Possibility of detecting relict massive neutrinos

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The coherent intensification of the interaction of relict massive neutrinos with grains of matter with a size on the order of the neutrino wavelength suggests that it might be possible to detect a galactic neutrino sea by virtue of the mechanical pressure which it exerts in the direction opposite that in which the solar system is moving in the galaxy.

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Experimental evidence[1] of the existence of neutrinos with a mass ~ 30 eV and analysis[2–10] of how relict massive neutrinos would affect the evolution of the universe and the formation of galaxies make it extremely urgent to search for laboratory methods for detecting relict massive neutrinos. In this letter we wish to call attention to an effect which was pointed out back in 1970 by one of the authors (B.F.S.): a coherent intensification of the mechanical effect of nonrelativistic neutrinos on grains of matter with a size on the order of the neutrino wavelength. This effect raises the possibility in principle of a laboratory test of the hypothesized cosmological role of massive neutrinos.[2–10]

The hot-universe theory predicts[2–10] a background of relict neutrinos in the modern universe with an average number density $150 \cdot N_\nu$ cm^{-3}, where N_ν is the number of types of neutrinos. If the relict neutrinos with mass $m_\nu \approx 30$ eV were distributed uniformly, they would currently have[2–10] an average velocity ~ 5 km/s and a wavelength $\lambda = h/mv = 0.2$ cm. Actually, massive neutrinos should be distributed nonuniformly,[2–6,9,10] concentrating in the local galaxy with an average number density $n_\nu \approx 10^7$ cm^{-3}. The average neutrino velocity in the local galaxy should be[4–6] on the order of the velocity at which the solar system moves through the galaxy, $v \approx 300$ km/s, and the neutrino wavelength should be correspondingly smaller: $\lambda \approx 4 \times 10^{-3}$ cm. Even in this case the neutrino wavelength is macroscopic, so that the scattering of neutrinos by dust particles of size $a < \bar{\lambda}$ should occur coherently. The same is true for an object whose volume is less than half filled by separate dust particles of size $a \lesssim \bar{\lambda}$ or for a porous object with pores of the same size. (If the object were filled to a greater degree by the dust particles, or if the pore size were smaller, there would be a destructive interference of the contributions of the individual dust particles or of the various parts of the porous object, and the coherence would be destroyed. Destructive interference also occurs if the dust particles are large, $a > \bar{\lambda}$.) Motion of the solar system with respect to the isotropic "galactic neutrino sea" causes an acceleration of such objects by virtue of the coherent scattering of neutrinos. This effect should be seen in experiments of the Eötvös type. At $m_\nu \approx 30$ eV the neutrino sea imparts an acceleration $\sim 10^{-22}$ cm/s^2 to 1 g of matter, as a result of 2×10^3 neutrino scatterings per 1 s.

Let us examine this effect more closely. The scattering of the ν_e neutrino by electrons results from an interference of neutral and charged currents, while the scattering of ν_e by nuclei or the scattering of ν_μ or ν_τ by nuclei or electrons would result exclusively from neutral currents. In the nonrelativistic limit the corresponding amplitudes for coherent scattering by a small sphere of density ρ and size $a \lesssim \lambda\!\!\!^{-}$ are as follows, the same for neutrinos and antineutrinos[11,12]:

$$A(\nu_\nu, \nu_\tau) = -\frac{Gm_\nu}{4\sqrt{2}\pi}(A - Z)N_A, \qquad (1)$$

$$A(\nu_e) = \frac{Gm_\nu}{4\sqrt{2}\pi}(3Z - A)N_A\,,$$

where Z is the charge and A the atomic number of the atoms of the material, m_ν is the neutrino mass, and $N_A = (\rho/Am_p)(4\pi/3)a^3$ is the number of atoms in the small sphere. If the neutrino mass matrix is diagonal, then ν_e, ν_μ, and ν_τ have definite masses. In this case we find the cross section for coherent neutrino scattering to be

$$\sigma = \sigma_0 N_A^2 k_L^2\,, \qquad (2)$$

where $\sigma_0 = (G^2 m_\nu^{\,2}/\pi) = 1.3 \times 10^{-53}$ cm^2 for $m_\nu = 30$ eV and $k_L = 3Z - A$ for ν_e or $k_L = Z - A$ for ν_μ and ν_τ. The scattering of the neutrino by the small sphere causes a momentum transfer $\Delta p \sim 2m_\nu v$ to the sphere, so that the coherent scattering of a neutrino flux $F_\nu = n_\nu v$ corresponds to the exertion of a force

$$f = \frac{dp}{dt} = F_\nu \sigma\, \Delta p = 2n_\nu v \sigma_0 N_A^2 k_L^2 m_\nu v \qquad (3)$$

on the small sphere, which would give it an acceleration

$$w = \frac{f}{AN_A m_p} = 10^{-22}(k_L/A)^2 \text{ cm/s}^2 \qquad (4)$$

for $n_\nu = 10^7$ cm^{-3}, $v = 3 \times 10^7$ cm/s, $a = \lambda\!\!\!^{-}$, and $\rho = 10^2$ g/cm^3. The acceleration described by (4) reaches a maximum at $a = \lambda\!\!\!^{-}$; this maximum value, $w_{\max} = 10^{-22}$ cm/s$^2(k_L/A)^2$, dose not depend on the neutrino mass. In principle, measurements of w for materials with various values of Z/A could make it possible to distinguish between the contributions of ν_e and the other types of neutrinos and thereby obtain information about the ν_μ and ν_τ masses which cannot be obtained by other laboratory methods.

If the mass matrix is instead nondiagonal, then ν_e, ν_μ, and ν_τ are superpositions of states ν_1, ν_2, and ν_3 with definite masses m_1, m_2, and m_3:

$$\nu_i = \sum_L a_{iL}\, \nu_L\,, \qquad L = e, \mu, \tau\,; \qquad i = 1, 2, \ldots .$$

In this case ν_i will be scattered coherently, with the cross section

$$\sigma_i = \sigma_0 N_A^2 k_i^2\,, \qquad (5)$$

where $k_i^2 = |A - Z - 2Z \sum_i a_{ei} a_{ej}^+|^2$. In this case, measurements of the acceleration in (4) for various materials could yield information about the mixing of neutrinos.

Several analogous effects have been studied previously. The coherent scattering of neutrinos by nuclei resulting from a neutral vector current was discussed in Refs. 13 and 14. The macroscopic manifestations of the coherent scattering of the massless neutrinos in matter were discussed in Refs. 11, 15, and 16, and the possibility of detecting neutrinos on the basis of their mechanical effects was discussed in Refs. 10–12, 15, and 16. A discussion[12] of the possible acceleration of an object due to the surface pressure exerted by relict massive neutrinos, caused by a change in the refractive index for neutrinos in the material, led to the conclusion that it would be impossible to detect this effect in practice. For a porous object or for one filled with dust particles, which we are discussing here, the effect is a volume effect, so that the acceleration of the object would be substantially increased ($w \sim 10^{-22}$ cm/s^2).

A further enhancement of the effect might be achieved by putting the scattering centers in a regular array at separations $\sim\bar{\lambda}$. In this connection it would be interesting to search for the effect by using a system of parallel wires $\sim\bar{\lambda}$ in diameter at a spacing of $\sim\bar{\lambda}$. The effect would be maximized if the wires were oriented perpendicular to the direction in which the solar system is moving through the galaxy.

At the present state of the art, it is possible to measure small accelerations of about 10^{-16} cm/s^2 over a time $\sim 10^7$ s. However, there is no fundamental limit on the measurements of arbitrarily small accelerations.[17] For an acceleration greater than 2×10^{-24} cm/s^2 (with a signal sampling time $\sim 10^7$ s, a modulation frequency $\sim 10^{-3}$ rad/s, and a test object with a total mass ~ 10 kg) it would not be necessary to use quantum nondestructive measurements.

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