THE INTERACTION BETWEEN ULTRAHIGH-ENERGY COSMIC RAYS AND NEUTRINOS IN THE UNIVERSE

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The interaction between cosmic rays and neutrinos in the universe is considered. It is shown that for cosmic-ray particles with energies larger than 10^{20} eV per nucleon it is necessary to take into account nuclear reactions with neutrinos in addition to the interactions with hydrogen and with thermal photons.

IN the determination of the lifetimes of cosmic rays it is customary to take into account only the interactions with the hydrogen and the helium which are present in galactic and intergalactic space.

It has already been shown earlier[1-3] that for primary nuclei with energies 10^{16} eV per nucleon photonuclear reactions with thermal photons emitted by the sun and the stars can be of importance.

In the present paper we shall deal with the question of the interaction between cosmic rays and neutrinos in the universe. It will be shown that the small cross section for the interaction may be compensated by the possibly enormous concentration of neutrinos in the universe. We shall first estimate possible values of the neutrino concentration, and then make a comparison of the effect of the interaction of cosmic rays with the neutrinos with that of nuclear reactions with hydrogen and with thermal photons.

To estimate the maximum energy density of neutrinos in the universe Zel'dovich and Smorodinskiĭ[4] have considered the gravitational action of these particles on the expanding universe. They showed that an upper limit on the energy density of the neutrinos is $\rho_\nu \leq 0.12$ MeV cm^{-3}. Using this value, we can determine the maximum concentration of neutrinos from the Pauli principle.

Assuming all the energy levels from 0 to E_0 to be filled, we get for the neutrino concentration the value $n_\nu \leq 10^7$ cm^{-3}. Then the maximum energy of the neutrinos is $E_0 \approx 10^{-2}$ eV. We can also get an estimate of the concentration of neutrinos by considering the accumulation, during the time the universe has existed, of neutrinos coming from various sources as indicated by the different hypotheses about the composition of the matter in the initial stages of the evolution of the universe. The neutrinos can have been produced both owing to various processes in stars[5] and also in nuclear reactions in interstellar gas under the action of cosmic rays. According to the hypothesis of Gamow[6] about the composition of the matter in the initial stage of the development of the universe the various sources of neutrinos will have produced a neutrino concentration $n_\nu \approx 10^7$ cm^{-3}.

Recently Zel'dovich[7] has put forward a new theory about the initial stage of the evolution of the universe. According to this theory the concentration of neutrinos in the universe should be $n_\nu = 10^{-5}$ cm^{-3}.

Thus according to existing data the neutrino concentration is somewhere in the broad range from 10^{-5} to 10^7 cm^{-3}. We note that the upper limit on the neutrino concentration agrees well with the fluctuation hypothesis of Pontecorvo and Smorodinskiĭ.[8]

Unfortunately the existing experimental data enable us to estimate only the concentration of neutrinos with relatively large energies. We are concerned with the experiments of Reines and Cowan[9] and of Davis[10] on the detection of the flux of antineutrinos from a pile. If we assume that in these experiments the effect that was observed when the reactor was turned off was entirely caused by neutrinos from cosmic space, then the concentration of neutrinos with energies ~ 1 MeV in the vicinity of the earth is $\sim 10^2$ cm^{-3}.

As has been shown, the concentration of neutrinos can reach the value 10^7 cm^{-3} with maximum energy 10^{-2} eV. The interaction of such neutrinos with stationary nuclei does not lead to any nuclear reaction. With high-energy nuclei it is different.

If in a coordinate system connected with the galaxy the neutrino has the energy ϵ_0 and the cosmic-ray nucleus has the energy ϵ_c, then in the coordinate system in which the nucleus is at rest the energy of the neutrino is

$$\varepsilon = \varepsilon_0 (\gamma + \sqrt{\gamma^2 - 1} \cos \alpha) \approx 2\gamma\varepsilon_0 \cos^2 (\alpha/2),$$

where $\gamma = \epsilon_c / Mc^2$, M is the rest mass of the nucleus, and α is the angle between the directions of motion of the nucleus and the neutrino. For $\gamma > 10^8$ the energy of the neutrino in the coordinate system connected with the nucleus will be larger than 1 MeV, and a nuclear reaction is possible. The value $\gamma = 10^8$ corresponds to cosmic ray energies of 10^{17} eV per nucleon.

Various nuclear reactions caused by free neutrinos have been considered by Pontecorvo.[11] Besides processes inverse to β decay, reactions of the types νp, νn, $\nu\alpha$, and so on are possible. There are data in the literature only on the cross sections for the processes inverse to β decay. The reaction cross section increases quadratically with the energy and reaches saturation at $\sim 10^{-38}$ cm^2 at energy 1 BeV[12] (which corresponds to cosmic-ray energies of 10^{20} eV per nucleon).

According to the data of Ginzburg and Syrovatskiĭ[13] the largest energies in the cosmic rays occur for heavy nuclei. For definiteness we shall take them to be iron nuclei. Then on iron the cross section will be $\sim 10^{-37}$ cm^2. It is obvious that the total cross section for interaction of neutrinos with an iron nucleus will be $\sigma > 10^{-37}$ cm^2. Then for the maximum density the lifetime of iron nuclei against reactions with neutrinos is $T^{\nu}_{min} \leq 10^{12}$ years, and for the minimum concentration it is $T_{max} \approx 10^{24}$ years.

For comparison we estimate the lifetime of cosmic rays against reactions with hydrogen and with thermal photons. At present it is believed that the concentration of hydrogen in the universe is 10^{-5} proton/cm^3, and the cross section for interaction of iron nuclei with protons is 7×10^{-25} cm^2. Then $T_N \approx 10^{11}$ years. Now let us consider the interaction of iron nuclei with the thermal photons emitted by the stars. The cross section for photonuclear reactions has a maximum in the region of the giant resonance (which corresponds to an energy of 10^{16} eV per nucleon), and then falls. According to the estimates of Gerasimova and Rozental'[3] the lifetime of nuclei with energy 10^{16} eV per nucleon against photonuclear reactions in intergalactic space is 10^9 years. In that paper,[3] however, the value used for the intergalactic density of radiation was 0.1 eV/cm^3, and according to later estimates this is too high. At present it is supposed[13] that the value is $\rho_{ph} = 10^{-2}-10^{-3}$ eV/cm^3. Then $T_{ph} = 10^{10}-10^{11}$ years for the energy 10^{16} eV per nucleon.

With increasing energy the cross section for photonuclear reaction falls, and according to Levinger's data[14] at energies of 10^{20} eV per nucleon we can expect that the cross section is several orders of magnitude smaller than at the giant resonance. Then for $\epsilon_c > 10^{20}$ eV per nucleon we have $T_{ph} > 10^{13}$ years. Thus for cosmic-ray particles with energies larger than 10^{20} eV per nucleon nuclear reactions with neutrinos can be important if the neutrino concentration is close to the maximum possible value.

[1] G. T. Zatsepin, DAN SSSR **80**, 577 (1951).

[2] N. M. Gerasimova and G. T. Zatsepin, JETP **38**, 1245 (1960), Soviet Phys. JETP **11**, 899 (1960).

[3] N. M. Gerasimova and I. L. Rozental', JETP **41**, 488 (1961), Soviet Phys. JETP **14**, 350 (1962).

[4] Ya. B. Zel'dovich and Ya. A. Smorodinskiĭ, JETP **41**, 907 (1961), Soviet Phys. JETP **14**, 647 (1962).

[5] B. Pontecorvo, UFN **79**, 3 (1963), Soviet Phys. Uspekhi **6**, 1 (1963).

[6] G. Gamow, Revs. Modern Phys. **21**, 367 (1949).

[7] Ya. B. Zel'dovich, Atomnaya énergiya **14**, 92 (1963).

[8] B. Pontecorvo and Ya. A. Smorodinskiĭ, JETP **41**, 239 (1961), Soviet Phys. JETP **14**, 173 (1962).

[9] Reines, Cowan, Harrison, McGuire, and Kruse, Phys. Rev. **117** 159 (1960).

[10] R. Davis Jr. and D. S. Harmer, Bull. Amer. Phys. Soc. **4**, 217 (1959).

[11] B. Pontecorvo, JETP **37**, 1751 (1959), Soviet Phys. JETP **10**, 1236 (1960).

[12] Ya. I. Azimov and V. M. Shekhter, JETP **41**, 592 (1961), Soviet Phys. JETP **14**, 424 (1962).

[13] V. L. Ginzburg and S. I. Syrovat-skiĭ, Proiskhozhdenie kosmichechikh lucheĭ (The Origin of Cosmic Rays), AN SSSR, 1963.

[14] J. S. Levinger, Nuclear Photodisintegration, Oxford, 1960.

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