Recent results of the neutrino mass squared measurements and the coherent neutrino–cold-dark-matter interaction

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It is argued that external coherent potentials for neutrinos in the electronvolts range would give a detectable modification of the electron spectrum in tritium beta decay. We show that such very large potentials may be obtained from a novel long-range interaction between neutrinos and galactic baryonic and/or nonbaryonic matter if the new force is mediated by massless vector particles. [S0556-2821(98)00508-6]

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According to the results of several recent experimental searches for neutrino mass in tritium beta decay, electron neutrinos [1,2,3,4,5,6,7] are found to have negative values of their mass squared ($m^2_{\nu_e}<0$). The best fits of all experiments require a negative mass squared for the electron neutrinos to be in the range $10-10^2$ eV^2. In view of the above results for the neutrino masses squared, two mechanisms with unconventional neutrino interactions have been proposed so far as an explanation for this effect. The first one [8] was based on the hypothesis that neutrinos are tachyons, while the other [9] considered the possibility that there is a hidden anomalous long-range interaction of neutrinos that is responsible for this effect. It is to be mentioned here that there is also an indication for the negative mass squared of muon neutrinos (see, e.g., Ref. [8] and the references therein) determined from the measured muon momentum in the π^+ decay at rest. Here we show that some unconventional interactions of electron antineutrinos from the decay process $^3\mathrm{H}\to{}^3\mathrm{He}+e^-+\overline{\nu_e}$ with a background of the galactic dark matter could induce the ''phase space mass'' for antineutrinos of a needful sign and magnitude (of a few eV) as to explain the effect. Apart from the above anomaly, which is located close to the end point, it is shown below that an external potential in the electronvolt range can also give an observable shift in the spectrum of beta decay at lower energies (far from the end point). This could be of relevance too, as some experimental data may indicate a discrepancy (in the electronvolt range) between the measurements of the ^{3}H-^{3}He mass difference employing β spectrometers and other methods (for a review, see Ref. [10]).

The effect of matter on neutrino propagation is contained in the ''phase space mass''; it is associated directly with the kinematics of the particle and can be given a clear operational definition in terms of phase space behavior for particle reactions. Indeed, the above effect would change the familiar Kurie plot $K(E)$ for the process $^3\mathrm{H}\to{}^3\mathrm{He}+e^-+\overline{\nu_e}$ to

$$K^2(E_e)\propto(Q-E_e-V_{\overline{\nu}_e})\sqrt{(Q-E_e-V_{\overline{\nu}_e})^2-m^2_{\overline{\nu}_e}},\qquad(1)$$

where E_e is the energy of the emitted electron, $m_{\overline{\nu}_e}$ is the vacuum neutrino mass, Q is the vacuum electron mass plus the energy release in the tritium decay, and $V_{\overline{\nu}_e}$ is the external potential for a $\overline{\nu_e}$ in a background of the galactic dark matter. Hence one requires that $-2(Q-E_e)V_{\overline{\nu}_e}$ be in the range $10-10^2$ eV^2. Since the effect of the mass of the electron antineutrino becomes appreciable only near the end point where $Q-E_e$ is comparable to $m_{\overline{\nu}_e}$, one needs $-V_{\overline{\nu}_e}\simeq O(eV)$. Here we do not aim to perform a fit to the experimental spectrum, but only to reproduce the ''negative mass squared.'' Let us stress that Eq. (1) is valid for Dirac neutrinos where the potential term acts on the left- and right-handed chiral components with the same strength and sign. In fact, for $m_{\overline{\nu}_e}=0$ the role of the potential in Eq. (1) is just to give an overall shift of the Kurie plot. In this case, one can obtain (with the appropriate sign for $V_{\overline{\nu}_e}$) that the measured spectrum of beta decay is larger than that for $m_{\overline{\nu}_e}=V_{\overline{\nu}_e}=0$ (a ''negative mass squared''), but is unable to account for a bumplike structure near the end point.

We presently use the constraints on novel long-range forces coupling neutrinos and galactic dark matter [11]; these forces may be responsible for bending of the neutrino trajectory and were assumed to be mediated by massless vector bosons coupled to a novel neutrino charge q_ν (which may represent, for example, a leptonic interaction). If the source of the force is dark matter particles with a charge q_x, a limit

$$|q_\nu q_x|\lesssim 3\times10^{-40}m_x/m_p\qquad(2)$$

was originally derived [11] from the observed duration of the neutrino pulse from the Supernova 1987A. However, it was observed [12] later on that because of screening effects which operate on galactic scales, the limit (2) does not actually depend on the neutrino charge q_ν and now takes the form

$$q_x\lesssim10^{-16}m_x/m_p\,.\qquad(3)$$

In addition, let us mention a very strong bound $q_{\nu_e}\lesssim10^{-24}$ [13] for the first generation, derived from Dicke's experimental limit on the equivalence between inertia and gravity. We restrict ourself here to the cold-dark-matter candidates such as dark baryons and weakly interacting massive particles (WIMPs) with masses in the range 1 GeV–1 TeV. There is, however, an obvious limitation here because of the vector character of the hypothesized new interaction, since heavy Dirac neutrinos have been ruled out as the primary component of the galactic halo by direct-detection experiment [14].

Our main observation here is that the external potential $V_{\bar{\nu}_e}$, arising from the coherent interaction of $\bar{\nu}_e$'s with dark matter constituents, depends only on the ratio of charges, but not on their absolute values, making thereby the value of $V_{\bar{\nu}_e}$ practically independent of the above constraints. In the framework of thermal field theory, $V_{\bar{\nu}_e}$ is based on the medium-induced self-energy for a $\bar{\nu}_e$ and the major contribution to $V_{\bar{\nu}_e}$ comes from the tadpole graph (where the massless vector boson carries no four-momentum and with dark-matter particles circulating inside the medium-induced loop). In the real-time version [15] of thermal field theory, the computation of $V_{\bar{\nu}_e}$ is straightforward and reads

$$V_{\bar{\nu}_e}=(q_\nu q_x/m_{\rm el}^2)(N_{\bar{x}}-N_x), \tag{4}$$

where the sign of the dark-matter asymmetry $N_x-N_{\bar{x}}$ is reversed for antineutrinos. It is not important that the dark-matter phase space distribution is precisely thermal. In the massless-soft regime, the resummation program developed by Braaten and Pisarski [16] must be applied, resulting in the use of the resummed propagator for the massless vector boson in Eq. (4). The static limit of the resummed propagator in then responsible for the appearance of $m_{\rm el}$ in Eq. (4), the inverse Debye length. Assuming a spherical and isotopic velocity distribution, the dark-matter halo density in the solar neighborhood is roughly $\rho_x \simeq 0.3$ GeV cm^{-3}. Since $V_{\bar{\nu}_e}$ has to be negative, also $N_x > N_{\bar{x}}$. The appreciable external potential is needed for a neutrino only, and so we have to assume that $q_e \ll q_{\nu_e}$. The pure neutrino coupling to a long-range force may represent a theoretical difficulty (see, however, Ref. [17]).

It can be shown that the major contribution to $m_{\rm el}^2$ comes from the CP-symmetric cosmic neutrino background with $T_\nu \simeq 1.9$ K, giving

$$m_{\rm el}^2=\frac{1}{3}\sum_r q_{\nu_r}^2 T_{\nu_r}^2 \langle v_{\nu_r}^{-1}\rangle, \tag{5}$$

where $\langle v_{\nu_r}^{-1}\rangle = m_{\nu_r}/3.15 T_{\nu_r}$ if $m_{\nu_r} \gtrsim T_{\nu_r}$; otherwise, $\langle v_{\nu_r}^{-1}\rangle \simeq 1$. If all neutrinos are nearly massless, even the cosmic neutrino background remains relativistic today, and to obtain $V_{\bar{\nu}_e}$ in the eV range one needs (for $q_{\nu_e}\equiv q_{\nu_\mu}\equiv q_{\nu_\tau}\equiv q_\nu$, $N_x = \rho_x/m_x$)

$$(q_x/q_\nu)(m_x/{\rm GeV})^{-1} \simeq O(10^7). \tag{6}$$

If neutrinos have nonrelativistic velocities, they can be polarized even more easily by a test charge $q_{\bar{\nu}_e}$, giving, for equal couplings,

$$(q_x/q_\nu)(m_x/{\rm GeV})^{-1}(m_\nu/10^{-4}\ {\rm eV})^{-1} \simeq O(10^6), \tag{7}$$

where m_ν is the highest mass component.

Finally, we consider the possibility that $m_{\rm el}^2$ is dominated by a neutrino weighing about 10 eV. Namely, such a neutrino is by far the most plausible candidate for the hot dark part of the matter and then $T_\nu \simeq 50$ K [18]. Then we get

$$(q_x/q_\nu)(m_x/{\rm GeV})^{-1}(m_\nu/10\ {\rm eV})^{-1} \simeq O(10^{12}). \tag{8}$$

For dark baryons the estimates above should be corrected by a fraction of the dark halo of our galaxy that can be accounted for by baryons [faint stars and massive compact halo objects (MACHOs)] and which is only 0.05–0.3 [19]. In addition, the extra correction ($\sim 10^{-2}$) in the last case [Eq. (8)] must be done when $q_x = q_\nu$ as light neutrinos constitute much smaller fraction of the density of the galactic halo [18] than they do of the cosmological density in a typical mixed-dark-matter scenario [20]. The vector character of the new interaction precludes any possible coupling to Majorana fermions (in general, mass eigenstates neutralinos are Majorana particles). For the case where the WIMP is a Dirac fermion, the estimates above should be corrected by a fraction of the halo that can be accounted for by Dirac WIMPs together with an asymmetry factor α/Y_∞. The relative abundance of WIMPs and anti-WIMPs should be the same as in the universe. Here α is the cosmic asymmetry scaled to the entropy density and Y_∞ is the asymptotic value of the corresponding abundance of WIMPs plus anti-WIMPs. We find that for $\alpha \sim 10^{-10}$ the asymmetry factor could be of order of unity in the preferred mass range. Obviously, the ratio q_x/q_ν from Eqs. (6), (7), and (8) (with all corrections just mentioned) is not affected by the constraints discussed above. Finally, as we are forced to speculate about a possible charge asymmetry of the universe (at least locally), the magnitudes of the charges are not restricted in our scenario so that any limit on the net charge can be respected.

In summary, we found that very large external potentials for the electron antineutrino emitted from tritium beta decay could be induced if there is a novel long-range force mediated by massless vector bosons, thereby coupling neutrinos and dark-matter particles residing in the galactic halo. This is due to the screening property of the resummed propagator for massless vector bosons used in the calculation of the tadpole self-energy diagram for antineutrinos. If the relic particle asymmetry is positive, an enhancement in the electron energy spectrum near as well as far from the end point can be obtained.

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