Neutrino Physics: Lecture 14

Neutrino masses: Dirac vs. Majorana

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Outline

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1. Dirac and Majorana masses for neutrinos

2. Neutrinoless double beta decay

Adding a right-handed neutrino

Properties of ν_R

- Interaction $-\lambda_\nu \overline{l_L} \Phi^C \nu_R$
- After EWSB, $-\lambda_\nu v \overline{\nu_L} \nu_R / \sqrt{2}$
- $m_\nu = \lambda_\nu v / \sqrt{2}$
- Eigenvalues of ν_R: (1,0) $\Rightarrow$ Singlet under $SU(2)_L \times U(1)_Y$

Why not add ν_R and be done with it ?

- Yukawa couplings too small: $\lambda_\nu \lesssim 10^{-11}$
- $SU(2)_L \times U(1)_Y$ allows more mass terms with ν_R

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Equations of motion for a fermion

Fermion Lagrangian and equations of motion

- Lagrangian:

$$\mathcal{L} = \overline{\psi} i\gamma^\mu(\partial_\mu\psi) - g\overline{\psi}\gamma^\mu A_\mu\psi - m\overline{\psi}\psi$$

- Equations of motion: $\boxed{\partial_\alpha\left(\frac{\partial\mathcal{L}}{\partial_\alpha\Psi}\right) = \frac{\partial\mathcal{L}}{\partial\Psi}}$

$$\begin{aligned} 0 &= i\gamma^\mu\partial_\mu\psi - g\gamma^\mu A_\mu\psi - m\psi \\ \partial_\mu(\overline{\psi} i\gamma^\mu) &= -g\overline{\psi}\gamma^\mu A_\mu - m\overline{\psi} \end{aligned}$$

- Dirac equation: $\gamma^\mu(i\partial_\mu - gA_\mu)\psi - m\psi = 0$
- Conjugate equation: $-(\partial_\mu\overline{\psi})(i\gamma^\mu) - g\overline{\psi}\gamma^\mu A_\mu - m\overline{\psi} = 0$

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Defining the antiparticle (CP-conjugate particle)

Conjugate equation and desired antiparticle equation

- Conjugate equation:

$$\begin{aligned} -(\partial_\mu \overline{\psi})(i\gamma^\mu) - g\overline{\psi}\gamma^\mu A_\mu - m\overline{\psi} &= 0 \\ -i{\gamma^\mu}^T(\partial_\mu \overline{\psi})^T - g{\gamma^\mu}^T A_\mu \overline{\psi}^T - m\overline{\psi}^T &= 0 \end{aligned}$$

- Desired equation, $\boxed{\psi^C = C\overline{\psi}^T}$, with unitary C:

$$\begin{aligned} i\gamma^\mu \partial_\mu \psi^C - g\gamma^\mu A_\mu \psi^C - m\psi^C &= 0 \\ i\gamma^\mu \partial_\mu C\overline{\psi}^T - g\gamma^\mu A_\mu C\overline{\psi}^T - mC\overline{\psi}^T &= 0 \end{aligned}$$

- Matching condition:

$$C{\gamma^\mu}^T = -\gamma^\mu C$$

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-(\partial_\mu \overline{\psi})(i\gamma^\mu) - g\overline{\psi}\gamma^\mu A_\mu - m\overline{\psi} &= 0 \\
-i\gamma^{\mu T}(\partial_\mu \overline{\psi})^T - g\gamma^{\mu T} A_\mu \overline{\psi}^T - m\overline{\psi}^T &= 0 \leftarrow \text{EOM}
\end{aligned}
$$

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Antiparticle spinors

ψ^C and $\overline{\psi^C}$

$$\psi^C = C\overline{\psi}^T = C\gamma^{0T}\psi^* = -\gamma^0 C\psi^*$$
$$\overline{\psi^C} = -\psi^T C^\dagger$$

Useful properties of C

- Unitary: $C^\dagger C = I$
- Matching condition: $C\gamma^{\mu T} = -\gamma^\mu C$
- $\psi = (\psi^C)^C \Rightarrow C^* C = -I$
- Antisymmetric: $C^\dagger = -C^* \Rightarrow C = -C^T$
- C exists: In Dirac basis and chiral basis, $C = i\gamma^2\gamma^0$

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Can particle = antiparticle ?

Particles charged under a gauge symmetry

- Particle satisfies $[\gamma^\mu(i\partial_\mu - gA_\mu) - m]\psi = 0$
- Antipaticle satisfies $[\gamma^\mu(i\partial_\mu + gA_\mu) - m]\psi^C = 0$
- Particle $\neq$ Antiparticle unless $g = 0$ for all gauge groups

Particles charged under a global symmetry

- Particle has charge $+q$, antiparticle has charge $-q$
- Particle $\neq$ Antiparticle as long as symmetry is conserved

The special case of ν_R

- Not charged under $SU(2)_L$ or $U(1)_Y$ (consequently $U(1)_Q$)
- The only relevant symmetry is L (lepton number)

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Lepton number conservation

- Accidental symmetry (no fundamental principle forbids it)
- A guiding principle of gauge theories: anything that is not forbidden by a symmetry should be allowed
- Lepton number can (has to) be violated

Not L, but $B - L$

- Perturbatively, no Feynman diagram that violates L
- Non-perturbatively,
  baryons $\leftrightarrow$ antileptons process possible
  (sphaleron solution to electroweak field equations:
  $B = L = \frac{1}{2}$
  Klinkenhamer and Manton, PRD30 (1984) 2212)
- Only $B - L$ conserved in the Standard Model
- Arguments mentioning L violation should, strictly speaking, use $B - L$ violation.

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Majorana mass term possible for ν_R

The term $-\frac{1}{2}m_R\overline{(\nu_R)^C}\nu_R$

- Obeys $SU(2)_L$ and $U(1)_Y$
- Violates lepton $(B-L)$ number by 2, allowed
- Majorana mass for neutrinos !
- $\mathcal{L}_M = -\frac{1}{2}m_R(\overline{\nu_R^C}\nu_R + \overline{\nu_R}\nu_R^C) = -\frac{1}{2}m_R(\overline{\nu_R^C}\nu_R + h.c.)$

- $\nu \equiv \nu_R + \nu_R^C$ is its own antiparticle: Majorana particle
- Majorana mass term $\mathcal{L}_M = -\frac{1}{2}m_R\,\overline{\nu}\,\nu$

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$N = \nu_R + \nu_R^c$

The Majorana Lagrangian

Factor of 1/2

$$\mathcal{L} = \frac{1}{2}(\overline{\nu_R} i\gamma^\mu \partial_\mu \nu_R + \overline{\nu_R^C} i\gamma^\mu \partial_\mu \nu_R^C) - \frac{1}{2} m_R (\overline{\nu_R^C} \nu_R + h.c.)$$
$$= \frac{1}{2}\overline{\nu}(i\gamma^\mu \partial_\mu - m_R)\nu$$

Another way of writing the mass term

$$-m_R \, \overline{\nu_R^C} \, \nu_R = +m_R \, \nu_R^T \, C^\dagger \, \nu_R$$

The Majorana Lagrangian

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$\overline{\nu_R^C} \nu_R$ $\quad$ $\overline{\nu}_R \nu_R^C$ $\quad$ $\nu_R^T \nu_R$ ← convention

Majorana mass term possible for ν_L ?

The term $-m_L \overline{(\nu_L)^C} \nu_L$

- Violates lepton $(B-L)$ number by 2, allowed
- Does not obey $SU(2)_L$ and $U(1)_Y$, but obeys $U(1)_Q$
- Allowed only after EWSB
- Effective Majorana mass for neutrinos after EWSB !
- $\mathcal{L}_M = -\frac{1}{2} m_L (\overline{\nu_L^C} \nu_L + \overline{\nu_L} \nu_L^C) = -\frac{1}{2} m_L (\overline{\nu_L} \nu_L^C + h.c.)$

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Magnitudes of Dirac and Majorana masses

- $m_D = \lambda_\nu v \lesssim v$ $\lesssim 200$ GeV
- m_R has no restriction: can be as heavy as M_{Planck}
- m_L depends on the theory, normally $m_L \ll v$

Implications of Majorana mass

- Lepton number violating processs: as yet unobserved
- "Forbidden" processes like $\nu_\mu N \to \mu^+ \ell^+ \ell^- X$, $\mu^- e^+ \to \mu^+ e^-$ possible at colliders
- New particles like the Majoron predicted for a class of models
- Heavy Majorana neutrinos may play an important role in Baryogenesis

Neutrinoless double beta decay !

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Neutrinoless double beta decay !

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The reaction

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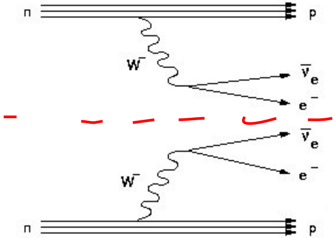
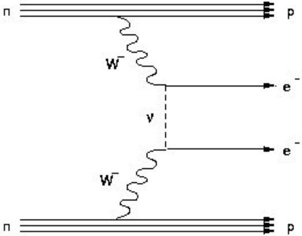




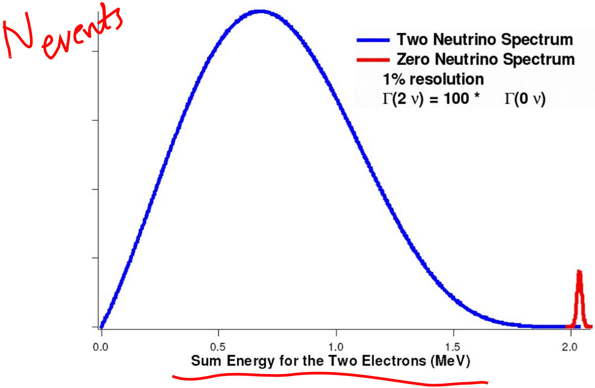
$${}^{A}_{Z}X \rightarrow {}^{A}_{Z+2}Y + 2e^{-} + 2\bar{\nu}_e \; ,$$

$$\boxed{2\nu\beta\beta}$$

$${}^{A}_{Z}X \rightarrow {}^{A}_{Z+2}Y + 2e^{-}$$

$$\boxed{0\nu\beta\beta}$$

The spectrum



$$^A_Z X \rightarrow ^A_{Z+2} Y + 2e^-$$

The reaction rate

Amplitude:

calculate $\longrightarrow$

$$A \propto \langle Y|H|X\rangle \sum_{i=1}^{3} m_i U_{ei}^2$$

Decay rate:

$$\Gamma \propto |\langle Y|H|X\rangle|^2 |m_{\beta\beta}|^2$$

$$m_{\beta\beta} = \sum_{i=1}^{3} m_i U_{ei}^2$$

Sensitivity to Majorana phases

$$|m_{\beta\beta}|^2 = \left| m_1 c_{12}^2 c_{13}^2 e^{2i\phi_1} + m_2 s_{12}^2 c_{13}^2 e^{2i\phi_2} + s_{13}^2 m_3 e^{-2i\delta} \right|^2$$

The only conceived experiment with sensitivity to ϕ_i

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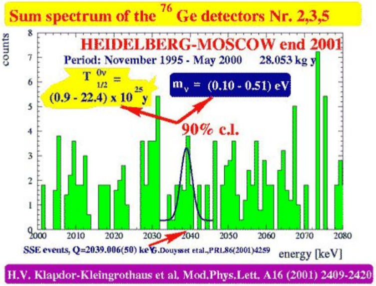
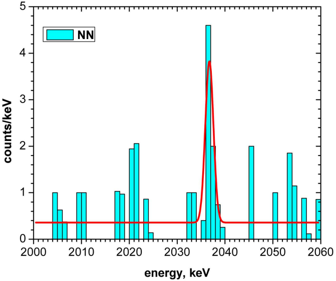
The only conceived experiment with sensitivity to ϕ_i

Isotopes, bounds and Future experiments

Isotope	$T^{2\nu}_{1/2}$ (10^{19}y)	$T^{0\nu}_{1/2}$ (10^{24}y)	Future Experiment	Mass (kg)	Lab
^{48}Ca	$(4.4^{+0.6}_{-0.5})$	> 0.0014	CANDLES		OTO
^{76}Ge	(150 ± 10)	> 19	GERDA	18-40	LNGS
		$22.3^{+4.4}_{-3.1}$			
		> 15.7	MAJORANA	60	SUSEL
^{82}Se	(9.2 ± 0.7)	> 0.36	SuperNEMO	100	LSM
^{96}Zr	(2.3 ± 0.2)	> 0.0092			
^{100}Mo	(0.71 ± 0.04)	> 1.1	MOON		OTO
^{116}Cd	(2.8 ± 0.2)	> 0.17			
^{130}Te	(68 ± 12)	> 2.94	CUORE	204	LNGS
^{136}Xe	> 81	> 0.12	EXO	160	WIPP
			KAMLAND	200	KAMIOKA
^{150}Nd	(0.82 ± 0.09)	> 0.0036	SNO+	56	SNOLAB

A signal ?

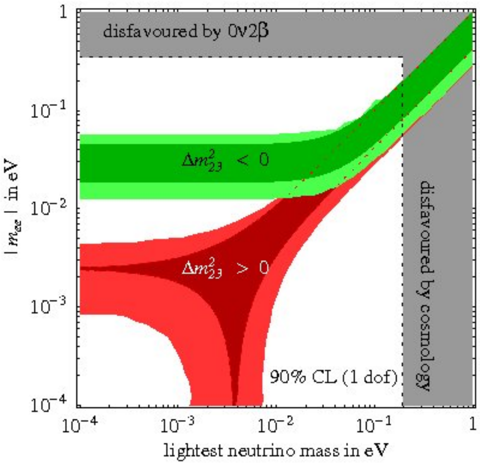




Mod.Phys.Lett.A 21 (2006) 1547

- Analysis not accepted by the collaboration
- Observation not confirmed by other experiments.

Constraining neutrino mass spectrum



Implications of $0\nu\beta\beta$ observation

- Confirm that neutrinos have Majorana mass
- Measurement of absolute neutrino mass
- Confirmation that $B - L$ is not conserved in nature