Dirac or Majorana: How Can We Tell?

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v Frontiers
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Based on —

Baha Balantekin, B.K.;
arXiv:1805.00922

and

Baha Balantekin, André de Gouvêa, B.K.;
in preparation

Is each neutrino mass eigenstate ν —

a Dirac fermion $\bar{\nu} \neq \nu$

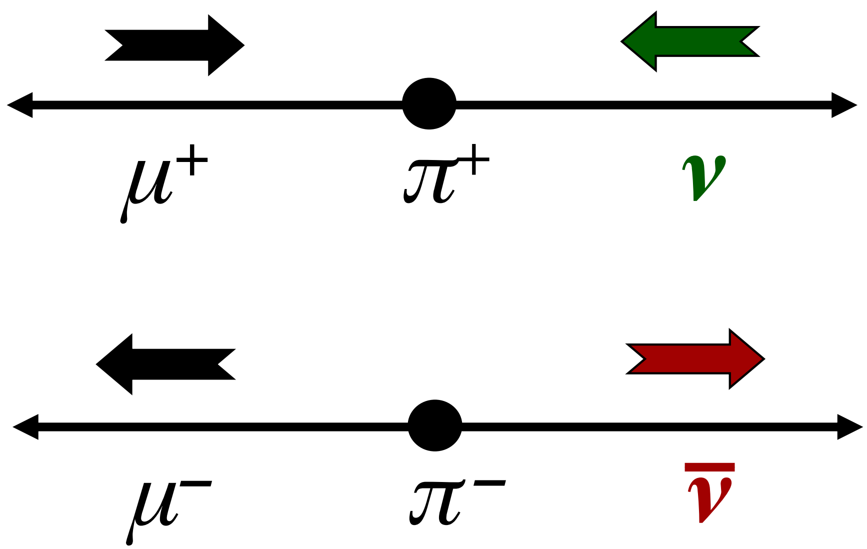
or

a Majorana fermion $\bar{\nu} = \nu$

Why is it so hard for us to find the answer to this question?

All the neutrinos we have been able to study directly so far have been **ultra-relativistic**.

Let us consider the neutrinos from pion decay.



The " ν " : ~ 100 % "Left-Handed" helicity

The " $\overline{\nu}$ " : ~ 100 % "Right-Handed" helicity

Suppose the neutral lepton from pion decay
has a charged-current interaction with some target.

<u>Majorana case</u>: The neutrinos from π^+ and π^- differ only in helicity.

$$\mathcal{L}_{\mathrm{CC}} \propto \bar{\mu}\underbrace{\gamma^{\lambda}\frac{(1-\gamma_5)}{2}\nu}_{\text{Absorbs only LH particle}} J_{\lambda}^{\text{Target}} + \bar{\nu}\underbrace{\gamma^{\lambda}\frac{(1-\gamma_5)}{2}}_{\text{Absorbs only RH particle}}\mu J_{\lambda}^{\text{Target}\,\dagger}$$

Creates $\boldsymbol{\mu^-}$
<u>Not</u> $\boldsymbol{\mu^+}$

Creates $\boldsymbol{\mu^+}$
<u>Not</u> $\boldsymbol{\mu^-}$

Absorbs only
LH particle

Absorbs only
RH particle

$$\boxed{\textbf{When neutrinos are ultra-relativistic in the target rest frame}}$$

In almost all circumstances —

When neutrinos are ultra-relativistic,
helicity* is a substitute for the *lepton number
that distinguishes antileptons from leptons.

Whether there is a conserved lepton number
or not makes no difference.

Majorana and Dirac neutrinos behave identically.

To determine whether the neutrinos are Majorana or Dirac particles, we have to find an exception to this rule, or find a way to work with non-relativistic neutrinos.

The Exception That Is Being Sought

Neutrinoless Double Beta Decay [$0\nu\beta\beta$]

Observation at any non-zero level would imply —

- Lepton number L is not conserved ($\Delta L = 2$)
- Neutrinos are Majorana particles

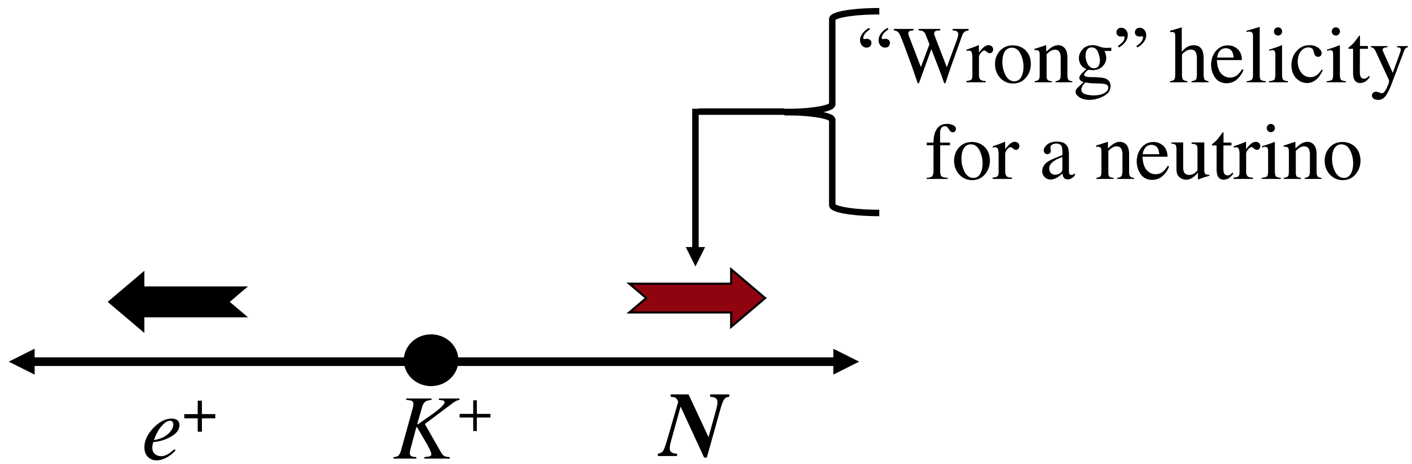
Get a large mass of the parent nucleus, and wait patiently.

A More Exotic Possible Exception

Suppose there is a heavy neutral lepton ***N*** with —

$$m_e \ll m_N \ll m_K$$

Then —



Interactions of ***N*** are *totally suppressed* if it is a *Dirac* particle, but *it can create an e^+* if it is a *Majorana* particle.

(B.K. and Shrock)

The sequence manifestly violates L conservation.

Another Possible Exception

The suppression of the Dirac/Majorana difference for relativistic neutrinos is due to the helicity-sensitive V – A character of the Standard-Model weak interaction

If there is a visible non-Standard-Model, non V – A, interaction (a scalar interaction, for example), there could be a visible Dirac/Majorana difference even for relativistic neutrinos.

(Rosen; Rodejohann, Xu, and Yaguna)

When Neutrinos Are Non-Relativistic

Non-Relativistic $\nu^{\text{D(irac)}}$ and $\nu^{\text{M(ajorana)}}$ Can Behave Quite Differently

Absorbs $\boldsymbol{\nu}^D$ but not $\bar{\boldsymbol{\nu}}^D$

Absorb $\boldsymbol{\nu}^M$

Absorbs $\bar{\boldsymbol{\nu}}^D$ but not $\boldsymbol{\nu}^D$

$$\mathcal{L}_{\text{CC}} \propto \underbrace{\bar{e}\gamma^\lambda \frac{(1-\gamma_5)}{2}\nu}_{\text{Absorbs either helicity}} J_\lambda^{\text{Target}} + \underbrace{\bar{\nu}\gamma^\lambda \frac{(1-\gamma_5)}{2}e}_{\text{Absorbs either helicity}} J_\lambda^{\text{Target}\,\dagger}$$

Creates e^- Not e^+

Creates e^+ Not e^-

Absorbs **either helicity**

Absorbs **either helicity**

When neutrinos are non-relativistic in the target rest frame

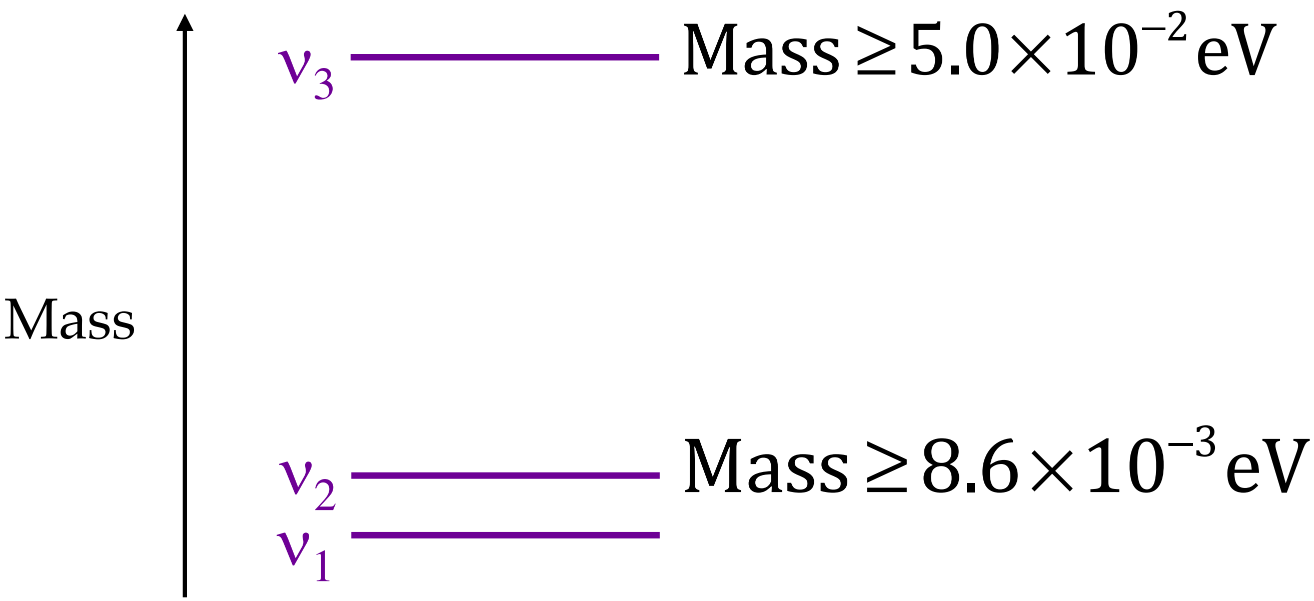
Where Can We Find Non-Relativistic Neutrinos?

With thanks for discussions to Petr Vogel, Baha Balantekin, and Amol Patwardhan.

Many, and perhaps all, of the neutrinos produced in the Big Bang are non-relativistic today.

These neutrinos are currently at $kT = 1.7 \times 10^{-4}\,\mathrm{eV}$.

From the mass-squared splittings measured in neutrino oscillation experiments, we know that if the mass ordering is *Normal* —



If the ordering is *Inverted*, $\mathrm{Mass}(\nu_1 \text{ and } \nu_2) \geq 5.0 \times 10^{-2}\,\mathrm{eV}$.

There are hopes of detecting the Big Bang relic neutrinos via their ***capture on tritium***.

(PTOLEMY)

Tritium β decay: ${}^3\mathrm{H} \rightarrow {}^3\mathrm{He} + e^- + \overline{\nu}_i$; $i = 1, 2,$ or 3

$$E_e \leq \left(m_H - m_{He}\right) - m_{\nu_i}$$

Capture of a very non-relativistic relic ν_i on tritium:

$$\nu_i + {}^3\mathrm{H} \rightarrow {}^3\mathrm{He} + e^-$$

$$E_e = \left(m_H - m_{He}\right) + m_{\nu_i}$$

The challenge: Demonstrate there are electrons with energies slightly beyond the decay endpoint.

How Does the Capture Rate Depend on the Majorana or Dirac Nature of the Relic Neutrinos?

1. How the current populations of the various non-relativistic neutrino spin states compare in the two cases.

The neutrinos are highly relativistic when they are produced in the early universe, so the rate of production of each helicity state is the same in the Dirac and Majorana cases.

After decoupling, the neutrinos free stream, and as they cool to being nearly at rest, helicity just becomes a spin direction.

If Majorana

At decoupling $\nu \big\downarrow \uparrow \quad \bar{\nu} \big\downarrow \downarrow$ Equally abundant

At earth, after expansion $\nu(\uparrow) \quad \bar{\nu}(\downarrow) \quad \nu(\downarrow) \quad \bar{\nu}(\uparrow)$

At decoupling $\nu \big\uparrow \downarrow \quad \bar{\nu} \big\uparrow \uparrow$

The total number of particles per unit volume is the same in the two cases, equally distributed among the four sub-populations. In the Dirac case, half of the particles cannot create an electron on ^3H.

2. How the cross sections for capture on ^3H compare in the two cases.

For the two sub-populations that are neutrinos (not antineutrinos) in both cases, we have for either case —

$$\text{Amplitude}\left(\nu+{}^3\text{H}\rightarrow{}^3\text{He}+e^-\right)\propto\bar{u}_e\gamma^\lambda\underbrace{\left(1-\gamma_5\right)}_{\text{Causes no suppression for neutrinos nearly at rest}}u_\nu J_\lambda^{\text{Hadronic}}$$

No Dirac-Majorana distinction.

For the two sub-populations that are antineutrinos in the Dirac case —

$$\text{Amplitude}\left(\bar{\nu}+{}^3\text{H}\rightarrow{}^3\text{He}+e^-\right)=0$$

But in the Majorana case, these two sub-populations contribute the same as the other two.

For a given total density of non-relativistic relic neutrinos here at the earth, the capture rate on tritium is twice as big if neutrinos are Majorana particles as it is if they are Dirac particles.

(Long, Lunardini, Sabancilar; B. K.)

(See also Lazauskas, Vogel, Volpe)

This illustrates that when neutrinos are non-relativistic, their Majorana or Dirac nature can make a big difference.

Actually using capture of the relic neutrinos on tritium to determine whether neutrinos are Majorana or Dirac particles would face very daunting obstacles:

- One must observe the process. This has not been done yet. Huge background from ^{3}H β decay.
- One must know the ***local*** (not universe-average) density of relic neutrinos.
  Estimates differ by orders of magnitude.
- If one of the three neutrino mass eigenstates is still relativistic today, two thirds of the captures could become indistinguishable from β decays.

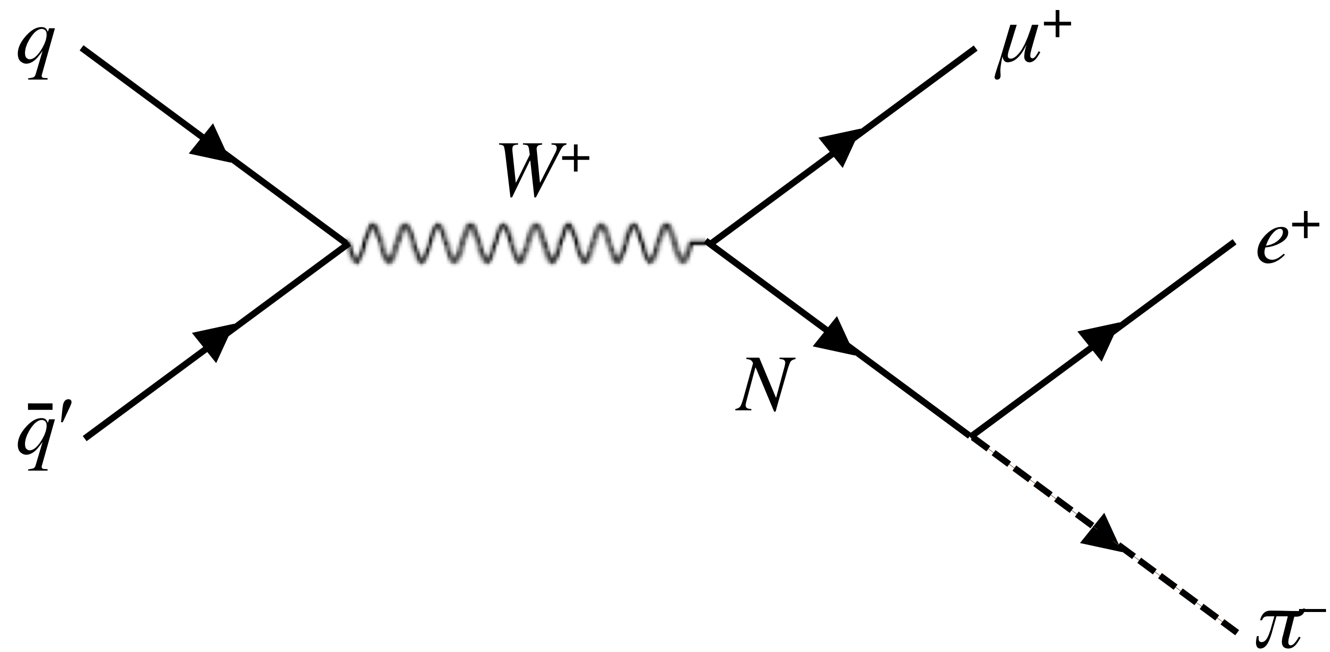
But if this approach to determining the Majorana or Dirac nature of neutrinos could be made to work…….

If There Is a Heavy Neutrino N

Decays of a Heavy Neutrino

Suppose there is a heavy neutral lepton ***N.***

A chain like —



would violate lepton number conservation,
and signal that N is a Majorana neutrino.

To look for this, a detector must have charge discrimination.

Very Neutral *N* Decay Modes

The decays —

$$N \to \nu + X$$

$$\nu_1, \nu_2, \text{or } \nu_3 \qquad X = \bar{X}$$

could also reveal whether neutrinos are Dirac or Majorana particles.

Depending on the mass of *N*, we could have —

$$X = \gamma, \pi^0, \rho^0, Z^0, \text{or } H^0.$$

For each of these decay modes,

$$\Gamma\left(N^{M} \rightarrow \nu^{M} + X\right) = 2\Gamma\left(N^{D} \rightarrow \nu^{D} + X\right)$$

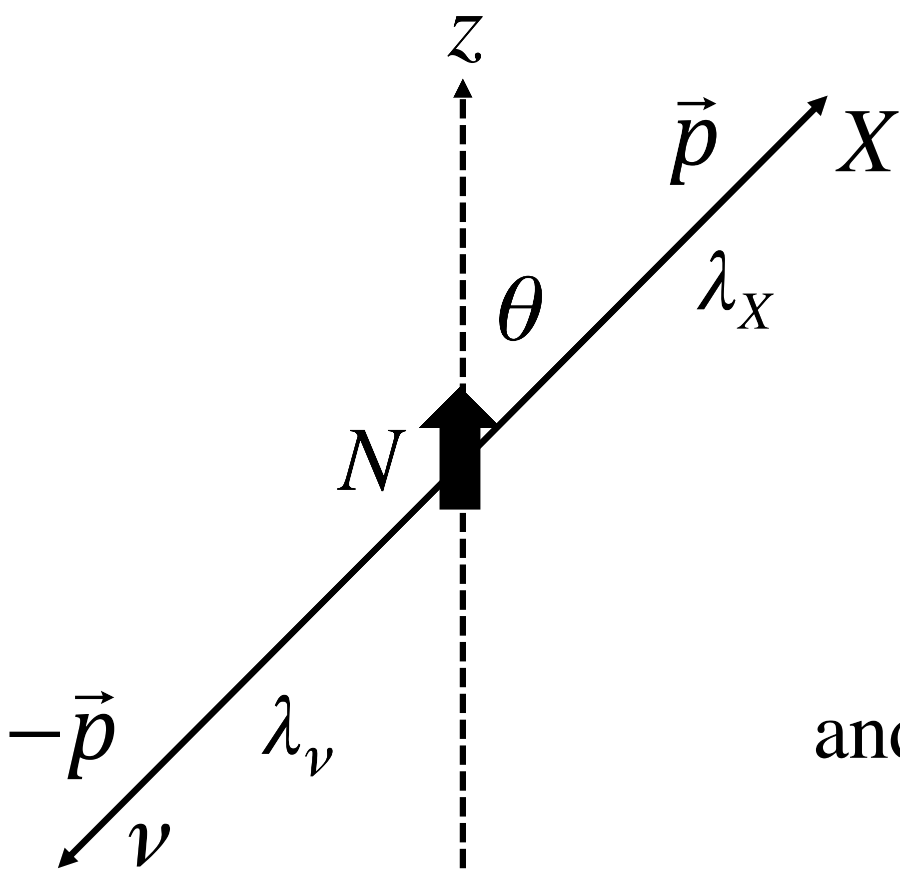
Majorana Dirac

(Gorbunov and Shaposhnikov)

This difference may not be too useful, because the decay rate also depends on unknown mixing angles.

The ***angular distribution*** of the daughter *X* in the *N* rest frame, when *N* has been polarized by the mechanism that produced it, also depends on whether neutrinos are Majorana or Dirac particles.

General analysis: Balantekin, de Gouvêa, B.K.



We assume
N is fully
polarized.

λ_X, λ_ν are helicities,
and $\lambda \equiv \lambda_X - \lambda_\nu = \vec{J}_{\text{final}} \bullet \hat{p}$.

Rotational invariance:

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

$$= \Gamma_0\left(1+\alpha\cos\theta\right) \; ; \; -1 \le \alpha \le +1$$

CPT and rotational invariance when neutrinos are Majorana particles:

$$\left|\left\langle X\left(\vec{p},\lambda_X\right)\nu^M\left(-\vec{p},\lambda_\nu\right)\middle|H\middle|N^M\left(\vec{s}\right)\right\rangle\right|^2 = \left|\left\langle X\left(-\vec{p},-\lambda_X\right)\nu^M\left(\vec{p},-\lambda_\nu\right)\middle|H\middle|N^M\left(\vec{s}\right)\right\rangle\right|^2$$

$$\Rightarrow \quad \Gamma_{\lambda=+1/2} = \Gamma_{\lambda=-1/2}$$

$$\Rightarrow \quad \alpha = 0$$

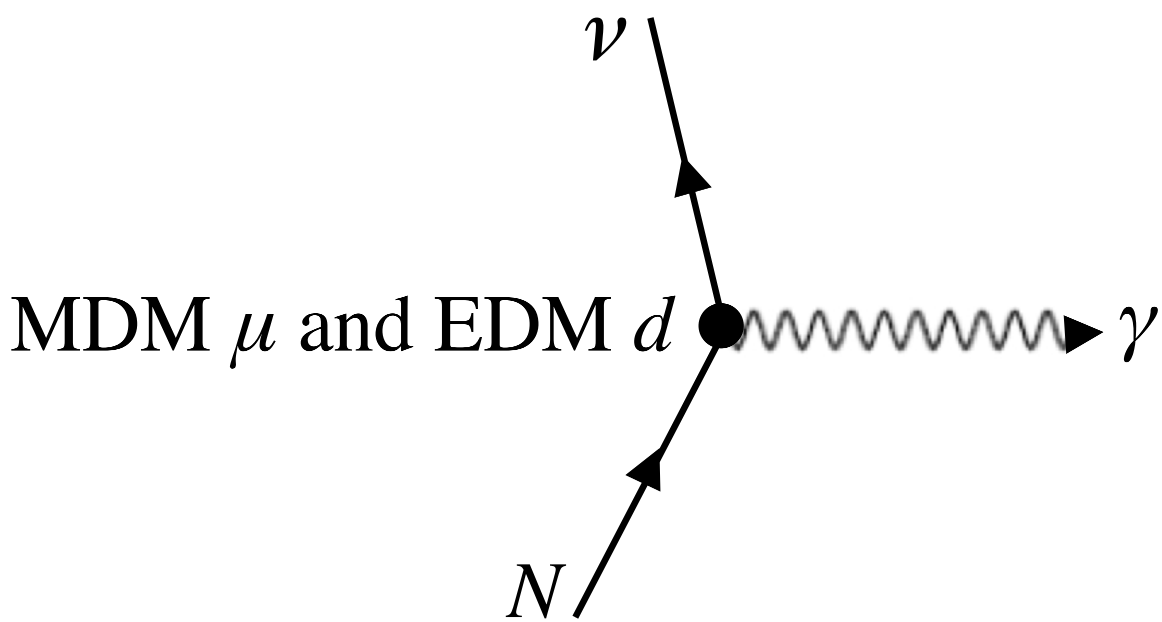
The angular distribution is isotropic.

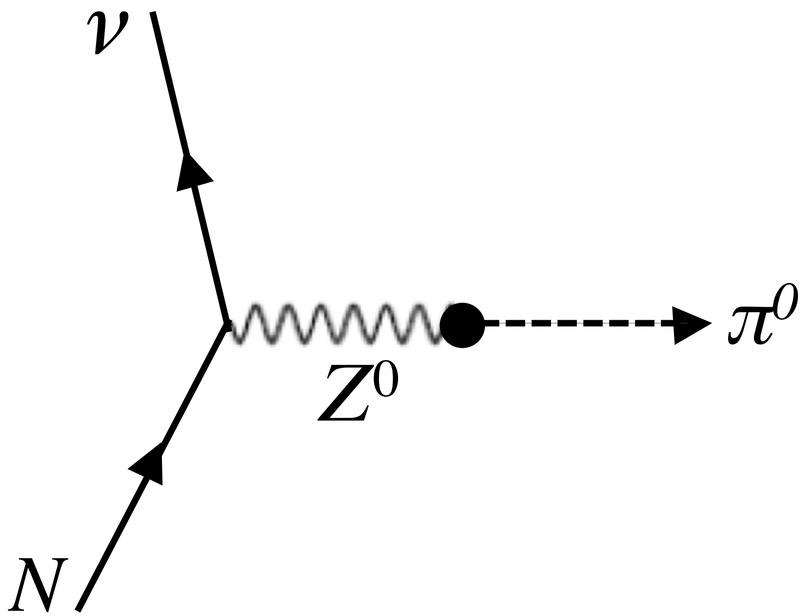
The isotropy in the Majorana case does not depend on the details of the interaction driving the decay.

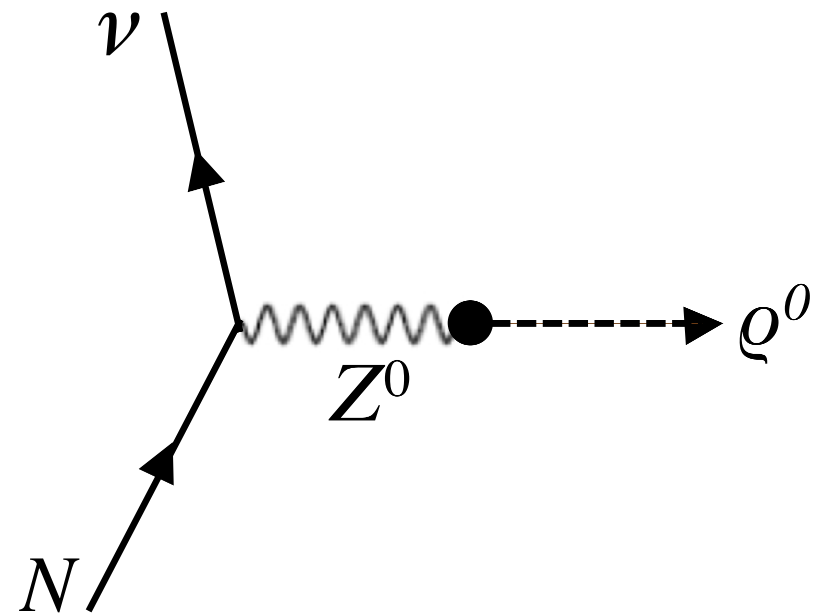
What Is the Angular Distribution in the Dirac Case?

This does depend on the interaction.

<u>What we assume</u>




ν
π^0
Z^0
N


ν
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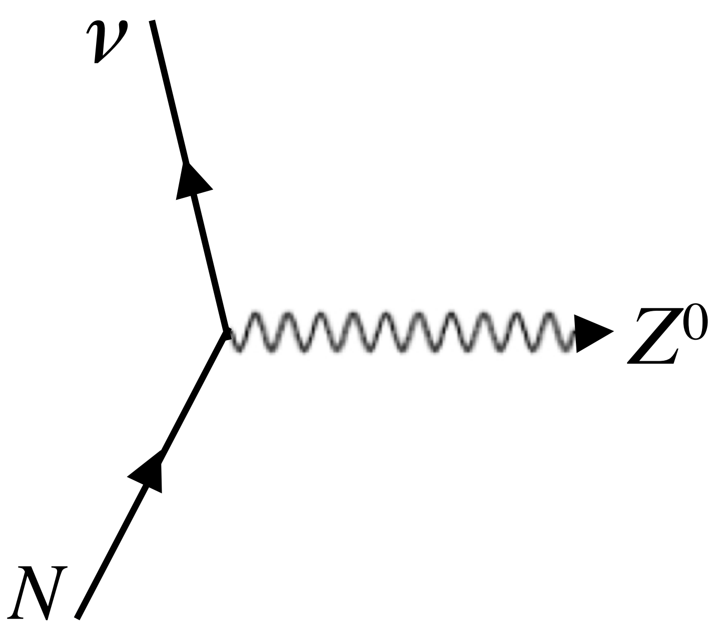
ν
Z^0
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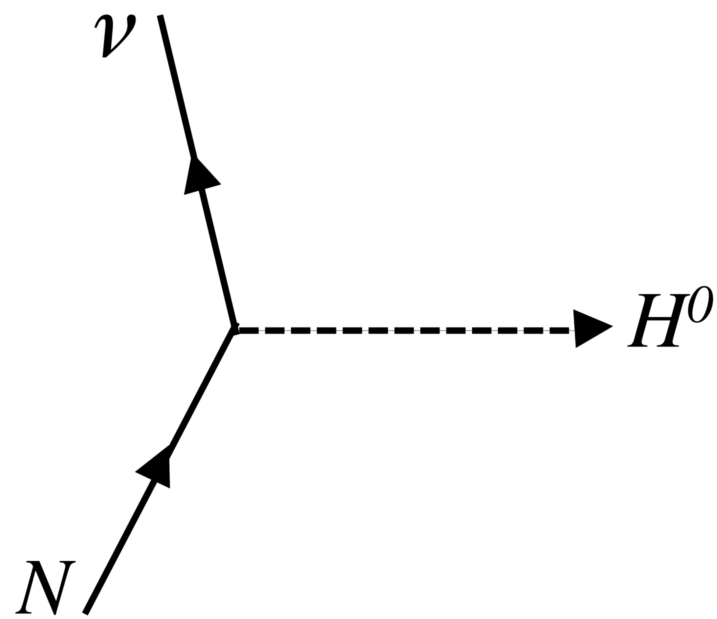

ν
H^0
N

An Example: $N^D \to \nu^D + \pi^0$

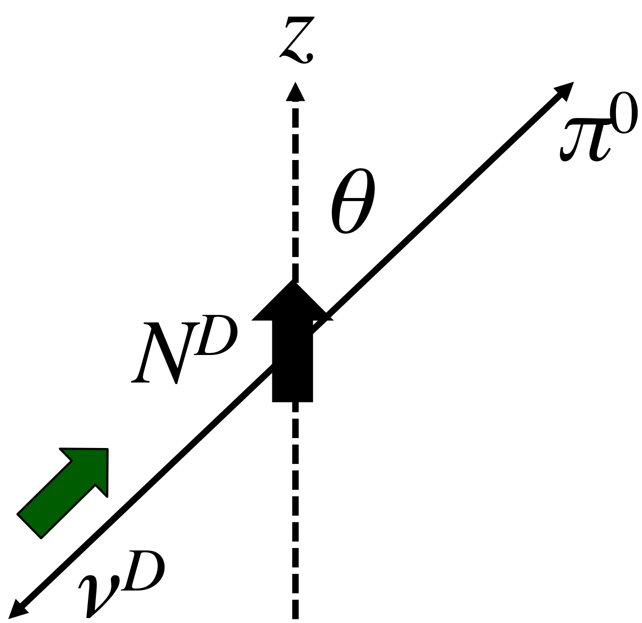
Pion momentum

Mass of N

$$\text{Amplitude}\left(N^D \to \nu^D + \pi^0\right) \propto \bar{u}_\nu \not{p}_\pi \frac{\left(1-\gamma_5\right)}{2} u_N = m_N \left[\frac{\left(1-\gamma_5\right)}{2} u_\nu\right]^\dagger \gamma^0 u_N$$

Dirac spinors

Allows only
LH ν helicity



yields $$\frac{d\Gamma}{d\left(\cos\theta\right)} \propto \left(1+\cos\theta\right)$$

Not isotropic.

The Angular Distributions in the Dirac Case

$$\frac{d\Gamma\left(N^D \rightarrow \nu^D + X\right)}{d\left(\cos\theta\right)} = \Gamma_0\left(1 + \alpha\cos\theta\right)$$

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

Except in very special circumstances, these angular distributions are not isotropic.

Once m_N is measured, most of them will not depend on any unknown parameters.

A heavy neutrino is being sought at the LHC.
(Federico Scutti's talk)

The discovery potential at Fermilab has been considered by Ballett, Pascoli, and Ross-Lonergan.

Some of the physics of a heavy neutrino has been discussed by Hernandez et al., Caputo et al., and Han et al..

The angular distribution and related photon polarization in radiative neutrino decays has been considered in specific formalisms as a probe of whether neutrinos are Dirac or Majorana particles by —

Li and Wilczek and by Shrock.

Conclusion

We could learn whether neutrinos are Dirac or Majorana particles by —

- Observing neutrinoless double beta decay,

  or
- Discovering and taking advantage of non-SM interactions,

  or
- Detecting the Big Bang relic neutrinos and knowing their local density,

  or
- Finding a heavy neutrino and studying its decays