Implication of Helicity Modifications of Primordial Neutrinos on Their Detection

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(with Gordon Baym, previous talk)

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Based on two papers:

Gordon Baym and Jen-Chieh Peng

PRL 126, 191803 (2021) and PRD 103, 123019 (2021)

Cosmic neutrino background (CνB) versus cosmic microwave background (CMB)

	CMB	CνB	Relation
Temperature	2.73K	1.9 K (1.7 x 10^{-4} eV)	$T_\nu/T_\gamma = (4/11)^{1/3}$ $=0.714$
Decoupling at	3.8 x 10^5 years	~ 1 sec	
Density	~ 411 / cm^3	~ 336 / cm^3	$n_\nu = (9/11)\ n_\gamma$

- CνB took a snapshot of the Universe at a much earlier epoch than CMB
- At least two of the three neutrinos are non-relativistic ($\beta = v/c \ll 1$), since $\Delta m_{21}{}^2 = (8.0\pm0.3) \times 10^{-5}\ eV^2$, and $|\Delta m_{32}{}^2| = (1.9 \rightarrow 3.0) \times 10^{-3}\ eV^2$

Incomplete list of proposed searches for CνB

1) Coherent ν-nucleus scattering (effect of order G_F^2)

(Zeldovich and Khlpov, 1981; Smith and Lewin, 1983; Duda, Gelmini, Nussinov, 2001)

Coherence over CνB wavelength implies an enhancement factor of $\sim 10^{20}$

2) "Neutrino Optics" (effect linear in G_F)

(R. Opher, 1974; R. Lewis, 1980)

Total reflection or refraction of CνB on a flat surface

3) Torque exerted on a polarized target (effect linear in G_F)

(Stodolsky, 1974)

Energy split of the two spin states of electron in the sea of CνB

The most promising technique (so far) to detect very-low-energy relic neutrinos

Capture of CνB on radioactive nuclei (positive Q value)

(S. Weinberg, 1962)

Tritium beta decay:

$$\boxed{a)\ {}^{3}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + e^{-} + \overline{\nu}_{e}}$$

3-body β-decay with Q-value of

$$Q_a = M({}^{3}\mathrm{H}) - M({}^{3}\mathrm{He}) - M(e^{-}) - M(\overline{\nu}_{e})$$

Inverse tritium beta decay (ITBD):

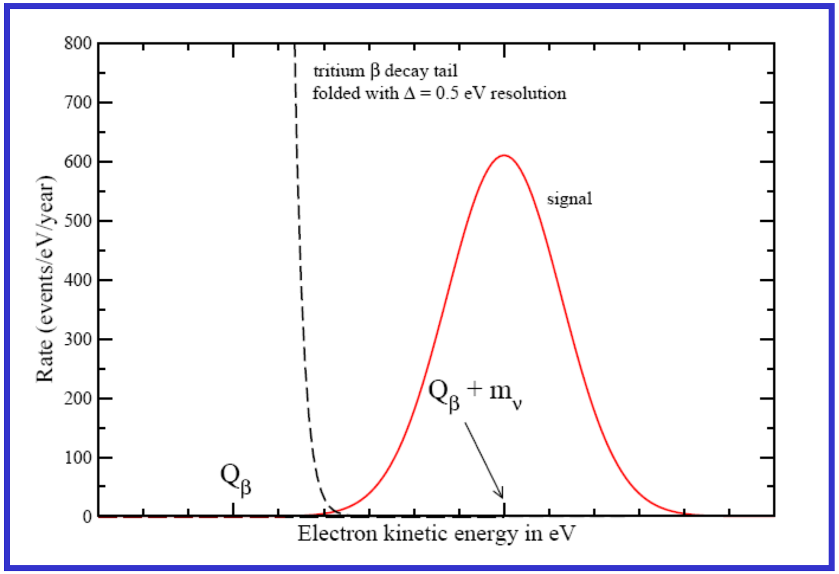
$$\boxed{b)\ \nu_{e} + {}^{3}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + e^{-}}$$

2-body reaction with the Q-value of

$$Q_b = M({}^{3}\mathrm{H}) - M({}^{3}\mathrm{He}) - M(e^{-}) + M(\overline{\nu}_{e})$$

Therefore, $Q_b = Q_a + 2M(\overline{\nu}_{e})$

Positive Q value implies low-energy relic neutrinos can be captured !



Look for a mono-energetic peak beyond the endpoint of tritium beta decay

PTOLEMY experiment for this search

Helicity dependence of the ITBD

$(\nu_e + {}^3H \rightarrow {}^3He + e^-)$

- ITBD for neutrino in mass eigenstate i and helicity h:

$$\sigma_i^h = \frac{G_F^2}{2\pi v_i} |V_{ud}|^2 |U_{ei}|^2 \, F(Z, E_e) \frac{m({}^3He)}{m({}^3H)} E_e p_e A_i^h (\overline{f}^2 + 3\overline{g}^2)$$

- The helicity-dependent factor, A_i^h , is given as

$A_i^{\pm} = 1 \mp \beta_i$; where $\beta_i = v_i / c$

- For relativistic neutrinos, $\beta_i \rightarrow 1$, we have

$A_i^+ \rightarrow 0$ and $A_i^- \rightarrow 2$

- For non-relativistic neutrinos, $\beta_i \rightarrow 0$, we have

$A_i^+ \rightarrow 1$ and $A_i^- \rightarrow 1$

- ITBD rate depends on the helicity, h, of neutrinos

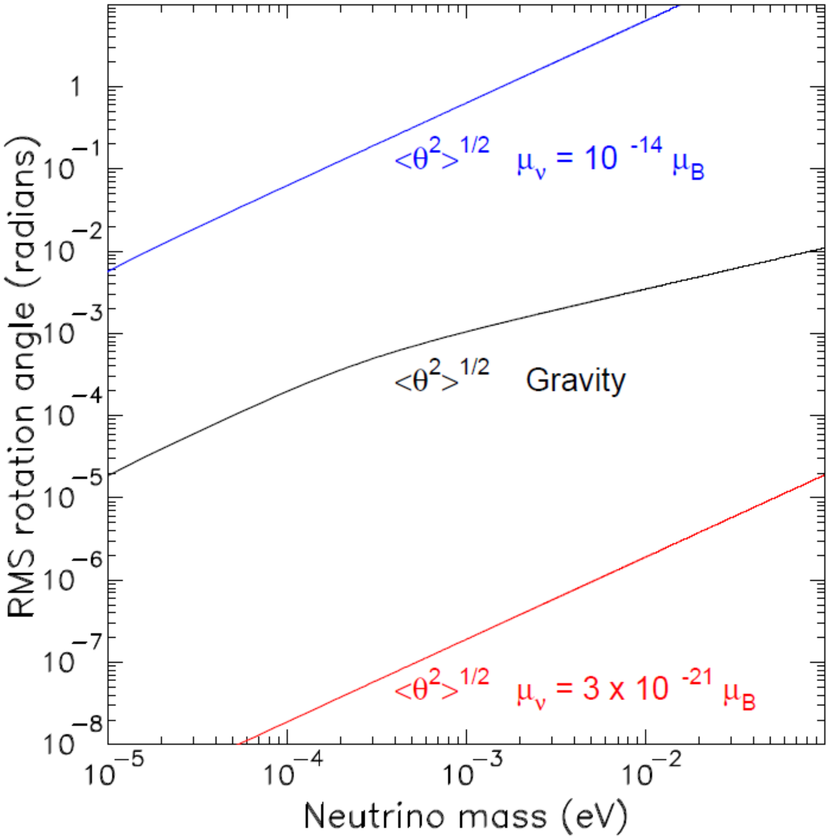
What are the helicities of relic neutrinos?

Time evolution of relic neutrino helicity

- Relic neutrinos decoupled at a temperature of ~ 1 MeV, and were highly relativistic. Neutrinos were produced essentially in $h = -1$ state, and antineutrinos in $h = +1$ state.
- Rotation of neutrino spin due to matter inhomogeneities is less than the rotation of neutrino momentum (gravitational lensing of neutrino), changing neutrino helicity.
- Dirac neutrino with non-zero magnetic moment will precess in galactic or cosmic magnetic fields, changing neutrino helicity.

RMS angle of relic neutrino spin relative to its momentum due to gravity and magnetic field

- See previous talk by Gordon Baym, and PRL 126, 191803 (2021); PRD 103, 123019 (2021)
- The RMS helicity rotation angle depends on neutrino mass and magnetic moment, and on the properties of the cosmic magnetic fields



For $\mu_\nu \sim 1.4-2.9\times10^{-11}\mu_B$, suggested by XENON1T, neutrino helicity would have been randomized

ITBD rate depends on the helicity, mass and type of relic neutrinos

- Helicity-dependent factor, A_i^h , is $A_i^{\pm} = 1 \mp \beta_i$; where $\beta_i = v_i / c$
- Define A_{eff} as the sum of A_i^h over mass state i and helicity h:

$$A_{eff} = \sum_{i,h=\pm} |U_{ei}|^2 \langle A_i^h \rangle_T$$

- T denotes the thermal average over the present momentum distribution, $f(p)$, of relic neutrinos:

$$f(p) = \frac{1}{e^{p/T_0} + 1} \quad \text{and} \quad T_0 = 0.1676\ meV$$

- For Dirac type, only neutrinos (not antineutrinos) contribute

$$A_{eff,D} = \sum_{i,h=\pm} |U_{ei}|^2 \langle A_i^h \rangle_T = 1 + \sum_i |U_{ei}|^2 \langle \beta_i \cos\theta_i \rangle_T$$

- For Majorana type, both neutrinos and antineutrinos contribute

$$A_{eff,M} = (1 + \sum_i |U_{ei}|^2 \langle \beta_i \cos\theta_i \rangle_T) + (1 - \sum_i |U_{ei}|^2 \langle \beta_i \cos\theta_i \rangle_T) = 2$$

ITBD rate for Dirac neutrinos without helicity flip

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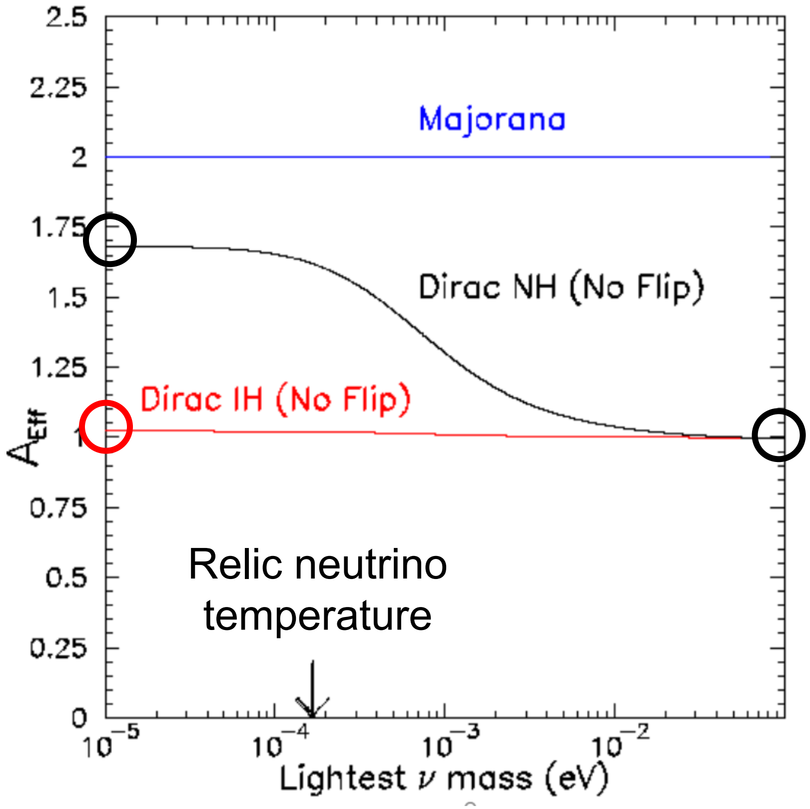


Relic neutrino temperature

- For Dirac neutrinos without helicity flip ($\cos\theta_i = 1$)

$$A_{eff,D} = 1+\sum_i |U_{ei}|^2 \langle \beta_i \rangle_T$$

- If all neutrinos are non-relativistic, $\beta_i \to 0$, then

$$A_{eff,D} = 1$$

- If the lightest neutrino is relativisitic, then

$$A_{eff,D} = 1+|U_{e1}|^2 = 1.68 \quad \text{for normal mass hierarchy}$$

$$A_{eff,D} = 1+|U_{e3}|^2 = 1.02 \quad \text{for inverted mass hierarchy}$$

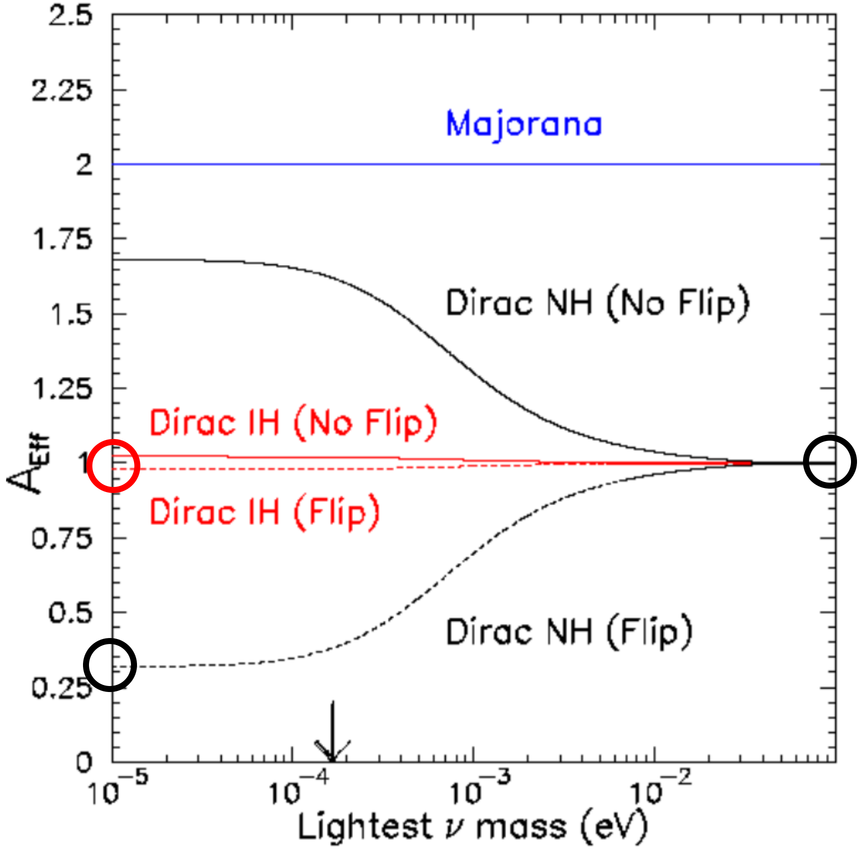
NH = normal hierarchy

IH = inverted hierarchy

ITBD rate for Dirac neutrinos with helicity flip

- For Dirac type, only neutrinos (not antineutrinos) contribute

$$A_{eff,D} = \sum_{i,h=\pm} |U_{ei}|^2 \langle A_i^h \rangle_T = 1 + \sum_i |U_{ei}|^2 \langle \beta_i \cos\theta_i \rangle_T$$



- Dirac neutrinos with helicity flip ($\cos\theta_i = -1$)

$$A_{eff,D} = 1 - \sum_i |U_{ei}|^2 \langle \beta_i \rangle_T$$

- If all neutrinos are non-relativistic, $\beta_i \to 0$,

$$A_{eff,D} = 1$$

- If the lightest neutrino is relativisitic,

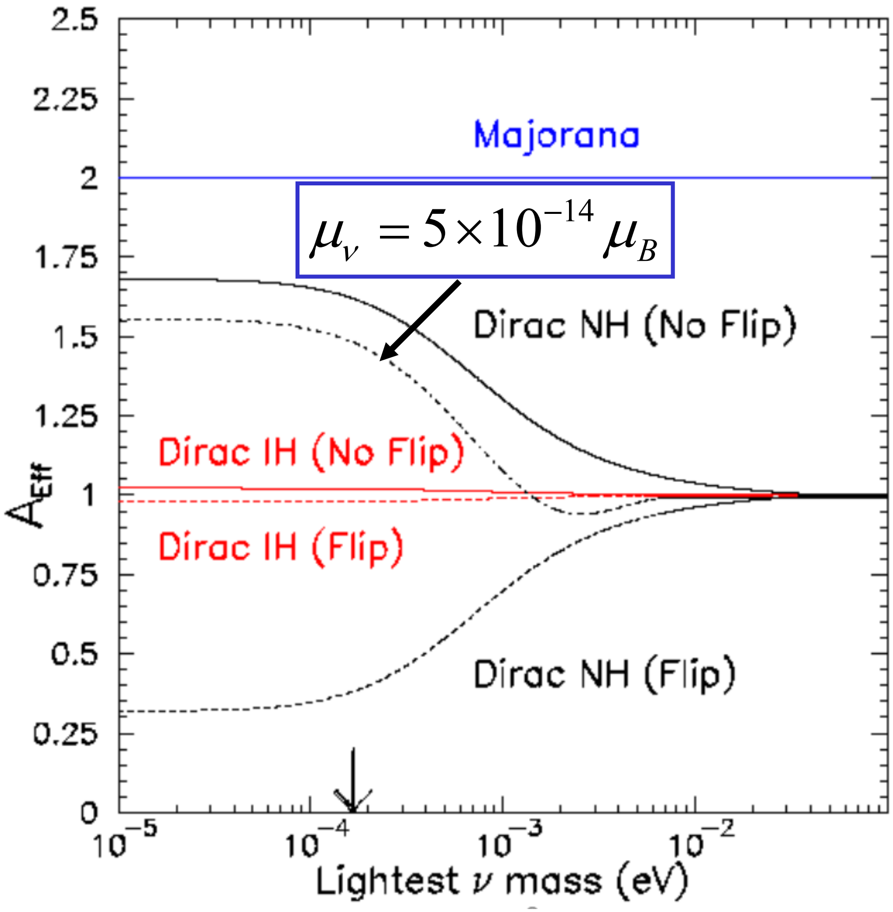
$$A_{eff,D} = 1 - |U_{e1}|^2 = 0.32 \quad \text{normal hierarchy}$$

$$A_{eff,D} = 1 - |U_{e3}|^2 = 0.98 \quad \text{inverted hierarchy}$$

ITBD rate for Dirac neutrinos with partial helicity flip

- For Dirac type, only neutrinos (not antineutrinos) contribute

$$A_{eff,D} = \sum_{i,h=\pm} |U_{ei}|^2 \langle A_i^h \rangle_T = 1 + \sum_i |U_{ei}|^2 \langle \beta_i \cos\theta_i \rangle_T$$



- For Dirac with NH, ITBD rate is modified even with a modest μ_ν of $5\times10^{-14}\mu_B$
- For Dirac with IH $A_{eff,D} \simeq 1$ insensitive to μ_ν
- For Majorana neutrinos $A_{eff,M} = 2$, independent of μ_ν

Conclusion

- Detection rate of relic neutrinos via the ITBD reaction is sensitive to the Dirac/Majorana nature of neutrino, and to the masses of neutrinos
- For Dirac neutrino with normal hierarchy, the ITBD rate also depends on neutrino helicity, which is sensitive to neutrino magnetic moment
- Detection of relic neutrinos, together with other ongoing measurements of neutrino masses and neutrinos-less double-beta decays, can reveal fundamental properties of neutrinos and the early Universe