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CAN WE OBSERVE NEUTRINO DECAY IN THE LABORATORY?

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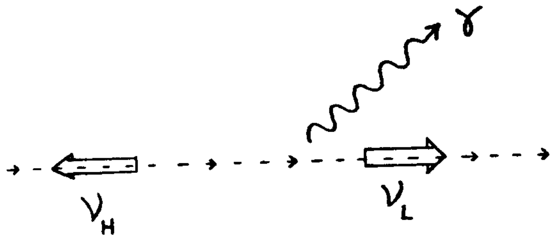
How can a neutral, heavy neutrino decay if it is too light to go into known particles and has no electric dipole moment to radiate photons? If it has a magnetic moment, perhaps it can undergo a magnetic dipole transition as sketched here, where a normal left handed neutrino flips to become a sterile right handed neutrino.



$$\nu_H \longrightarrow \nu_L + \gamma$$

For such a process to take place the neutral particle must have a magnetic moment, so what could we expect for its size?

1) Composite sub-quark models of leptons and quarks could readily imply magnetic moments for neutrinos just as quark models account for magnetic moments of n, $\Lambda°$, $\Sigma°$, and $\Xi°$. In that case, however, we might expect the magnetic moment of the neutrino to be large, comparable to that of the electron or muon.

$$\mu_\nu \sim \mu_e$$

2) Without any such model one might guess the magnetic moment of a particle with a vanishingly small mass might be extremely large.

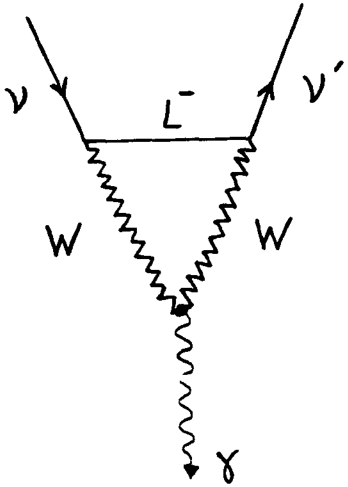
$$\mu_\nu \sim e\hbar/2m_\nu \to \infty$$

3) Or, since its charge is zero, the magnetic moment might be zero.

$$\mu_\nu \overset{?}{=} 0.$$

No. Not if we believe we understand electro-weak interactions. There are a half dozen diagrams with charged current loops that must contribute something to a magnetic moment.[1]

For example:



If we express the neutrino magnetic moment as a multiple of the electron Bohr magneton, as is commonly done, we write

$$\mu_\nu = f\ \mu_B,\ \text{where}\ \mu_B = e\hbar/2m_e.$$

The electro-weak theory implies a lower limit to the neutrino magnetic moment of $f \approx 10^{-8}$. So that without reference to experimental data we might expect

$$10^{-8}\ \mu_B < \mu_\nu < \infty.$$

The most substantial laboratory experiment we have comes from nuclear reactor data of Cowan and Reines.[2] For reactor neutrinos of a few MeV kinetic energy the weak interaction cross section is small enough that a magnetic moment of $10^{-9}\ \mu_B$ would dominate the neutrino-electron scattering. Bethe calculated the cross section for this in 1935.[3] The Cowan-Reines result of -1 ± 3 counts per second puts a limit on f.

$$\sigma(\nu_e + e) \sim f^2 \Rightarrow f \leq 10^{-9}$$

Cosmic philosophers also present "data" on the neutrino magnetic moment. For them $f < 10^{-10}$, even lower than the electro-weak lower limit. Much of this data is summarized by Bernstein, Ruderman, and Feinberg.[4]

Let us assume an optimistic model and couple it with today's rumors about the neutrino mass and look for an easy (clean) laboratory experiment. We would like to observe $\nu_H \to \nu_L + \gamma$ decay in which the magnetic moment (and helicity) flips. At the same time, the light neutrino assumes the "wrong" helicity and effectively vanishes as far as its interactions are concerned.

Optimistic Model

1. Neutrino Constituents have charge $Q \sim e/3$.
2. Constituent radius $r \approx 0.01$ F.
3. Heavy Neutrino mass $m_{\nu_H} \sim 35$ eV.
4. $m_{\nu_H} - m_{\nu_L} \approx 1$ eV.
5. $v \approx c$ for constituents.

The optimistic consequences of such a model (which some people will feel contradicts available "data") is that the lifetime of the heavy neutrino in its rest system is

$$\tau_{\nu_H} \sim 4 \times 10^7 \text{ seconds}$$

This corresponds to a heavy neutrino magnetic moment of

$$\mu_{\nu_H} \sim 10^{-3}\ \mu_B$$

instead of $10^{-8}\ \mu_B$ or $10^{-10}\ \mu_B$ suggested by "data". Perhaps one should consider that the "data" may not refer to the neutrino which we wish to observe decaying.

Can the optimistic decay be observed at a reactor? Assume a flux of electron neutrinos from a reactor that is a linear combination of light and heavy neutrinos. $\nu_e \sim (a\ \nu_L + b\ \nu_H)$. One might construct a vacuum decay box 3 meters x 3 meters x 10 meters deep surrounded by suitable anticoincidence counters and shielding. NaI or CsI counters in the box would be needed to convert and detect the soft x-rays and γ's Doppler shifted up in energy from the neutrino decay. For this geometry and the optimistic model one expects

1. Neutrino flux $\approx 2.2 \times 10^{18}$ ν's/sec.
2. Relativistic $\gamma \sim 3 \times 10^4 \Rightarrow \tau_{LAB} \sim 10^{12}$ sec.
3. One neutrino decay every 10 seconds.

The conclusion is that even with this optimistic model the experiment looks hard -- not impossible.

There is always a possibility that one might stimulate the neutrino to decay rather than waiting for the spontaneous emission discussed above. Relatively small electric and magnetic fields in the laboratory become enormous in the rest system of near massless neutrinos.

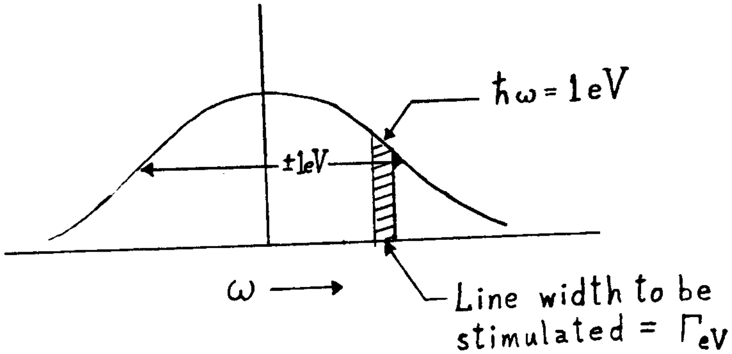
$$E_\perp' = \gamma\left(E_\perp + \frac{\vec{v}}{c} \times \vec{B}_\perp c\right) \qquad \text{(MKS Units)}$$
$$B_\perp' c = \gamma\left(B_\perp c - \frac{\vec{v}}{c} \times \vec{E}_\perp\right)$$

$$\frac{v}{c} \to 1 \text{ for } m_{\nu H} = 35 \text{ eV}/c^2$$

$$\gamma \to 3 \times 10^4 \text{ for 1 MeV reactor } \nu\text{'s}$$

20 kG in the lab becomes 1 Giga Gauss or 2×10^{13} Volts/meter in the ν rest system. E and B are orthogonal and have equal energy in their fields like a plane wave in the ν rest system.

If necessary we could change the sign of B_{lab} (or E_{lab} more easily) every few centimeters to give a frequency spectrum that reaches up to $\hbar\omega = 1eV = m_{\nu_H} - m_{\nu_L}$.



The effective fraction of the electromagnetic field energy that is available to stimulate the ν decay is Γ_{eV}/1eV. The optimistic model estimates

$$\Gamma(\nu_H \to \nu_L + \gamma) \sim 1.6 \times 10^{-23} \text{ eV}.$$

From Ed Kolb's earlier talk we learned

$$\Gamma(\nu_H \to 3\ \nu_L)/\Gamma(\nu_H \to \nu_L + \gamma) = 1.7 \times 10^{3}.$$

So assume $\Gamma_{eV} = 2.7 \times 10^{-20}$ eV. We can approximate the photon density by $(B^2/\mu_0)/h\omega(1eV)$ and optimistically assume the cross section for stimulated emission is comparable to the geometrical size assumed for ν_H, $\sigma(\text{stimulated}) \sim \pi(0.01F)^2$. The best all this optimism can do is to stimulate one decay per hour. This is to be compared to one spontaneous decay every 10 minutes.

Nevertheless, the fields may not be completely negligible. There are two other observable effects. (1) The magnetic field makes a neutrino magnetic moment precess, and (2) a large electric field can polarize charged constituents.

The expectation value <S> of the spin angular momentum will precess through an average angle <θ> if the neutrino has a magnetic moment μ_ν.

$$\frac{d\langle S\rangle}{dt} = |\vec{\mu}_\nu \times \vec{B}|.$$

$$\langle\theta\rangle = f\ e\ Bt/m_e = f\ e(\gamma B_{lab})\cdot(t_{lab}/\gamma)/m_e$$

Thus the rotation angle does not depend on the relativistic γ but only on the laboratory field B_{lab} and the time spent in it. This effect has been discussed by Cisneros.[5] As the spin flips 180° we lose left handed neutrinos and they become sterile, non interacting right handed neutrinos.

For a 20 kG field which is typical in neutrino experiments using magnetized iron one can expect 1% of the neutrinos to become sterile in a distance L_{lab} (1%). In our optimistic model where $\mu_\nu \approx 10^{-3}\ \mu_B$, L_{lab} (1%) = 15 cm. For the lower limit one expects from electro-weak interaction theory with $\mu_\nu \approx 10^{-8}\ \mu_B$, L_{lab} (1%) $\approx$ 11 km.

If a constituent model is applicable, ν_H and ν_L may have different electric polarizabilities. In that case one can expect to observe differences in neutrino oscillations produced by laboratory magnetic fields. The effective electric field in the rest system of ν_H is $E_\perp \approx \gamma B_\perp c$. Suppose the polarization energy of the light neutrino $E_L = 0$ and that of the heavy neutrino is large and of the order of $E_H \approx QE_\perp r_\nu$, where $Q \approx e/3$ is a constituent charge and r_ν is a neutrino radius of 0.01 F. Then the wave function of the heavy neutrino has a phase factor $(E_H t/\hbar) = \Delta\phi$ in the electric field which the light neutrino doesn't have. Again $(E_H \cdot t)$ is independent of the relativistic γ. To produce a 1% change in neutrino oscillations between ν_L and ν_H requires a 1% change in cos (Δϕ). One could achieve this with about 13 meters of magnetized steel. We thus may have the possibility of controlling neutrino oscillation frequencies with external fields.

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