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THE NEUTRINO AND COSMIC RAY INTENSITY AT GREAT DEPTHS

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From an analysis of the intensity of charged penetrating particles at great depths the following conclusions are drawn: 1) the energy density of energetic neutrinos ($E_\nu \gtrsim 1$ BeV) in the universe is at least three orders of magnitude smaller than the total nucleon energy density 2) The neutrino-nucleon scattering cross section ($E_\nu \gtrsim 1$ BeV) is less than 10^{-34} cm^2.

INTRODUCTION

DATA on the intensity of cosmic rays at large depths are of great significance from various points of view. In the present paper we show that these data make it possible to obtain important information on the neutrino. They yield for the energy density of the high-energy neutrino in the universe and for the neutrino-nucleon scattering cross sections upper limits that are smaller than those heretofore known. We use in this paper the results of Miyake et al[1], who measured the intensity of charge particles at depths down to 6,380 meters of water equivalent (w.e.), thus adding much to our knowledge of the intensity of muons at large depths. In these experiments there were registered charge particles capable of penetrating through 5 cm of lead at depths 816, 1812, 3410, 4280, and 6380 meters w.e., and the values obtained for the vertical intensity (in cm^{-2} sec^{-1} sr^{-1}) were respectively 2.48×10^{-6}, 1.78×10^{-7}, 1.31×10^{-8}, 2.85×10^{-9}, and 1.62×10^{-10}. The intensity vs. depth curve continued to drop, down to a depth of 6,380 meters w.e., in accordance with a law that was fully compatible with the hypothesis that the registered particles are muons from pion decays. This means that even at the greatest depth only an insignificance fraction of the observed charge particles can result from neutrino interactions. Therefore, ascribing the observed particles to the effect of the neutrino, we obtain reliable upper limits for the quantities of interest to us.

UPPER LIMITS OF THE NEUTRINO AND ANTINEUTRINO ENERGY DENSITY IN THE UNIVERSE

According to a previously formulated[2] fluctuation hypothesis the separation of matter and antimatter was the result of fluctuations in a PC-symmetrical universe, in which the matter consisted of a neutrino-antineutrino "background." It was noted at the same time that the fluctuation hypothesis required merely that sometime in the past there should have existed a neutrino and antineutrino energy density considerably higher than the density of the total energy of the nucleons in the universe. At the same time, the experimental data analyzed in [2] do not exclude for the energy density of the high-energy neutrinos values that are comparable with the energy density of the nucleons at the present time. On the other hand, the work of the Japanese physicists[1] makes it possible to show that the energy density of neutrinos with energy $\gtrsim 1$ BeV is at least several orders of magnitude smaller than the energy density of the nucleons.

The upper limit of the neutrino density ρ can be obtained by assuming that the charged particles measured in [1] (muons) were produced in the reactions $\bar{\nu} + p \rightarrow \mu^+ + n$ and $\nu + n \rightarrow \mu^- + p$ by isotropically distributed cosmic neutrinos with energy $\gtrsim 1$ BeV and with cross section $\sigma_\mu \approx 8 \times 10^{-39}$ cm^2/nucleon[3]:

$$\rho c \sigma_\mu N R / 4\pi \ll 1.6 \cdot 10^{-10} \text{ cm}^{-2} \text{ sec}^{-1} \text{ sr}^{-1}$$

where N is the number of nucleons per gram of substance and R is the range of muons with energy $\gtrsim 1$ BeV in g/cm^2. We thus obtain that the density of neutrinos with energy $\gtrsim 1$ BeV is much smaller than 10^{-8} cm^{-3}. This corresponds to a neutrino energy density smaller than 10^{-5} MeV/cm^3, which is three orders of magnitude smaller than the energy density of the protons, 10^{-2} MeV/cm^3 ($\sim 10^{-29}$ g/cm^3). We note once more that this result in itself does not contradict the fluctuation hypothesis at all.

SCATTERING OF NEUTRINOS BY NUCLEONS

In the generally accepted universal theory of weak interactions with charged currents only[4] the neutrino-nucleon scattering process

$$\nu + N \rightarrow \nu + N \qquad (1)$$

occurs only in second order in the weak-interaction constant. On the other hand, if neutral symmetrical currents[5] $\bar{e}e$, $\bar{\mu}\mu$, $\bar{\nu}\nu$, $\bar{p}p$, $\bar{n}n$, and $\bar{\Lambda}\Lambda$ also exist in the weak interactions in addition to the charged currents, then reaction (1) is of first order in the weak-interaction constant. The cross section $\sigma_{\nu N}$ of reaction (1) is expected in this case to be of the order of magnitude 10^{-39} cm^2 ($E \gtrsim 1$ BeV), and the process can apparently be observed only with the aid of experiments analogous to those being carried out at the present time in Brookhaven and at CERN to detect neutrino-induced processes with emission of charged leptons. In addition, however, there are other reasons for which the process (1) is of interest.

First, independently of the theoretical predictions, neutrino-nucleon scattering should be investigated experimentally for its own sake.

Second, the problem is important in connection with the problem of the existence of anomalous muon interaction. If two types of neutrinos exist in nature, electronic and muonic, then the anomalous interaction, if it does exist for the muon, could also apply to muonic neutrinos and nucleons[6]. From this point of view the search for the anomalous neutrino-nucleon scattering is in the same class as the searches for the anomalous muon-nucleon scattering and is apparently the most powerful method of investigating the non-electromagnetic and the "not weak" properties of the muon.

From the experiment on the determination of the $(g-2)$-muon[7], Kobzarev and Okun'[6], taking the measurement errors into consideration, found an upper limit for the effective phenomenological constant F of the four-fermion anomalous interaction ($F \lesssim 10^{-1}/M^2$ where M is the nucleon mass). Corresponding to this limit (which exceeds the weak-interaction constant $G = 10^{-5}/M^2$ by four orders of magnitude) are the maximum cross sections of the muon-nucleon and neutrino-nucleon scattering, of the order of 10^{-31}/cm^2, at incident-particle energies on the order of 1 BeV in the laboratory system. We see that the experimental information published up to now afford a wide range for the possible existence of anomalous interaction.

A recent paper[8] reported an investigation performed on the proton synchrotron of the Joint Institute for Nuclear Research, where the νN scattering cross section was found to be $< 10^{-32}$ cm^2, for neutrinos with energy $\gtrsim 1$ BeV. The measurements of the Japanese physicists make it possible to reduce appreciably this upper limit. To this end we start from the well known calculations by Zatsepin and Kuz'min[9] of the intensity, spectrum, and angular distribution of the neutrinos produced by cosmic rays in the earth's atmosphere. If we assume that the charged particles registered at the depth 6,380 meters w.e. are recoil protons from neutrino-proton scattering, we obtain

$$I\sigma_{\nu N} N R_{\text{nuc}} < 1.6\cdot 10^{-10}, \quad I = 2\cdot 10^{-2}\ \text{cm}^2\text{-sec}^{-1}\text{-sr}^{-1},$$

where I is the intensity of the "atmospheric" neutrinos after [9] and R_{nuc} is the absorption range of the protons (~ 150 g/cm^2). Thus, the upper limit of the scattering cross section of the high-energy neutrino by nucleons turns out to be $\sigma_{\nu N} \ll 10^{-34}$ cm^2.

From this limit we obtain an upper limit for the constant F of the effective four-fermion anomalous neutrino-nucleon interaction, $F < 3 \times 10^{-3}\ M^2$, i.e., only two orders of magnitude larger than the constant G of the weak interactions. We see that the results of the underground experiments greatly reduce the probability of occurrence of anomalous interaction.

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