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Abstract

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Neutrino and Antineutrino in Free Space

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The stars of our world are powerful sources of neutrinos. The stars of "antiworlds," if such exist, are sources of antineutrinos. Another source of antineutrinos could have been the decay of neutrons of the primordial neutron cloud, if such a cloud existed. Neutrinos and antineutrinos interact very weakly with matter.

At present, the nonidentity of the neutrino and antineutrino has been established, and the cross section σ_0 of the reaction $\mathrm{p} + \tilde{\nu} \rightarrow \mathrm{n} + \mathrm{e}^+$ has been determined for slow antineutrinos: $\sigma_0 = 1.1 \cdot 10^{-43}$ cm^2 (1). Owing to the smallness of the cross section σ_0 and the absence of charge in the neutrino, the universe is practically transparent to neutrinos and antineutrinos: at an average density of $10^{-3} \div 10^{-4}$ hydrogen atoms per 1 cm^3, a path of $\sim 10^{28}$ light years and corresponding times are required for one interaction, which far exceeds possible maximum estimates of the size and age of the universe. Thus, the fluxes of neutrinos and antineutrinos existing in free space carry information about the very earliest stages of existence and about the whole universe as a whole.

The existing fluxes of neutrinos and antineutrinos may originate from the following three sources.

1. Antineutrinos (and neutrinos in the case of a symmetric world) could have arisen from the decay of neutrons of the initial cloud. Their number is proportional to the density of matter in the universe and is equal to

$$n_{1\nu} \simeq 3 \cdot 10^5 [(1 \div 10)\Delta_\mathrm{g} + (1 \div 10)] \ \mathrm{cm}^{-2}\mathrm{sec}^{-1}.$$

The first term in brackets is stellar matter, the second is intergalactic matter; Δ_g is the average number of galaxies in a cube with side 10^6 years ($\Delta_\mathrm{g} \simeq 0.1 \div 3,$ see $(^2), p.189; (^3), p.284$).

2. If it is assumed that the intensity of energy emission by stars due to fusion reactions was constant throughout the entire time T of the universe' s existence, then the neutrino flux accumulated during this time is

$$n_{2\nu} \simeq 2(10^{-5} \div 10^{-6})\Delta_\mathrm{g} T \text{ years.}$$

Measurement of the neutrino and antineutrino fluxes in space will make it possible to test the assumption of the existence of an initial neutron cloud, or else the existence of antiworlds. In the latter case it will be possible to find the value of T.

For a “long” time scale ($T \sim 10^{15}$ years), $n_{2\nu}$ and $n_{2\tilde{\nu}}$ (in the case of a symmetric world) turn out to be greater than those from the decay of the initial neutron cloud. This may be so, naturally, only if, in the process of development of the visible world, the transformations $\mathrm{p} \to \mathrm{n}$ and $\mathrm{n} \to \mathrm{p}$ occurred many times, each time with the emission of neutrinos and antineutrinos, without their subsequent absorption. Other sources of slow neutrinos and antineutrinos (for example, radioactive decay) give a small additional contribution.

3. Cosmic rays propagating in galactic space are a source of fast neutrinos. Although the flux of fast neutrinos will be smaller than the fluxes of slow neutrinos considered above, they can be recorded with considerably greater efficiency than slow ones:

$$\sigma = 10^{-44}(E-a)\left[(E-a)^2-1\right]^{1/2}, \qquad a \sim 2.5,$$

where E is in units of $m_e c^2$ (^{4}). This formula is valid at least up to neutrino energies of the order of several Bev. At higher energies, the presence of nucleon structure (form factor) leads to a leveling off of the cross section.

Neutrinos and antineutrinos are generated by cosmic rays within galaxies in interstellar matter and propagate throughout all space. If one assumes that the intensity of cosmic rays in all galaxies is the same as in ours and has retained its value for T years, then the corresponding fluxes of neutrinos and antineutrinos will be

$$N_{\nu,\tilde{\nu}} \simeq 3\left(10^{-11} \div 10^{-14}\right) kT \text{ per year},$$

where k is the average number of neutrinos or antineutrinos produced in a single disintegration caused by cosmic-ray particles. One may take k equal to $3n_s/2$, where n_s is the number of shower particles. At average energies in disintegrations caused by protons, n_s is of the order of several units.

For a long time scale, $N_{\tilde{\nu}} \sim 10^4$ cm^{-2}sec^{-1}, and for $\sigma = 10^{-40}$ cm^2, a detector with a volume of several cubic meters can register them at a counting rate of $\sim 1 \div 5 \cdot 10^{-2}$ per day.

An experiment to detect the flux of fast antineutrinos can evidently be set up under conditions at the Earth’ s surface. Antineutrinos can be recorded by the reaction

$$\mathrm{p} + \tilde{\nu} \to \mathrm{n} + \mathrm{e}^+, \qquad \mathrm{e}^+ + \mathrm{e}^- \to 2\gamma, \qquad \mathrm{n} \to \mathrm{p} + \mathrm{e}^- + \tilde{\nu}.$$

It is apparently most effective first to register the appearance of a positron, and then the annihilation of the positron, with a lifetime in 30% of cases of $\sim 2 \cdot 10^{-9}$ sec. (water ([5])). Registration of neutron decay in this case is apparently inadvisable because of the large neutron background from nuclear disintegrations caused by cosmic rays.

A large Cherenkov counter made of a light substance may serve as a detector of fast antineutrinos. The dimensions of the counter must be much greater than the range of electrons with energy ~ 10 Mev.

To eliminate the nuclear-active neutral component of cosmic rays, the apparatus is placed underground at a depth of $20 \div 30$ m. With the aid of large flat Cherenkov counters, all fast charged particles can be excluded. What remain are the equilibrium neutral nuclear-active and photon components accompanying the flux of μ-mesons, provided there is no accompanying charged particle. The photon component can be absorbed by a filter. In addition, one can use the circumstance that both components will give electrons traveling from above downward, whereas the Cherenkov radiation can be registered only for positrons produced by antineutrinos coming from below. Then the thickness of the terrestrial globe will serve as a quite reliable shield, while the probability of absorption of antineutrinos by the Earth in traversing it along a diameter will be $\sim 10^{-7} + 10^{-8}$. The backflow of particles from the ground will be excluded by primary μ-mesons. The backflow of fast neutral particles generated by fast neutral particles accompanying the flux of μ-mesons will be vanishingly small. Local generation of fast neutrinos and antineutrinos by cosmic rays in the atmosphere and in the Earth is small.

When fast antineutrinos are registered, radioactive contamination is not dangerous, since the corresponding effects can be separated by energy-

released. Likewise, in order to register a flux of slow antineutrinos of 10^6 cm^{-2} sec^{-1}, the admixture of β-active atoms must be less than 10^{-14}. In ([6]) Reines has indicated that if an unstable isotope Li^4 exists, then the principal source of stellar energy should be a "lithium" cycle, in which neutrinos with an energy of 10 Mev are formed. If this is so, then in the presence of antimatter there should exist corresponding fluxes of antineutrinos that could be detected. It is obvious that at an energy of ~ 10 Mev it is possible to register antineutrino fluxes several orders of magnitude lower than the antineutrino fluxes of the "ordinary" cycle.

Consideration of neutrino fluxes imposes restrictions on the choice of possible cosmogonic hypotheses; moreover, any hypothesis that assumes a continuous alternation of repeated stages in the development of the universe must provide for such states in which absorption would occur of neutrinos and antineutrinos accumulated in previous stages of development. At the present stage of development of the visible part of the universe, neutrinos or antineutrinos cannot remain bound for a long time. After an antineutrino is absorbed by a free proton, the resulting neutron decays after ~ 17 min with emission of an antineutrino. As a result, the antineutrino is regenerated with degradation of its energy. When neutrinos and antineutrinos are absorbed by bound nucleons (nuclei), short-lived β-active isotopes are formed. After the energies of the neutrinos and antineutrinos degrade below the thresholds of the corresponding reactions ($\sim 1 \div 3$ Mev), further degradation of the energies will proceed through electromagnetic interactions of the weak magnetic moment of the neutrino ($< 10^{-9}$ Bohr magneton).

For "binding" neutrinos and antineutrinos one may propose the following process of "double neutrino capture" : a β-active isotope, produced after absorption of a neutrino (or antineutrino), before its decay absorbs an antineutrino (or neutrino). As a result, the initial stable isotope and an electron-positron pair are again obtained. In the first act a relatively fast particle must be absorbed; in the second, apparently, an arbitrarily slow one can also be absorbed, and it may be assumed that the cross section of the second reaction will be several orders of magnitude larger than the cross section of the first reaction.

The rate of the "binding" reaction is proportional to the densities of the neutrino flux and the antineutrino flux and to the density of matter. In order that there should exist an equilibrium between the processes of generation and binding of neutrinos by double neutrino capture in the "ordinary" matter known to us in the visible part of the universe, fluxes of $\sim 10^{31} \div 10^{32}$ neutrinos and antineutrinos per 1 cm^2 per second are necessary.

At low matter density the process of annihilation of neutrinos and antineutrinos proves more effective. According to an estimate by S. A. Kheifets (private communication), the cross section of such a process is $\sigma_{\text{ann}} = 4 \cdot 10^{-45} E(E^2 - 1)^{1/2}$, where E is the energy of the neutrino or antineutrino in units of $m_e c^2$. The "equilibrium" flux for this process is $\gtrsim 10^{15}$ cm^2 sec^{-1}.

One may think that observational data already indicate that such fluxes do not exist. An upper estimate of the magnitude of the fluxes can be obtained from the following considerations. With a flux of $\sim 10^{22} + 10^{23}$ neutrinos cm$^{-2} \cdot$sec^{-1}, the amount of heat released in the earth because of absorption of neutrinos and antineutrinos will be the same as that from the Sun. Since underground heat constitutes not a very large part of the heat received from the Sun and can be fully explained by other causes, the fluxes of neutrinos and antineutrinos in the surroundings traversed by the solar system are in any case less than $10^{20} + 10^{21}$ cm^2 sec^{-1}. A lower estimate may apparently be obtained from the heat balance of Neptune or Pluto.

One more estimate can be obtained from the consideration that the mass of the neutrino and antineutrino field must be small in comparison with the mass of visible matter. If this is so, then the fluxes of neutrinos and antineutrinos must be less than 10^{10} cm^{-2} sec^{-1}. A flux of $\sim 10^{13}$ cm^{-2} sec^{-1} corresponds to a den
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of interstellar matter. Fluxes of such and greater magnitude must, apparently, affect the dynamics of stellar motion.

The density of neutrino fluxes may increase sharply during the compression of the universe, or of its separate parts, if one assumes that space is "drawn in" together with matter. Clumps of matter of nuclear density could also serve as effective "sinks" of neutrinos and antineutrinos. These would have to be superheavy dwarfs with a mass of not less than 0.1—0.01 solar masses.

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