Registration of neutrinos produced in relativistic collapse

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A possibility is indicated of registering high-energy neutrinos ($E_\nu \gtrsim 30$ MeV) by means of the reaction $A^Z(\nu, e^-)E^{Z+1}$, with subsequent emission of a neutron from the highly-excited nucleus A^{Z+1}.

Modern theory predicts large fluxes of high-energy neutrinos ($E_\nu \approx 20-60$ MeV) in a relativistic collapse of stars, which can be accompanied by supernova explosion.[1-4] With an energy release ~10^{53} erg as a result of the collapse, the neutrino flux is $L_\nu \approx 2\times 10^{11}$ (10 kpc/R)^2(30 MeV/E_ν) cm^{-2}, where R is the distance to the collapsing star. The registration of neutrinos from a supernova explosion or from a quiescent collapse is a most important problem for the entire theory of stellar evolution. We note that the observation of the neutrino is apparently the only possible check on the phenomenon of non-stopping "quiescent" spherically-symmetrical collapse.

The problem of recording such neutrinos was considered in[5]. In addition to the radiochemical method used to search for of neutrinos from the sun, it is proposed in that paper to register the fast electrons produced in the reaction $A^Z(\nu, e^-)E^{Z+1}$, and separated against the background of the natural radioactivity of the detector. An analysis of the angular correlations and of the cross sections of the reaction for different light nuclei was carried out in[6]. The choice of the light nuclei proposed in[5] is governed by the fact that they have large cross sections per unit detector weight.

However, the high energies of the relativistic-collapse neutrinos can offer new possibilities of their registration. When a high-energy neutrino interacts with a heavy nucleus, it is captured, with high probability, on a highly-excited level of the nucleus, as a result of which free neutrons can be emitted. The subsequent registration of the fast electron and absorption of a free neutron can serve as an indication of an interaction of a nucleus with a high-energy neutrino, and the two events should be correlated.

As a rough approximation to the description of sufficiently heavy nuclei, we use a model wherein the nucleus is regarded as a Fermi gas of proton and neutrons. We consider, within the framework of this model, the interaction of a high-energy neutrino with a heavy nucleus. For a flux L_ν of neutrinos of energy 20—60 MeV we obtain for the probability W_ν of neutrino capture per nucleus the following formula

$$W_\nu = \frac{L_\nu}{c} 2\pi^2 \left(\frac{h^2}{Z_e m_\mu e^2}\right)^3 \frac{N}{Z_e} \frac{W_\mu}{p_\nu} \frac{8}{3} \frac{mc\,p_o^2}{(mc+p_o)^3} \frac{\phi_e}{5\cdot 10^5 (m_e c)^3},$$

$$\phi_e = (p_\nu - p_{\nu o})^4 + \left(1 - \frac{p_o}{mc}\right) p_{\nu o} (p_\nu - p_{\nu o})^3. \tag{1}$$

Here W_μ is the experimentally known probability of absorbing a muon by a nucleus in a mesic atom,[7] Z_e is the effective charge of the nucleus for the μ-capture reaction, p_0 is the Fermi momentum of the protons in the nucleus, m is the effective mass of the nucleon in the nucleus, p_ν is the neutrino momentum, $m_\mu = 207 m_e$ is the rest mass of the muon, and $cp_{\nu 0} = \Delta$ is the threshold for the absorption of a neutrino by the nucleus. Using as an estimate the numerical values $m = 920 m_e$ and $p_0 = 420 m_e c$, we obtain

$$W_\nu = 5\cdot 10^{-43} L_\nu \frac{N}{Z_e^4} W_\mu \left(\frac{c p_\nu}{30\ \text{MeV}}\right)^3 \left(1 - \frac{p_{\nu o}}{p_\nu}\right)^4. \tag{2}$$

Assuming $W_\mu = 5\times 10^6$,[7] $Z_e = 20$ for Fe^{56}, and $N = 30$, we obtain for the neutrino-capture cross section σ_ν:

$$W_\nu = L_\nu \sigma_\nu, \quad \sigma_\nu \approx 4\cdot 10^{-40} \left(\frac{p_\nu c}{30\ \text{MeV}}\right)^3 \text{cm}^2.$$

The maximum energy of excitation of a nucleus in our model is

$$Q_{max} = c p_\nu \frac{2p_o}{mc + p_o} - \Delta. \tag{3}$$

At $E_\nu = 30$ MeV we obtain $Q_{max} = 14$ MeV and $\Delta = 5.1$ MeV for the reaction $Fe^{56} + \nu \to e^- + Co^{56}$. At a nuclear excitation energy ≈14 MeV, the neutron-emission probability is quite large. The probability of capturing a high-energy neutron on a highly-excited level of the nucleus can be comparable with or larger than the probability of an allowed transition to a lower level, owing to the large number of final phase states and the participation of all the neutrons of the nucleus in the reaction. Calculations for the interaction of the C^{12} nucleus with a neutrino[8] have shown that neutron emission takes place in half the absorption acts at $E_\nu \approx 60$ MeV. For heavy nuclei, the effect of level smearing is much stronger. Therefore the probability of exciting the nucleus to high energies, followed by neutron emission, can become appreciable much earlier. This occurs at approximately $E_\nu \approx 30$ MeV, in accordance with our rough calculations made under the assumption of complete level mixing, i.e., under conditions when the matrix element is constant.

By means of this article we wish to call attention of physicists engaged in the neutrino registration problem to the fact that high-energy neutrinos from supernova flares or from relativistic collapse can be observed by recording the electrons from the reaction $A^Z(\nu, e^-)A^{Z+1}$ with subsequent registration of the neutron emitted by the A^{Z+1} nucleus. The detector should be in this case a heavy nucleus, such as Fe^{56}, since it has a large number of closely-lying excited levels and is readily available. If the detector were to be a component of a transparent substance, then all the events accompanying the neutrino capture could be directly observable, in analogy with the results of the Reines experiment.[9]

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