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Neutral current induced neutrino oscillations in a supernova

Alexander Kusenko*
Theory Division, CERN, CH-1211 Geneva 23, Switzerland
and
Gino Segrè†
Department of Physics and Astronomy, University of Pennsylvania
Philadelphia, PA 19104-6396

Abstract

Neutral currents induced matter oscillations of electroweak-active (anti-)neutrinos to sterile neutrinos can explain the observed motion of pulsars. In contrast to a recently proposed explanation of the pulsar birth velocities based on the $\nu_{\mu,\tau} \leftrightarrow \nu_e$ oscillations, the heaviest neutrino (either active or sterile) would have to have mass of order several keV.

* email address: kusenko@mail.cern.ch
†email address: segre@dept.physics.upenn.edu

Neutrino physics continues to be at the forefront of research in particle physics and astrophysics. There are many clues but the neutrino mass matrix is still unknown and even the number of neutrino species is still undetermined [1, 2]. Although the number of light electroweak active neutrinos is known from LEP, there are reasons to believe that massive sterile neutrinos may exist and mix with the electroweak active neutrinos. First, a variety of experimental [1, 2, 3] and astrophysical [4] data can only be explained simultaneously if there are more than three neutrino species. Second, a standard model singlet fermion can naturally appear as a modulino in models with broken supersymmetry.

It was recently pointed out [4] that the proper motions of pulsars can be explained if adiabatic neutrino oscillations take place inside a cooling neutron star created in a supernova explosion. The star's magnetic field affects the location of the resonance in an up-down asymmetric manner and causes the neutrinos of a certain flavour to be emitted from different depths in different directions. Since the temperature inside a cooling neutron star depends on the depth, the momentum distribution of the outgoing neutrinos will not be spherically symmetric. This can give the pulsar a sufficient recoil velocity in good agreement with data [4].

If the pulsar motions are related to neutrino oscillations, they can be used as a source of information about neutrino masses and provide for new astrophysical "laboratory" to complement the high-energy experiments. It is, therefore, important to examine variations of the scenario proposed in Ref. [4] and their ramifications for neutrino physics. In this letter we concentrate on the effects sterile neutrinos can have on the motion of pulsars and estimate the magnitude of the pulsar birth velocity due to sterile-to-active neutrino oscillations. The main difference on the theoretical side between this effect and that discussed in Ref. [4] is that neutral currents play a crucial role in the oscillations of sterile neutrinos.

As neutrinos pass through matter, they experience an effective potential

$$V(\nu_s) = 0 \tag{1}$$

$$V(\nu_e) = -V(\bar{\nu}_e) = V_0\,(3\,Y_e - 1 + 4\,Y_{\nu_e}) \tag{2}$$

$$V(\nu_{\mu,\tau}) = -V(\bar{\nu}_{\mu,\tau}) = V_0\,(Y_e - 1 + 2\,Y_{\nu_e}) \ + \ c_{_L}^{z}\,\frac{\vec{k}\cdot\vec{B}}{k} \tag{3}$$

where Y_e (Y_{ν_e}) is the ratio of the number density of electrons (neutrinos) to that of neutrons, $\vec{B}$ is the magnetic field, $\vec{k}$ is the neutrino momentum, $V_0 = 10\,\mathrm{eV}\,(\rho/10^{14}\mathrm{g\,cm^{-3}})$ and

$$c_{_L}^{z} = \frac{eG_{_F}}{\sqrt{2}}\left(\frac{3N_e}{\pi^4}\right)^{1/3} \tag{4}$$

The magnetic field dependent term in equation (3) arises from a one-loop finite-density contribution [5] to the self-energy of a neutrino propagating in a magnetized medium[1]. An excellent review of the neutrino "refraction" in magnetized medium is found in Ref. [1].

Only electrons contribute to the one-loop neutrino self-energy diagram with a charged current and an external photon source (magnetic field). There are contributions from both electrons and protons to the the diagram with a neutral current and an external photon source. In a neutral plasma in equilibrium, the neutral current diagrams with electrons and protons cancel the charged current contribution [5]; therefore, there is no $(\vec{k}\cdot\vec{B})$ term in equation (2). In the case of ν_μ and ν_τ, the charged current diagram is absent and the effective potential (3) is magnetic field dependent.

The condition for resonant oscillation $\nu_i \leftrightarrow \nu_j$ is

$$\frac{m_i^2}{2k}\,cos\,2\theta_{ij} + V(\nu_i) = \frac{m_j^2}{2k}\,cos\,2\theta_{ij} + V(\nu_j) \tag{5}$$

where $\nu_{i,j}$ can be either a neutrino or an anti-neutrino.

We consider a hierarchical mass matrix for neutrinos with $m(\nu_\tau) \gg m(\nu_\mu) \gg m(\nu_e)$. Most of the time after the onset of the supernova explosion, the right-hand sides of equations (2) and (3) are negative because the deleptonization of nuclear matter during the first second causes the ratio Y_e to drop from 0.4 to about 0.1; as the cooling of the neutron star proceeds, Y_e further decreases to 0.04. $Y_{\nu_e} \sim 0.07$ is also small.

The sign of the mass difference determines whether or not the resonant oscillations of a certain type can occur. If the sterile neutrino is heavier than other species, the oscillations of the type $\nu_s \leftrightarrow \bar{\nu}_i$ can take place. If, on the other hand, ν_s is lighter than, *e. g.*, ν_τ, oscillations

[1] We emphasize the difference between these chirality-preserving oscillations and the spin and flavor precession of neutrinos in magnetic field studied, *e. g.*, in Refs. [6, 7], which can occur if the neutrino magnetic moment is sufficiently large. Such oscillations can also have an effect on the pulsar motions if the magnetic field is inhomogeneous [7].

$\nu_s \leftrightarrow \nu_\tau$ are possible inside the neutron star.

The neutron star will receive a kick if the following two conditions [4] are satisfied: (1) the adiabatic oscillation $\nu_i \leftrightarrow \nu_j$ occurs at a point inside the i-neutrinosphere but outside the j-neutrinosphere; and (2) the difference $[V(\nu_i) - V(\nu_j)]$ contains a piece that depends on the relative orientation of the magnetic field $\vec{B}$ and the momentum of the outgoing neutrinos, $\vec{k}$. If the first condition is satisfied, the effective neutrinosphere of ν_j will coincide with the surface formed by the points of resonance. The second condition ensures that this surface (a "resonance-sphere") will be deformed by the magnetic field in such a way that it will be further from the center of the star when $(\vec{k} \cdot \vec{B}) > 0$, and nearer when $(\vec{k} \cdot \vec{B}) < 0$. The average momentum carried away by the neutrinos depends on the temperature of the region from which they exit. The deeper inside the star, the higher is the temperature. Therefore, neutrinos coming out in different directions will carry momenta which depend on the relative orientation of $\vec{k}$ and $\vec{B}$. This causes the asymmetry in momentum distribution. An 1% asymmetry is sufficient to generate birth velocities of pulsars consistent with observation [4].

Since the sterile neutrinos have a zero-radius neutrinosphere, $\nu_s \leftrightarrow \bar{\nu}_{\mu,\tau}$ oscillations can be the cause of the pulsar motions if $m(\nu_s) > m(\nu_{\mu,\tau})$. If, on the other hand, $m(\nu_s) < m(\nu_{\mu,\tau})$, $\nu_s \leftrightarrow \nu_{\mu,\tau}$ oscillations can play the same role. We emphasize that oscillations between a sterile neutrino and an electron (anti-) neutrino are irrelevant for the recoil velocity of a pulsar. We will come back to this point below when we discuss the constraints from the supernova 1987A.

In the case of active neutrino oscillations, the magnitude of the "kick" was found [4] to be

$$\frac{\Delta k}{k} = \frac{e}{3\pi^2} \left(\frac{\mu_e}{T} \frac{dT}{dN_e} \right) B, \tag{6}$$

The following changes occur for the active to sterile neutrino oscillations: $N_e \equiv Y_e N_n$ is replaced by $N_n/2$, and there is an overall factor of 2 because, for a hierarchical mass matrix, the oscillations of both ν_μ and ν_τ occur at nearby points, both subject to the asymmetry in the magnetic field. Therefore, for the neutral current induced oscillations, the size of the asymmetry in momentum distribution is

$$\frac{\Delta k}{k} = \frac{4e}{3\pi^2} \left(\frac{\mu_e}{T} \frac{dT}{dN_n} \right) B, \tag{7}$$

To calculate the derivative in (7), we use the relation between the density and the temperature of a non-relativistic Fermi gas:

$$N_n = \frac{2(m_n T)^{3/2}}{\sqrt{2}\pi^2} \int \frac{\sqrt{z}dz}{e^{z-\mu_n/T}+1} \tag{8}$$

where m_n and μ_n are the neutron mass and chemical potential. The derivative (dT/dN_n) can be computed from (8). Finally,

$$\frac{\Delta k}{k} = \frac{4e\sqrt{2}}{\pi^2} \frac{\mu_e \mu_n^{1/2}}{m_n^{3/2} T^2} B. \tag{9}$$

It is instructive to compare the magnitude of this asymmetry to that produced by the active neutrino oscillations [4]. The latter agreed well with the observed velocities of pulsars for $B \sim 10^{14}$ G. The right-hand side of equation (6) is different from equation (9) by the factor $X = 4\sqrt{2\mu_n}\mu_e/m_n^{3/2}$, which is maximized when the oscillations take place in the dense interior of the star where the density is of order $10^{14}\,\mathrm{g\,cm^{-3}}$. This corresponds to $N_n \sim (100\,\mathrm{MeV})^3 \approx (4/3\sqrt{2}\pi^2)(\mu_n m_n)^{3/2}$. Therefore, $X \leq 0.15$. If the sterile neutrino oscillatiosn are to explain the observed birth velocities of pulsars, the magnetic field inside the star must be at least a factor of 6 greater than that needed for the active neutrino oscillations to produce the required asymmetry, or of order $B \sim 10^{15}$G.

We conclude, therefore, that the active $\leftrightarrow$ sterile neutrino oscillations, biased by the magnetic field, can result in the kick velocities of order ~ 500 km/s if the resonant conversion takes place at densities of order $\sim 10^{14}$ g/cm^3, one neutrino has a mass in the keV range, and the magnetic field is $B \sim 10^{15} G$. This requires the mass of one of the neutrinos to be in the 3 keV to 10 keV range. This value of B is, as was stated earlier, an order of magnitude larger than the B field needed in (6), but is still an order of magnitude smaller than the B field needed to begin to explain the kick by other weak interactions [7, 8]. Of course, it is not obvious that such large magnetic fields are possible inside a neutron star.

The mixing angle can be very small, because the adiabaticity condition is satisfied if

$$l_{osc} \approx \left(\frac{1}{2\pi} \frac{\Delta m^2}{2k} \, sin\, 2\theta \right)^{-1} \approx \frac{10^{-2}\,\mathrm{cm}}{sin\, 2\theta} \tag{10}$$

is smaller than the typical scale of the density variations. Thus the oscillations remain adiabatic as long as $sin^2 2\theta > 10^{-8}$.

Since the sterile neutrino oscillations are assumed to occur inside the $\bar{\nu}_e$-sphere, the flux of electron anti-neutrinos observed by IMB and Kamiokande [9] is not affected as long as the sterile neutrinos don't overcool the star. In the mass range of interest, $\Delta m \sim 3 - 10$ keV, there is an upper limit [10] on the mixing angle of the sterile neutrino and the electron neutrino, $sin^2 2\theta_{e,s} > 10^{-6}$. For larger mixing angles, too big of a fraction of the energy is carried off by the sterile neutrinos, and the flux of electron neutrinos diminishes, in contradiction with the observation of $\bar{\nu}_e$ events following SN1987A by IMB and Kamiokande [9].

Some comments are in order. The above estimate of the asymmetry in the momentum of the outgoing neutrinos is reliable when only a small fraction of the total energy is emitted as sterile neutrinos. In the case of active neutrino oscillations [4], only 1/6 of all neutrino types exhibit the asymmetry, while the temperature distribution is determined by the emission of all six. The effect of the change in the position of the resonance on the overall temperature distribution is then small (next order in 1/6 treated as a small perturbation on the isotropic flux) and, to first approximation, can be neglected. In the case of active to sterile neutrino oscillations, it is typically 1/3 of the total neutrino flux that is asymmetric. This is because, for the hierarchical mass matrix with $m(\nu_s) \gg m(\nu_{e,\mu,\tau})$, the $\nu_s \leftrightarrow \bar{\nu}_\tau$ oscillations will take place at approximately the same density as the $\nu_s \leftrightarrow \bar{\nu}_\mu$ oscillations. However, it is still reasonable to use the same approximation as before.

Another possible caveat should be mentioned. The temperature and density change rapidly in the vicinity of the neutrinospheres, where the cooling takes place. Therefore, in calculating the momentum anisotropy in Ref. [4], one could safely neglect the change in the luminous area when the position of the resonance changed slightly. In general, the total momentum is proportional to $T^4 \times (\mathsf{area})$, but as long as the temperature varies faster than $1/R^2$, the area factor can be considered constant. Sterile neutrino oscillations may occur, however, deeper inside the neutron star, where the change in temperature is not so rapid, and the changes in the luminous area can modify the above estimate.

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