Decays of Heavy Majorana and Dirac Neutrinos

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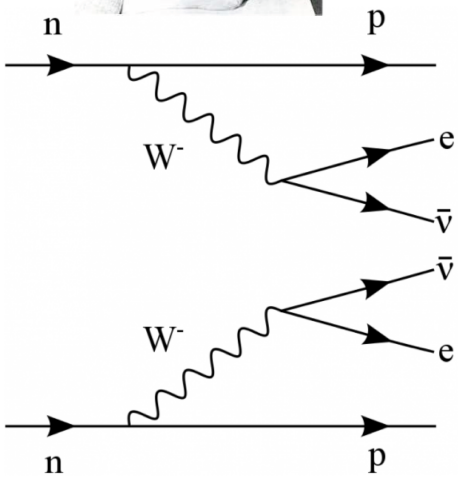
Physics Opportunities in the Near DUNE Detector Hall:
PONDD

How can we tell if neutrinos are Dirac or Majorana particles?

- Neutrinoless double beta decay. Only possible for Majorana neutrinos.

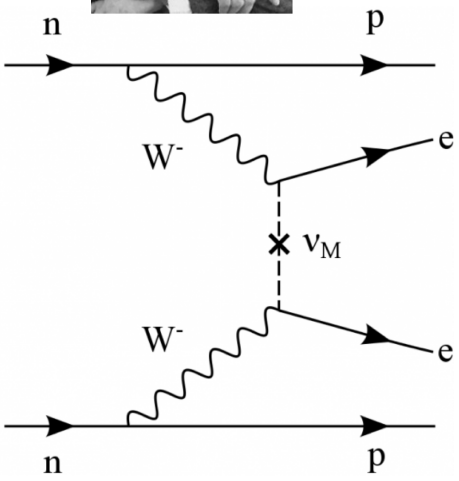
2νββ

Meyer

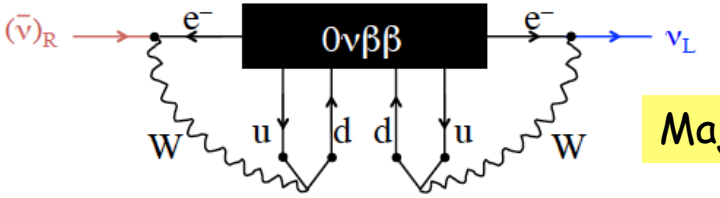


0νββ

Racah



0νββ decay



Majorana mass

How can we tell if neutrinos are Dirac or Majorana particles?

- Neutrinoless double beta decay. Only possible for Majorana neutrinos.
- Capturing cosmic background neutrinos. At least two of them are non-relativistic where what kind of mass you have matters. Very difficult experiments with significant uncertainties due to the lack of knowledge of the local neutrino density.

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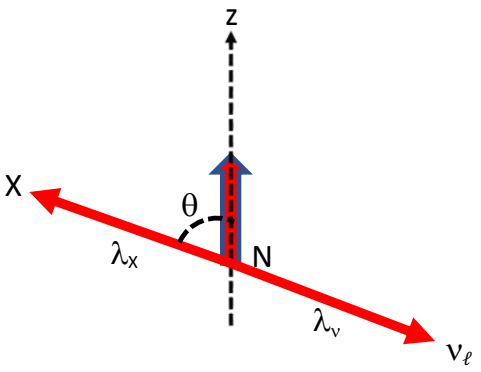
- Measure the angular distribution in decays.

Helicity Formalism



Angular momentum conservation for the decay $N(j,m) \to X + \nu_\ell$:

$$\text{Amplitude} = D^{j*}_{m,\lambda}(\phi,\theta,-\phi)A_{\lambda_\nu,\lambda_X}, \quad \lambda = \lambda_X - \lambda_\nu, |\lambda| \leq j = 1/2$$

$$\lambda = +\frac{1}{2} : \langle X(\theta,\lambda_X = +1)\,\nu_\ell(\pi-\theta,\lambda_\nu = +\frac{1}{2})|\mathcal{H}_{\text{int}}|N(\uparrow)\rangle = \cos\frac{\theta}{2}A_{+1,+1/2}$$

$$\lambda = -\frac{1}{2} : \langle X(\theta,\lambda_X = -1)\,\nu_\ell(\pi-\theta,\lambda_\nu = -\frac{1}{2})|\mathcal{H}_{\text{int}}|N(\uparrow)\rangle = \sin\frac{\theta}{2}A_{-1,-1/2}$$

Decay properties

$$\lambda = +\frac{1}{2} : \langle X(\theta, \lambda_X = +1)\, \nu_\ell(\pi - \theta, \lambda_\nu = +\frac{1}{2}) | \mathcal{H}_{\rm int} | N(\uparrow) \rangle = \cos\frac{\theta}{2} A_{+1,+1/2}$$

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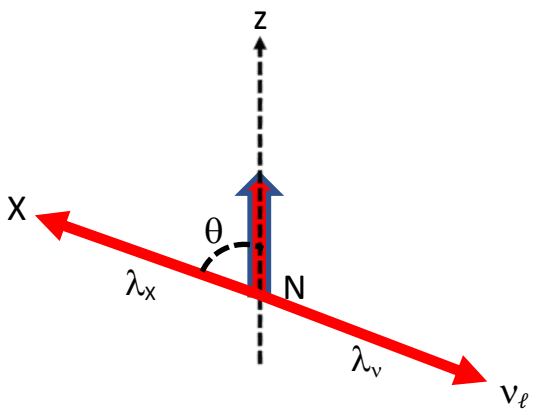
$$\frac{d\Gamma(N \to \nu_\ell + X)}{d(\cos\theta)} = \frac{\Gamma_{\lambda=+1/2}}{2}(1 + \cos\theta) + \frac{\Gamma_{\lambda=-1/2}}{2}(1 - \cos\theta)$$

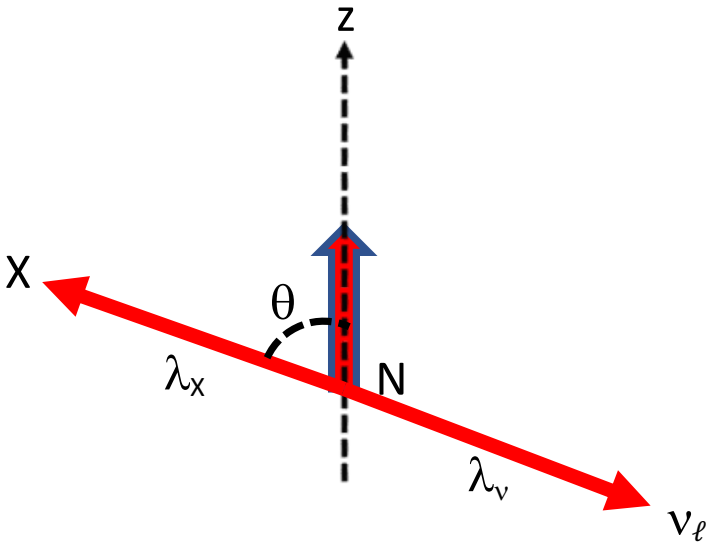


$$\frac{d\Gamma(N \to \nu_\ell + X)}{d(\cos\theta)} = \frac{\Gamma}{2}(1 + \alpha\cos\theta)$$

$$\Gamma = \Gamma_{\lambda=+1/2} + \Gamma_{\lambda=-1/2} > 0$$

$$\alpha = (\Gamma_{\lambda=+1/2} - \Gamma_{\lambda=-1/2})/\Gamma$$

CPT invariance:



$$\zeta\, \mathcal{H}_{\rm int}\, \zeta^{-1} = \mathcal{H}_{\rm int}$$

ζ : CPT operator

$$\begin{aligned} & |\langle X(\theta,\lambda_X)\, \nu_\ell(\pi-\theta,\lambda_\nu) \mid \mathcal{H}_{\rm int} \mid N(\uparrow)\rangle|^2 \\ = \quad & |\langle X(\theta,\lambda_X)\, \nu_\ell(\pi-\theta,\lambda_\nu) \,|\zeta^{-1}\zeta\, \mathcal{H}_{\rm int}\, \zeta^{-1}\zeta|\, N(\uparrow)\rangle|^2 \end{aligned}$$

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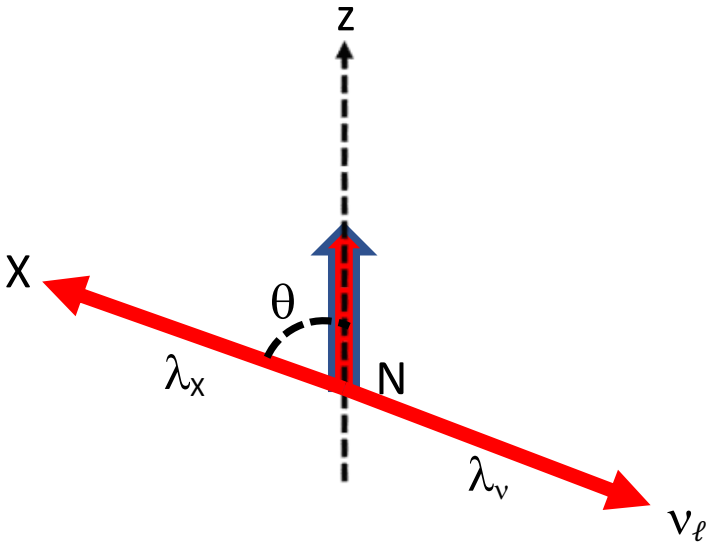

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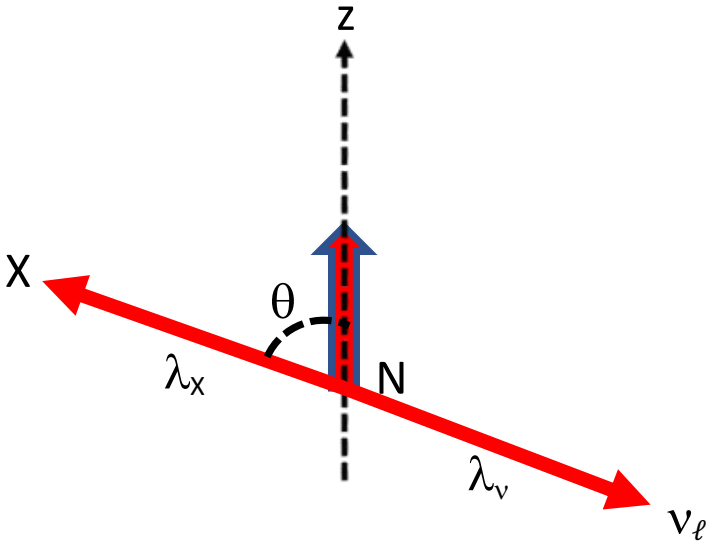

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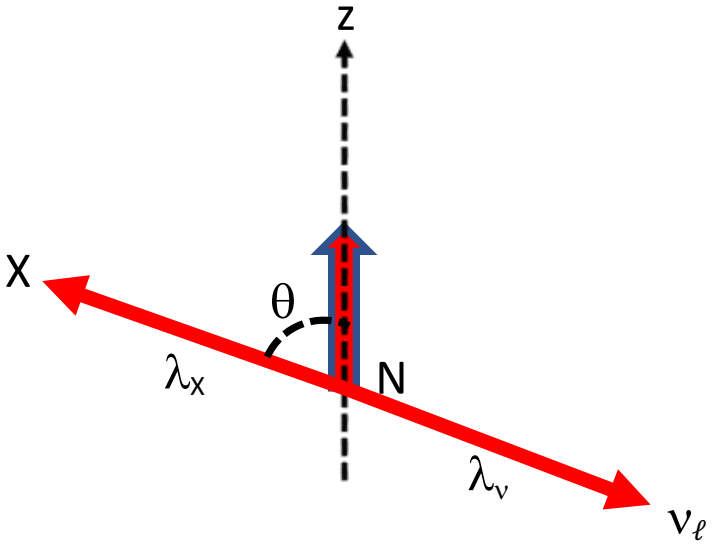
= \;& |\,\langle \zeta\mathcal{H}_{\rm int}\zeta^{-1}\zeta N(\uparrow)\mid \zeta X(\theta,\lambda_X)\,\nu_\ell(\pi-\theta,\lambda_\nu)\rangle\,|^2 \\
= \;& |\,\langle \mathcal{H}_{\rm int}\bar{N}(\downarrow)\mid X(\theta,-\lambda_X)\,\bar{\nu}_\ell(\pi-\theta,-\lambda_\nu)\rangle\,|^2
\end{aligned}$$

CPT invariance:



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\end{aligned}
$$

$$\alpha = (\Gamma_{\lambda=+1/2} - \Gamma_{\lambda=-1/2})/\Gamma$$

$$\lambda = +\frac{1}{2}: \sum_{|\lambda_X-\lambda_\nu|\leq=1/2} |\text{Amplitude}|^2 \Rightarrow \Gamma_{\lambda=+1/2} = \overline{\Gamma}_{\lambda=-1/2}$$

$$\lambda = -\frac{1}{2}: \sum_{|\lambda_X-\lambda_\nu|\leq=1/2} |\text{Amplitude}|^2 \Rightarrow \Gamma_{\lambda=-1/2} = \overline{\Gamma}_{\lambda=+1/2}$$

$$\overline{\Gamma} = \Gamma, \quad \overline{\alpha} = -\alpha$$

CPT invariance

We showed

$$\frac{d\Gamma(N \to \nu_\ell + X)}{d(\cos\theta)} = \frac{\Gamma}{2}(1 + \alpha\cos\theta)$$

$$\frac{d\Gamma(\bar{N} \to \bar{\nu}_\ell + X)}{d(\cos\theta)} = \frac{\Gamma}{2}(1 - \alpha\cos\theta)$$

Since $\alpha = -\bar{\alpha}$, for Majorana neutrinos we get $\alpha = 0$. This result holds for any self-conjugate boson X.

A.B. Balantekin, B. Kayser, Ann. Rev. Nucl. Part. Sci. **68** (2018) 313-338 (arXiv:1805.00922)
A.B. Balantekin, A. de Gouvêa, B. Kayser, arXiv:1808.10518

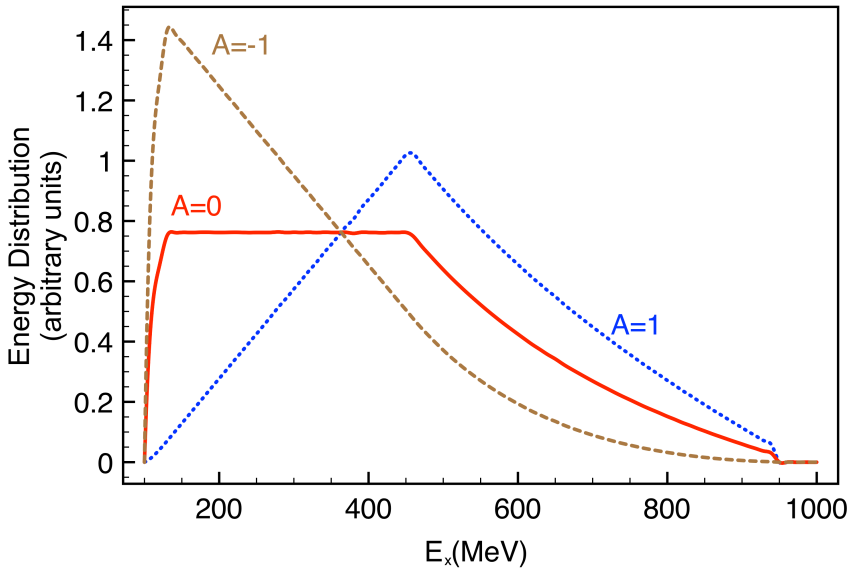
Energy distribution in the Laboratory

Parent's rest frame for $N \to \nu_\ell + X$

$$\frac{dn_X}{d\cos\theta_X} \propto (1 + A\cos\theta_X), \quad A = \alpha \times \text{polarization}$$

Lab frame with $r = m_X^2/m_N^2 < 1$

$$\frac{dn_X(E_N, E_X)}{dE_X} \propto \frac{2}{p_N(1-r)}\left[1 + A\left(\frac{2}{(1-r)}\frac{E_X}{p_N} - \left(\frac{1+r}{1-r}\right)\frac{E_N}{p_N}\right)\right]$$

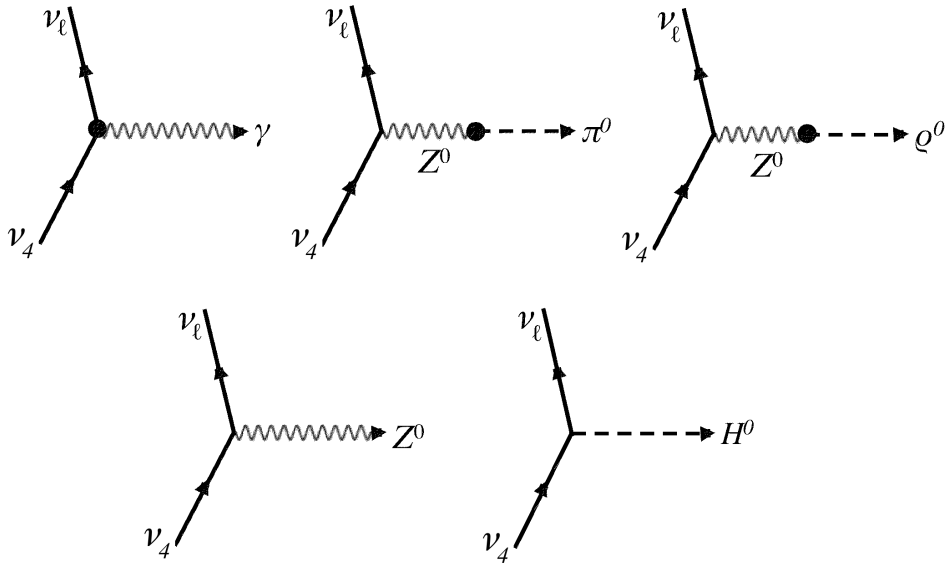


$m_X = 100\ \mathrm{MeV}$

$m_N = 300\ \mathrm{MeV}$

$500\ \mathrm{MeV} < E_N < 100\ \mathrm{MeV}$

Heavy Neutral Leptons



Boson	γ	π^0	ρ^0	Z^0	H^0
α	$\frac{2\Im(\mu d^*)}{\lvert\mu\rvert^2+\lvert d\rvert^2}$	1	$\frac{m_4^2-2m_\rho^2}{m_4^2+2m_\rho^2}$	$\frac{m_4^2-2m_Z^2}{m_4^2+2m_Z^2}$	1

Relevance to the near detectors at DUNE

Note that the previous arguments also hold if the final state particles are not neutral, but charged:

$$N \to \underbrace{\ell^{\pm}}_{e \text{ or } \mu} + \underbrace{X^{\mp}}_{\pi \text{ or } \rho}$$

Hence a detector in a neutrino facility which can identify e, μ, or τ, but has no electric charge discrimination, including indiscriminately both $\ell^+ X^-$ and $\ell^- X^+$ events can determine the Majorana vs. Dirac nature of N.

Concluding Remarks

- Using only angular momentum and CPT invariance we demonstrated that decays of Majorana neutrinos are isotropic, but the decays of Dirac neutrinos almost never are. This is a very general - albeit approximate - result true only to lowest order. It is true to all orders is the neutrino sector is CP-invariant.
- Future work: Three-body decays and decays of non-relativistic neutrinos.

Concluding Remarks

- In order to have a sufficiently large decay rate of the heavy neutrino its lifetime should be short enough. A significant number of such decays require masses larger than tens of MeV.
- Experiments such as SHiP at CERN and DUNE can search for heavy neutrinos by producing them in meson decays. If the heavy neutrinos have masses around ~ 500 MeV these experiments are capable of observing hundreds of decays in the decay channels $\pi^0 \nu_\ell$, $\pi^+ e^-$, and $\pi^+ \mu^-$.
- To establish isotropy of the heavy neutrino decay in its rest frame its momentum needs to be well characterized. If they come from meson decays they inherit the momentum distribution of parent mesons. Two-body decays from decay-at-rest beams produce monochromatic heavy neutrinos.

Concluding Remarks

- If the parent neutrino is heavy enough to decay into charged particles its Majorana/Dirac character can be determined in neutrino-beam or meson-factory experiments employing detectors without charge discrimination.
- If the heavy-neutrino mass is above tens of GeV, then it is accessible at LHC where the initial state has lepton number zero. It is then possible to characterize the lepton number in the final state.