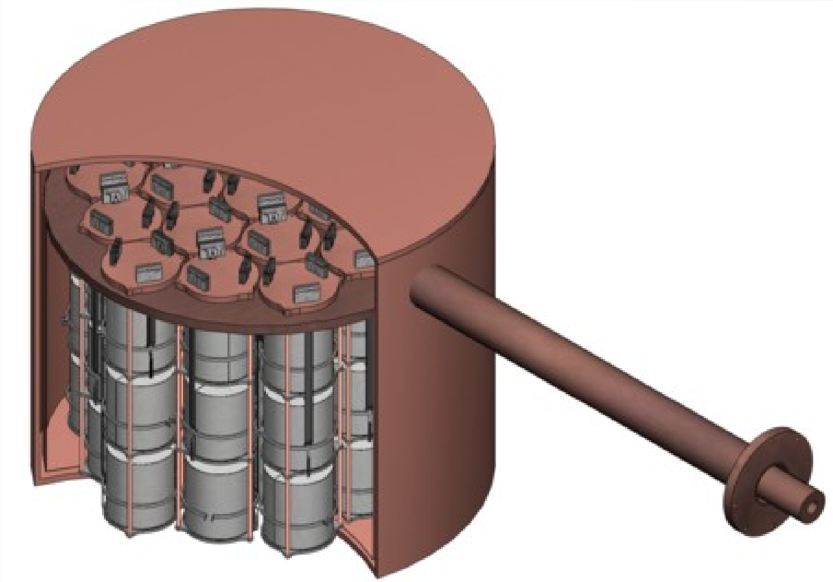
- Look at an atom which decays by beta decay twice.
- Should release two anti-neutrinos if Dirac particles.
- If Majorana, one “anti-neutrino” can become a “neutrino” and be absorbed in the next decay to repress the emittance of an “anti-neutrino”.
- Different recoil kinematics of resulting atom results in a reconstructed mass peak at the tail of the decay spectrum corresponding to the lost energy.
- Subtle shifts in the peak allow for measurement of the mass of the neutrino.

Experimental Searches

- Several previous experiements such as IGEX, NEMO 1 and 2 have set limits. The Heidelberg-Moscow experiment claims to have seen evidence to ~6σ but is very controversial.
- Current or proposed experiments such as EXO, NEMO3, and Majorana.



Majorana



- Uses 120 kg of 86% enriched ^{76}Ge with the objective to search for neutrinoless double beta decay as well as background limits and mass limits.
- Will use Ge crystals which will double as the source and as the detector elements. Will use segmentation and low background copper material to reduce background (physically or via signal processing).
- Surrounded by an active veto system that produces low background and will be located underground (DUSEL).

Final Note on Majorana Neutrinos

- Generation of Dirac neutrino masses is allowed in the standard model, using a variation of the Higgs mechanism, but it requires a priori couplings which vary drastically over all particle ranges.
- If neutrinos are Majorana particles, at the tree level, it will violate SU(2) symmetry (similar to violating U(1)), which will prevent a Higgs mechanism. A mass term can be constructed by extra loop diagrams, but these still must violate lepton number which tends to suggest New Physics.

References

- I. Aitchison and A. Hey. Gauge Theories In Particle Physics. 3rd Edition. New York: Taylor and Francis, 2003.
- F. Halzen and A. Martin. Quarks & Leptons: An Introductory Course in Modern Particle Physics. John Wiley & Sons, 1984.
- P. Renton. Electroweak Interactions. Cambridge: Cambridge University Press, 1990.
- M. Srednicki. Quantum Field Theory. Cambridge: Cambridge University Press, 2007.
- E. Akhmedev, hep-ph/0001264v2 (2000).
- http://majorana.npl.washington.edu/