Anisotropic neutrino emission in β processes induced by an intense magnetic field

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The conditions for an asymmetric emission of neutrinos in β processes involving free nucleons under the influence of an intense magnetic field at high densities and temperatures are studied.

Relativistic neutrino processes are emerging as some of the most urgent problems in astrophysics. Although the outlook for the direct detection of neutrinos produced in supernovae is not bright at this point, it is extremely important to search for observable effects which would accompany neutrino emission.

Let us examine the consequences of the effect of intense magnetic fields on so-called URKA processes. As has been shown in several studies,[1] these reactions are responsible for most of the irreversible energy loss of stars at high densities ($\rho > 10^8$ g/cm^3) and high temperatures ($T > 7\times 10^9$ K). When we also take into account the suggestion that about 99% of all the energy released during gravitational collapse is transformed into a neutrino flash (see Ref. 2, for example), we would expect that the intense magnetic fields of stars would give rise to a global manifestation of parity breaking in weak interactions.

Let us consider the situation in which a kinetic equilibrium with respect to β processes is established primarily through the interaction of electrons and positrons with free nucleons, and β processes involving nuclei can be ignored. We also assume that the collapsing core of a star is transparent to neutrinos and antineutrinos and that the neutron-proton gas is nondegenerate. These approximations are justified by the high boundary values[3] of the critical temperature for nontransmission, $T > 5\times 10^{10}$ K, and of the degeneracy density, $\rho_d > 6\times 10^{13}$ g/cm^3.

The probabilities for URKA processes involving free nucleons in an intense magnetic field,

$$n \to p + e^- + \tilde{\nu}, \quad e^- + p \to n + \nu, \quad e^+ + n \to p + \tilde{\nu}, \tag{1}$$

can be calculated in a common manner by using the theory of allowed β transitions and the procedure for exactly incorporating the effect of a field on light charged particles.[4]

The asymmetry of the neutrino emission is determined by the coefficient of the function $\cos\theta_\nu$,

$$\frac{dN}{d\Omega_\nu} = N_0(1 + k\cos\theta_\nu), \tag{2}$$

where θ_ν is the neutrino (or antineutrino) emission angle, reckoned from the direction of the magnetic field, and $k = k_1 + k_2$ is the total asymmetry coefficient. Here

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$$k_2 = 2S_n \alpha (1 \pm \alpha)/(1 + 3\alpha^2), \quad (3)$$

where $S_n = \pm 1$ corresponds to the projections of the spin of the nucleon in its initial state onto the direction of the magnetic field, $\alpha = |G_A/G_V|$, G_A and G_V are the axial and vector constants of the V-A model of the weak interaction, and k_1 is a complicated function of the temperature, the density, the field H, and also the parameter α. The different signs in (3) correspond to the cases of the neutron initial state (+) and the proton initial state (−) of the nucleons.

If we eliminate the magnetic field from consideration, we conclude that an asymmetry could arise only by virtue of a polarization $\sim k_2$ of the nucleons.[5] In the absence of such a polarization we would have $k_2 = 0$, and there would be absolutely no anisotropy. In an intense magnetic field the contribution of neutrino emission to the asymmetry coefficient, $\sim(\mathbf{S}_n \mathbf{p}_\nu)$, is accompanied by a contribution from the correlation between the neutrino emission direction and the direction of the magnetic field, $\sim(\mathbf{H}\mathbf{p}_\nu)$ (the coefficient k_1).

Let us consider the most natural case, in which the polarization of the nucleons is determined exclusively by the paramagnetic susceptibility of the nucleon gas. We also assume that the electron gas is degenerate, with an eye on a subsequent assessment of the typical situation in the collapse of massive stellar cores.[1] In the case of a degenerate electron gas, $\Phi \ll \mu (\Phi = kT/mc^2)$, where the chemical potential μ incorporates the rest energy of the electron and is expressed in units of mc^2, and under the further condition $\mu > \epsilon_0 = 2.53$ (ϵ_0 is the mass difference between the neutron and the proton, expressed in units of the rest mass of the electron), the neutronization of matter dominates the scene,[3] and the anisotropy of the neutrino emission results primarily from the reaction $e^- + p \rightarrow n + \nu$. Figure 1 illustrates the effect of a magnetic field on neutronization.

The maximum neutrino asymmetry coefficient is determined by the relation between the Fermi and Gamow-Teller coupling constants:

$$(k_1)_{\max} = (G_V^2 - G_A^2)/(G_V^2 + 3G_A^2). \quad (4)$$

This maximum value is reached at a magnetic field

$$H \geqslant H_c(\mu^2 - 1)/2, \qquad H_c = m^2c^3/e\hbar = 4.414 \times 10^{13} \text{ G}. \quad (5)$$

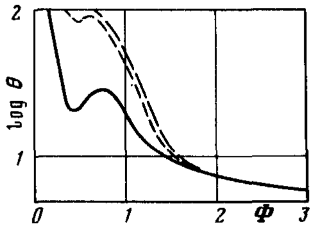

FIG. 1. The neutronization parameter θ (the ratio of the neutron and proton densities) versus the temperature $\Phi = kT/mc^2$ for a chemical potential $\mu = 3$ and several magnetic fields: Long dashes—$H/H_c = 0.1$; short dashes—$H/H_c = 1$; solid line—$H/H_c = 10$.

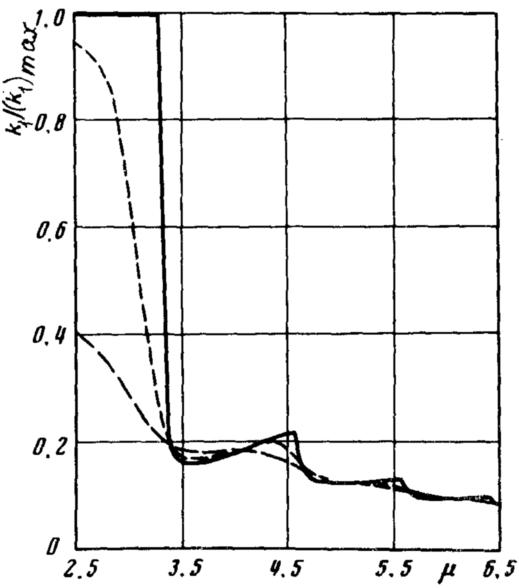

FIG. 2. The asymmetry coefficient $k_1/(k_1)_{\max}$ versus the chemical potential μ for a magnetic field $H/H_c = 5$ and for various values of the temperature parameter Φ: Solid line—$\Phi \ll \mu$; short dashes—$\Phi = 1/12$; long dashes—$\Phi = 1/6$.

In the relativistic region, $\mu \gg 1, \epsilon_H \gg mc^2$, which is the region of most interest for possible astrophysical applications, we can arrange the condition $2\sqrt{\epsilon_H} \geq \epsilon_F (mc^2)^{-1/2}$, according to (5), where ϵ_F is the Fermi energy, $\epsilon_H = \mu_e H$, and μ_e is the Bohr magneton. This condition guarantees maximum polarization of the magnetic moments opposite the field in the degenerate electron gas. In weaker fields the asymmetry coefficient of the neutrino emission due to the $(\mathbf{Hp}_\nu)$ correlation falls off essentially linearly with decreasing field (Fig. 2), and in the relativistic case it falls off quadratically with increasing chemical potential:

$$k_1 = (k_1)_{\max} \, 2H / [H_c (\mu^2 - 1)] \,. \tag{6}$$

It can be shown[4] that the contribution of the coefficient k_1 is predominant for a wide range of values of the chemical potential of a relativistic degenerate electron gas. The asymmetry of the neutrino emission in β processes (1) results from the polarization of light charged particles. The contributions of channels with various particle spins are determined primarily by the characteristic constants G_A and G_V for all of reactions (1) (see Ref. 4). A point which must be stressed here is that the $(\mathbf{Hp}_\nu)$ correlations lead to an asymmetry of the same spin in all of reactions (1): The emission of neutrinos (or antineutrinos) in the direction opposite the magnetic field is predominant. A star would evidently recoil along the field direction.

As was shown in Ref. 4, the observed velocities of pulsars, on the order of 100 km/s, can be attributed to an asymmetry of the neutrino emission if the condition $\mu^2 = 20H/H_c$ holds. It follows from this expression that if the temperature and chemical potential of the electron gas lie in the intervals $T = (30\text{–}40) \times 10^9$ K and $\mu = (3\text{–}4)\Phi$, as they typically would for the collapsing core of a massive star,[1] the magnetic fields would have to be on the order of $10^{14}\text{–}10^{15}$ G. Fields of this strength are predicted on the basis of an analysis of data on the magnetic moments of x-ray pulsars.[6]

If it proves possible to detect a correlation between the direction in which pulsars are moving and the orientation of their magnetic moments, this discovery would be a strong argument in favor of the mechanism outlined above for the loss of energy by stars in the form of neutrino emission.

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