NEUTRINO

Searching for it's nature : Dirac or Majorana

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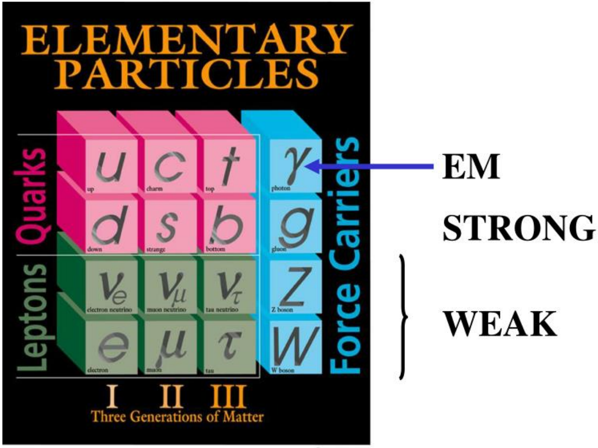
Outline

- Neutrinos in Standard Model
- Dirac and Majorana Neutrinos
- Neutrino Oscillation : In Dirac and Majorana Fields
- Neutrinoless Double Beta Decay Experiment
- Conclusion

Neutrino in Standard Model

The Standard Model of Particle Physics



Neutrinos in Standard Model

In Standard Model,

- Neutrinos have zero mass.
- There are exactly three neutrinos, one for each of the three charged leptons, and lepton number is conserved separately for each of the three lepton families (e, ν), (μ, ν_μ), (τ, ν_τ).
- Neutrinos and anti-neutrinos are distinct.
- All ν are left handed and all $\bar{\nu}$ are right handed.

Dirac and Majorana Neutrinos

Dirac fermion is a spin 1/2 particle which is different from it's antiparticle.
Dirac equation is given by,

$$(i\gamma^{\mu}\ \partial_{\mu} \text{ - m })\ \psi(x) = 0$$

.
The associated Dirac matrices are,
$\gamma^i = \begin{pmatrix} 0 & \sigma^i \\ \text{-}\sigma^i & 0 \end{pmatrix}$ and $\gamma^0 = \begin{pmatrix} 0 & I \\ I & 0 \end{pmatrix}$
$\gamma^5 = \mathrm{i}\gamma^0\ \gamma^1\ \gamma^2\ \gamma^3$, which obeys $(\gamma^5)^2 = I$.
Using γ^5 we can define projection operator $P_{R,L} = 1/2\ (1 \pm \gamma^5)$.

Dirac and Majorana Neutrinos

Now, any Dirac spinor field can be decomposed into right and left chiral components. ie,

$$\psi = P_R\,\psi + P_L\,\psi = \psi_R + \psi_L$$

Dirac spinor which is a 4 component object constructed from a pair of (1/2, 0) and (0, 1/2) Weyl spinors ϕ , χ via,

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

In terms of Dirac spinor,a Dirac mass is written as ,
L = -m $\bar{\psi}\ \psi$

Dirac and Majorana Neutrinos

$$\mathrm{L} = \text{-m} \; (\; \phi^\dagger \; , -\chi^\dagger) \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} \phi \\ \chi \end{pmatrix} = \text{m} \; (\phi^\dagger \; \chi \text{ - } \chi^\dagger \; \phi)$$

Non zero Dirac mass requires a particle to have both left and right chiral state.

Before going into Majorana mass, lets talk about Charge conjugation. Charge conjugation operator $\hat{C}$ flips a particle into antiparticle state.Using Dirac matrices $\hat{C}$ can be written as,

$$\hat{C} = i\gamma^2\gamma^0$$

If ψ is the spinor field of free neutrino, then charge conjugated field is,

$$\psi^C = C\psi^*$$

While Dirac spinor is composed of two Weyl spinors, a Majorana spinor is a four component object composed of single Weyl spinor.

$$\psi_M = \begin{pmatrix} \phi \\ \epsilon\phi \end{pmatrix}$$

Dirac and Majorana Neutrinos

Lets first split Dirac lagrangian to its chiral components,
$\text{L} = \bar{\psi}\,(i\gamma^{\mu}\,\partial_{\mu} - \text{m})\,\psi$
$\text{L} = \bar{\psi}_R\,(i\gamma^{\mu}\,\partial_{\mu} - \text{m}\psi_L)\,\psi_R + \bar{\psi}_L\,(i\gamma^{\mu}\,\partial_{\mu} - \text{m}\psi_R)\,\psi_L$
Using Euler Lagrange equation we will get two equations for both right handed and left handed,

$$i\gamma^{\mu}\,\partial_{\mu}\,\psi_L = \text{m}\psi_R$$
$$i\gamma^{\mu}\,\partial_{\mu}\,\psi_R = \text{m}\psi_L$$

If field were massless, we will get Weyl equations,

$$i\gamma^{\mu}\,\partial_{\mu}\,\psi_L = 0$$
$$i\gamma^{\mu}\,\partial_{\mu}\,\psi_R = 0$$

Neutrino is now described by two independent 2 components spinors with helicity eigen states and describes two states with opposite helicity (ν_L and ν_R).

Dirac and Majorana Neutrinos

Since right handed Neutrino doesnt exist, we describe neutrino with single massless left handed field in Standard Model.
Now for describing massive neutrino with single left handed field, Ettore Majorana found a way.
Taking hermitian conjugate of second Dirac equation we get,

$$\text{-i}\partial_\mu \; \bar{\psi}_R \; \gamma^\mu = \text{m} \; \bar{\psi}_L$$

Now taking transpose and applying charge conjugation $\text{C}\gamma^{\mu\,T} = \text{-}\gamma^\mu\text{C}$, we get,

$$\text{i}\gamma^\mu \; \partial_\mu \text{C} \; \bar{\psi}_R{}^T = \text{mC} \; \bar{\psi}_L{}^T$$

This equation has same structure of right handed component of ψ.

$$\psi_R = \text{C}\bar{\psi}_L{}^T$$

Dirac and Majorana Neutrinos

If this field is right handed then,1/2(1- γ^5) $\psi_R = 0$.We can write Dirac equation only in terms of ψ_L.
Majorana field now becomes,

$$\psi = \psi_L + \psi_R = \psi_L + \mathrm{C}\bar{\psi_L}^T = \psi_L + \psi_L^T$$

Taking charge conjugation of Majorana field,

$$\psi^C = (\psi_L + \psi_L^C)^C = \psi_L^C + \psi_L = \psi$$

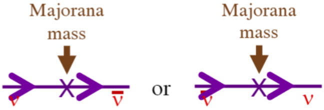
ie, charge conjugation of field is the same field itself. Majorana particle is it's own antiparticle.So, if neutrino is Majorana particle ν and $\bar{\nu}$ will be same.

Mass term in the Lagrangian couples left- and right-handed neutrino states. If particle is Majorana, we can make mass term with left handed component.

$$L_L^M = \text{-}1/2 \text{ m } \bar{\nu_L^C} \, \nu_L$$

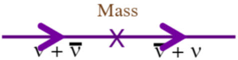
Dirac and Majorana Neutrino

The mass eigen states when mass terms are Majorana ,



$$H\ |\nu_1> = m1\ |\nu_1>$$

Then the mass eigen state is $\nu_1 = \nu + \bar{\nu}$

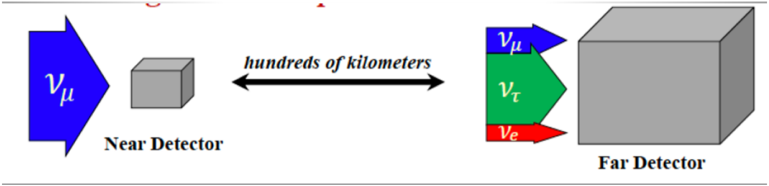


ie, in Majorana field,mass eigen states are their own antiparticles.

$$\nu_i = \bar{\nu}_i$$

Neutrino Oscillations

- A quantum mechanical phenomenon
- Neutrino with specific flavor can later be measured to have a different flavor.
- Probability of measuring a particular flavor varies between 3 states as it propogates through space.



Neutrino Oscillations

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} Cos\theta & Sin\theta \\ -Sin\theta & Cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Oscillation probability,

$$\text{P} = |<\nu_\alpha|\nu_\beta>|^2 = 1/2 \; sin^\theta \; sin^2(1.27(m)^2 L/E)$$

$$U_{PMNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \text{diag}(\text{exp}(\text{i}\alpha_1, \text{exp}(\text{i}\alpha_2, 1)$$

Oscillation amplitude,

$$<\nu_\alpha|\nu_\beta> = \sum U_\alpha^\dagger \; \text{exp(-}\alpha) \; U_\beta$$

$$\text{Probability} = |<\nu_\alpha|\nu_\beta>|^2$$

Neutrino oscillations

$$= |\sum U_D\ U_M\ (\ U_D\ U_M)^\dagger exp(-i\alpha)|^2$$

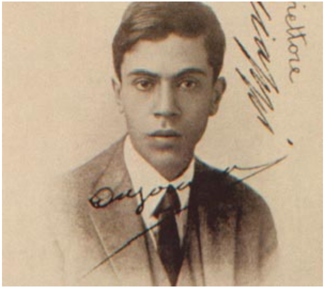
$$= |\sum U_D\ U_M\ U_M\dagger\ U_D\dagger)^\dagger exp(-i\alpha)|^2$$

$$= |\sum U_D\ U_D^\dagger\ \text{exp(-i}\alpha)|^2$$

- Probability of oscillation depends only on Dirac term and is independent of Majorana term.
- P(ν_μ -> ν_e) $\neq$ P($\bar{\nu_\mu}$ -> $\bar{\nu_e}$)
- Not able to probe the nature of Neutrino from oscillations.

Neutrinoless Double Beta Decay Experiment

$0\ \nu\ \beta\ \beta$ is the only experiment that can probe the Majorana nature of the neutrino where δL$=$ 2 lepton number violation if neutrino is Majorana particle.



To decay via double beta decay, a nuclear process whereby the nuclear charge changes by 2 units while the atomic mass is left unchanged.

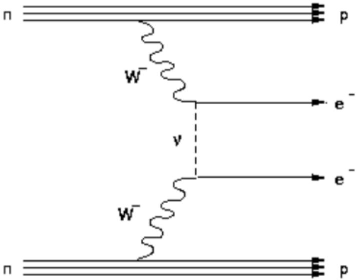
$$(\mathrm{Z},\ \mathrm{A}) \rightarrow (\mathrm{Z}+2,\ \mathrm{A}) + 2\ e^{-} + 2\ \bar{\nu}_{e}$$

Neutrinoless Double Beta Decay

Provided ν has mass and a Majorana particle zero-neutrino double beta decay is also possible.

$$(\mathrm{Z, A}) \rightarrow (\mathrm{Z+2, A}) + 2\, e^{-}$$

This process violated lepton number conservation by 2.

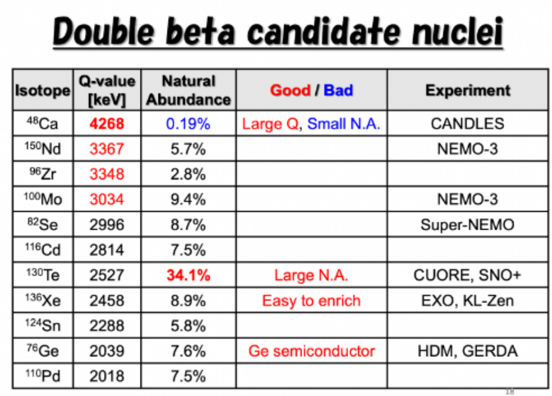


Neutrinoless Double Beta Decay

- The ν and $\bar{\nu}$ should be same for this process to happen.
- The chiral right-handed $\bar{\nu}$ emitted by the first decay must be able to evolve a left-handed chiral component as it propagates towards the second interaction.
- The only way it can do this is if the neutrino has a mass. The observation of neutrino-less double beta decay shows both that the neutrino is Majorana and have absolute mass.
- 0 ν β β experiment probes the Majorana nature of the neutrino, ie , $\nu = \bar{\nu}$

Neutrinoless Double Beta Decay (Expt)

- Tracker and calorimeter are two possible choices for $0\ \nu\ \beta\ \beta$.
- In search of "Neutrinoless Double Beta Decay" two neutrino double beta decay in the background which measured in more than 10 isotopes.



Double beta candidate nuclei

Isotope	Q-value [keV]	Natural Abundance	**Good / Bad**	Experiment
^{48}Ca	**4268**	0.19%	Large Q, Small N.A.	CANDLES
^{150}Nd	3367	5.7%		NEMO-3
^{96}Zr	3348	2.8%		
^{100}Mo	3034	9.4%		NEMO-3
^{82}Se	2996	8.7%		Super-NEMO
^{116}Cd	2814	7.5%		
^{130}Te	2527	**34.1%**	Large N.A.	CUORE, SNO+
^{136}Xe	2458	8.9%	Easy to enrich	EXO, KL-Zen
^{124}Sn	2288	5.8%		
^{76}Ge	2039	7.6%	Ge semiconductor	HDM, GERDA
^{110}Pd	2018	7.5%		

Quick Summary

- Dirac and Majorana particles are qualitatively different.
- In Standard Model, neutrinos have no mass. Beyond Standard model, neutrino oscillation is responsible for neutrino mass.
- Since neutrinos are ultra-relativistic, its very difficult to address whether they are Dirac or Majorana particle.
- Neutrinoless double beta decay experiment is the best candidate for probing the nature of neutrinos.

THANK YOU