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Speculations on Detection of the "Neutrino Sea"

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If there is a high density of ambient neutrinos—a "neutrino sea"—then on the conventional weak-interaction theory two types of possibly measurable effects exist. In one the spin direction of a transversely polarized moving electron rotates in field-free space. In the other the motion of the earth creates a torque on a ferromagnet.

The hypothesis[1] of a sea of neutrinos, filling all space and carrying a major portion of the energy density in the universe, is certainly one of the most intriguing ideas in contemporary astrophysics. Despite their possibly large numbers such neutrinos are very difficult to detect, as a result of their low energy and their exclusively weak interactions.

Here I would like to consider some possibilities for detecting such a "sea" based on the electron-neutrino interaction present in the usual theory of weak interactions.[2] Since the effects will be proportional to the lepton-number density, i.e., the *number* of neutrinos *minus* the number of antineutrinos, let us for simplicity specialize to the case of complete degeneracy and assume that we have only neutrinos or antineutrinos present, constituting a degenerate Fermi gas with Fermi level p_F. Although we will speak only of electrons, the point applies equally well to μ's if there is a μ-neutrino "sea." If the controversial "neutral weak currents" exist the sea could also affect nucleons in a way that can be easily calculated by using the method to be presented.

Let us imagine an electron moving in this "sea." In the conventional current-current $V-A$ theory the interaction density (after a Fierz transformation) is

$$\mathcal{H}(x)=(G/\sqrt{2})\overline{\psi}_e\gamma_\mu(1+\gamma_5)\psi_e\overline{\psi}_\nu\gamma_\mu(1+\gamma_5)\psi_\nu. \quad (1)$$

G is the weak coupling constant, $G\simeq 10^{-5}/m_p^{\,2}$ (we use units $\hbar=c=1$). (If the currents exist the coupling strength may be modified by a numerical factor of order 1.) In Eq. (1) the factor bilinear in the neutrino fields is essentially the neutrino (minus antineutrino) number density. The factor with the electron fields is proportional to $1-\vec{\sigma}\cdot\vec{v}$, where $\vec{\sigma}$ and $\vec{v}$ are the electron spin and velocity. This means that the two helicity states for an electron, characterized by $\vec{\sigma}\cdot\hat{v}=\pm 1$, are split in energy, and by an amount proportional to the neutrino density. It is their splitting, characteristic of the parity violation in the weak interaction, that I intend to exploit.

To estimate the magnitude of this splitting, it is simplest to go into the rest frame of the electron. In the rest frame of the "sea," defined as the frame where the neutrino velocities are isotropically distributed, the neutrinos have a density ρ, and the electron a velocity $\vec{v}$. In the rest frame of the electron, the neutrino current density has a streaming component

$$\vec{J}=2\rho\vec{v}/(1-v^2)^{1/2}, \quad (2)$$

while the pseudovector part of the electron current simply becomes its spin. Thus in the electron rest frame the spin-dependent energy is

$$2(G/\sqrt{2})\vec{\sigma}\cdot\vec{J} \quad (3)$$

and the energy difference between the two spin states is

$$\Delta E=2\sqrt{2}G\rho\vec{v}/(1-v^2)^{1/2}, \quad (4)$$

so that the effect, as claimed, is proportional to the number density of neutrinos. If both ν and $\overline{\nu}$ are present, then ρ is to be replaced by $\rho_\nu-\rho_{\overline{\nu}}$. If we assume the degenerate Fermi gas, then ρ is given by the Fermi momentum:

$$\rho=(6\pi^2)^{-1}p_F^{\,3}. \quad (5)$$

For numerical purposes we express p_F in terms of electron volts: $p_F=n$. This then gives for the energy splitting

$$\Delta E \simeq 0.6\times 10^{-24} n^3 v/(1-v^2)^{1/2} \text{ eV}. \quad (6)$$

What can we suppose for the Fermi level n? In his book[3] Weinberg quotes observational arguments from β decay, giving $n \leq 60$, and from cosmic-ray transmission, giving $n \lesssim 1$. On the other hand, a theoretical limit set by the condition that the neutrino energy density not be greater than the presumed "cosmological" energy density of 10^{-29} g/cm^3 is considerably smaller: $n \lesssim 0.75\times 10^{-2}$. It appears then, that we must contemplate detection of a spin-dependent energy splitting at most of the order of 10^{-24} eV.

One type of phenomenon that might be considered is a variation on an effect I recently discussed for the passage of transversely polarized neutrons through matter.[4] A transversely polarized spin-$\frac{1}{2}$ particle is a coherent linear combination of $\pm$ helicity states. In moving through a medium the $\pm$ helicity states are split by the weak interaction, as we have shown. This causes a phase difference to develop between the components of the transversely polarized state, corresponding to a rotation of the polarization. In other words as a transversely polarized electron moves through the neutrino "medium" its spin rotates around the line of flight, a kind of "optical activity." The angle of rotation is the phase difference between the helicity components. Working in the electron rest frame this phase difference is $(\Delta E)t$. Now expressing t in terms of the time elapsed in the rest frame of the "sea," $t \to t(1-v^2)^{1/2}$, the phase φ is

$$\varphi = 2\sqrt{2}G\rho\frac{v}{(1-v^2)^{1/2}}(1-v^2)^{1/2}t = 2\sqrt{2}G\rho v t$$
$$= 2\sqrt{2}G\rho z. \quad (7)$$

The rotation thus depends only on the distance z traveled by the electron through the "sea."[5] Numerically, using Eq. (5), we have

$$\varphi/z = 3\times 10^{-20} n^3 \text{ rad/cm}, \quad (8)$$

which appears to imply that very long flight paths for the electron must be employed: In one light year a relativistic transversely polarized electron would experience a spin rotation on the order of n^3 deg. In this approach it would be necessary to build a container for fast electrons which would be stable for a year and not disturb the helicity states of the electron.[6] Alternatively, we might sacrifice a factor 10^{-3} and use the motion of the solar system[7] around the galactic center. With the assumption that the "sea" is at rest relative to the galaxy, an electron or a system of electrons polarized at right angles to this motion and at rest on the earth, which moves at 250 km/sec ($v \simeq 10^{-3}$), will undergo a spin rotation of

$$\varphi/z \cong 0.08 n^3 \text{ sec/yr}. \quad (9)$$

Variants on this method, such as changes in magnetic resonance or hydrogen maser frequencies according to the spin direction in space, yield analogously small shifts (in terms of cycles per year).

Another, perhaps more promising, line of attack would be to use a macroscopic sample of aligned electrons to magnify the miniscule 10^{-24} eV in Eq. (7). For example, with a ferromagnet weighing 1 ton we have $\sim 10^{27}$ aligned electron spins. Once again taking the earth to move with $v \simeq 10^{-3}$ through the neutrino sea, we have that the energy of such a ferromagnet will vary according to whether it points parallel to or antiparallel to the earth's velocity; i.e., it will experience a torque. According to Eq. (6) this energy difference is roughly

$$10^{27}\times 10^{-24}\times 10^{-3} n^3 \text{ eV} \simeq n^3 \text{ eV}. \quad (10)$$

This is still not a very large energy, but in gravity-wave detectors, which our hypothetical device in some ways resembles,[8] energies on the order of kT or substantially less, depending on the "Q" of the system, can be detected.[9] If an appropriate mechanical configuration can be found (a hanging magnet would act as a pendulum, for example), this would suggest that levels of the "sea" even below the "cosmological" value 0.75×10^{-2} eV could be plumbed.

Since it appears impossible to get a sample of aligned electrons without simultaneously getting a magnet, the great problem here, as with the other approaches, would seem to be the control or elimination of external magnetic fields to a very great accuracy. This effect is in most respects simply like the presence of a weak external magnetic field, with one important difference, due to the $\vec{\sigma}\cdot\vec{v}$ structure of the interaction: The "field" is always in the direction of the velocity. This feature may be helpful in distinguishing the effect from that of fixed external fields. In any case, the difficulty of the magnetic background problem seems to imply that magnetic shielding with superconductors must be used. The ferromagnet completely enclosed in superconductor, for example, would be a sample of aligned electrons that would not act as a magnet, at least in principle.

Finally, it is worth noting that if we interpret the recent experimental results[10] in favor of the existence of "neutral weak currents" to mean that a conventional weak interaction with parity violation exists between the neutrino and the neutron, then the effects just discussed will exist not only with electrons but also for neutrons, or more generally for nuclei, and with roughly similar strength. Since nucleons or nuclei have much smaller magnetic moments than electrons, and are therefore less subject to magnetic disturbance, they might turn out to be a more suitable probe than electrons. In this connection[11] Professor Fairbank points out that the ability of dilute solutions of He^3 in low-temperature He^4 to retain their nuclear polarization for long times could be used to search for the kind of effect estimated in Eq. (9); in other words, the motion of the earth would cause the oriented He^3 nuclei to rotate their spins. Although present technique is not yet at the levels implied by Eq. (9), this would appear to be an interesting line to pursue further.

The possible experiments certainly do not appear easy. On the other hand the detection of the kind of "spin ether" that a positive effect would imply would be very fascinating and of profound importance for our understanding of the universe.

I would like to thank the members of the gravity-wave detector group at the Max-Planck-Institut for useful discussions, and G. Börner and P. Kakfa for conversations on astrophysics. Talks with A. Zichichi and G. Cocconi were of great help and I would like in particular to thank L. Wolfenstein for his suggestions.

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[1]S. Weinberg, Phys. Rev. 128, 1457 (1962).

[2]The conventional weak interaction theory is discussed by J. J. Sakurai, "Invariance Principles and Elementary Particle" (unpublished). It should be borne in mind that although νe elastic scattering as we need it is predicted on the conventional theory, it is yet to be directly observed. This is presumably due to its very small cross section at low energy. Experiments by F. Reines and collaborators are presently in progress to observe this process.

[3]See S. Weinberg, *Gravitation and Cosmology* (Wiley, New York, 1972), Sect. 15.6.

[4]L. Stodolsky, Phys. Lett. 50B, 352 (1974).

[5]It is amusing that Eq. (8) agrees with the answer that would follow from direct application of the index of refraction formula for an ordinary gas, as in Ref. 4, although it is not entirely clear that the formula should apply to a "neutrino gas." An apparent factor-of-2 discrepancy between Eq. (7) and the corresponding Eq. (8) of Ref. 4 is resolved if we realize that the "electron gas" in ordinary matter is a mixture of both left- and right-handed particles and thus only half as effective in creating the "weak optical activity."

[6]A. Zichichi has speculated that this might be possible with a variant of the $g-2$ experiment (private communication).

[7]I am grateful to L. Wolfenstein for a comment stimulating this line of thought.

[8]I would also like to thank G. Cocconi for pointing out the analogy with gravity-wave detectors and an interesting discussion on the point.

[9]W. Winkler, private communication. Gravity-wave detectors are discussed by J. Weber, Phys. Today 21, No. 4, 34 (1968).

[10]F. J. Hoser *et al.*, Phys. Lett. 46B, 138 (1973).

[11]W. Fairbank, private communication.