DOMOKOS: Can you deduce from your observations any characteristics of the primary interactions? The theories of high-energy collisions presented yesterday would predict some characteristics. Firstly, the nuclei would become transparent and you would get extreme cascade processes; secondly, that you would observe a decrease of transverse momentum. Could you explain exactly what is the characteristic change that you observe at energies greater than 10^{14} eV?

MIURA: In collisions with primary energies greater than 10^{14} eV, single very high energy secondaries will be observed rather frequently and sometimes they will have large transverse momenta.

NEUTRINOS AND THE COSMIC RAY INTENSITY AT GREAT DEPTHS

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INTRODUCTION

Data on the cosmic ray intensity at great depths are of great interest from several points of view. Below it is shown that they yield important information on neutrinos, namely they give new upper limits on the energy density of high energy neutrinos in the universe and on the neutrino-nucleon scattering cross-section. Use is made of the work of Miyake *et al.*[1] who considerably widened our knowledge on cosmic rays underground by measuring the intensity of charged particles at depths as large as 6380 m of water equivalent (m.w.e.). In these experiments the vertical intensity of charged particles capable of penetrating through a 5 cm thick lead absorber at depths 816, 1812, 3410, 4280 and 6380 m.w.e., was found to be, 2.48×10^{-6}, 1.78×10^{-6}, 1.31×10^{-8}, 2.85×10^{-9} and 1.62×10^{-10} $\mathrm{cm^{-2}\,sec^{-1}\,sr^{-1}}$ respectively. The curve intensity-depth keeps falling at the greatest depths investigated according to a law in full agreement with the assumption that the detected particles are muons from pions produced in the earth's atmosphere. This means that even at the greatest depths at which measurements were performed, only a very small fraction of the charged particles observed could have been generated by neutrinos. Thus safe upper limits can be obtained on the values of interest, if the charged particles observed at the greatest depths are attributed to the action of neutrinos.

UPPER LIMITS OF THE NEUTRINO AND ANTI-NEUTRINO DENSITY IN THE UNIVERSE

Recently[2] there was formulated the fluctuation hypothesis, according to which the separation of matter from antimatter came out as a result of fluctuations in a PC symmetrical universe, in which matter would mainly consist of neutrino and anti-neutrino. It was noted that the fluctuation hypothesis requires only that sometimes in the past the energy density of neutrinos and anti-neutrinos in the universe considerably surpassed the total energy density of nucleons. Anyhow the experimental data, which were analysed in (2), did not exclude present day energy densities of high energy neutrinos comparable with the total energy density of nucleons. The work of the Japanese physicists [1], as a matter of fact, permits us to demonstrate that the energy density of energetic ($E_\nu \gtrsim 1$ GeV) neutrinos is less by several orders of magnitude than the energy density of nucleons.

The upper limit of the neutrino density, ρ, may be obtained by assuming that the charged particles detected in (1) are muons produced with a cross-section $\sigma_\mu \approx 8.10^{-39}$ cm^2 [3] in the reactions $\nu+p\rightarrow\mu^+ +n$, $\nu+n\rightarrow\mu^- +p$ by isotropically distributed cosmic neutrinos of energies $\gtrsim 1$ GeV:

$$\frac{\rho c \sigma_\mu N R}{4\pi} \ll 1.6\times10^{-10}\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}\ \mathrm{sr}^{-1}$$

where N is the number of nucleons per gram of matter and R is the range in gr cm^{-2} of muons with energy $\gtrsim 1$ GeV. Thus it is found that the density of neutrinos of energies $\gtrsim 1$ GeV is less than 10^{-3} cm^{-3}. This corresponds to an energy density of high energy neutrinos less than 10^{-5} MeV cm^{-3}, which is by three orders of magnitude less than the total energy density of protons $\sim 10^{-2}$ MeV cm^{-3} ($\sim 10^{-29}$ gr cm^{-3}). It should be noted again that this result does not contradict the fluctuation hypothesis.

SCATTERING OF NEUTRINOS BY NUCLEONS

In the conventional universal theory of weak interactions with charged currents [4], the neutrino-nucleon scattering process

$$\nu+N\rightarrow\nu+N \tag{1}$$

is due to a second order process in the weak interaction constant. However, reaction (1) is a first order process, if neutral " symmetrical " currents [5] $\bar{e}e$, $\bar{\mu}\mu$, $\bar{\nu}\nu$, $\bar{n}n$, $\bar{p}p$, $\bar{\Lambda}\Lambda$ are present in the weak interaction Lagrangian in addition to charged currents. In such a case the cross-section $\sigma_{\nu N}$ of reaction (1) is expected to have an order of magnitude of 10^{-39} cm^2 ($E_\nu \gtrsim 1$ GeV). Process (1) might thus be observed in experiments similar to those which are being performed by the Brookhaven and CERN groups with the aim of observing neutrino processes with the emission of charged leptons. There are, however, other reasons which make the study of process (1) of great interest.

Firstly neutrino-nucleon scattering is a process of great importance in its own right and is to be experimentally investigated from a phenomenological point of view, independently from theoretical predictions.

Secondly, the task is important in connection with the muon anomalous interaction problem. Suppose there is an anomalous muon interaction. If in nature there are 2 types of neutrinos, it might well be that, besides the muons and the nucleons, muon neutrinos also undergo such anomalous interaction [6]. From this point of view the search for the anomalous neutrino-nucleon scattering is similar to the search for the anomalous muon-nucleon scattering and gives perhaps the most powerful method of investigating the muon properties which are neither electromagnetic nor " weak ". Kobzarev and Okun [6] have taken into account the errors of the muon (g—2) classical experiment [7], and have found an upper limit of the effective four-fermion anomalous interaction constant F ($F \lesssim 10^{-1}/M^2$, where M is the nucleon mass). This limit, which is by four orders of magnitude greater than the weak interaction constant $G = 10^{-5}/M^2$, corresponds to maximum values for the muon-nucleon and neutrino-nucleon scattering cross-sections of the order of 10^{-31} cm^2 at energies $\gtrsim 1$ GeV. Clearly there was plenty of room for the existence of an anomalous interaction.

Recently there was published an investigation [8] performed by means of the JINR synchro-phasotron, in which the cross-section for neutrino-nucleon scattering was found to be less than 10^{-32} cm^2 ($E_\nu \gtrsim 1$ GeV). The measurements of the Japanese physicists permit us to improve considerably this upper limit. For this, the intensity, the spectrum, and the angular distribution of neutrinos produced by cosmic rays in the earth atmosphere, which were calculated by Zatsepin and Kuz'min [9], may be used. If one assumes that the charged particles detected at 6380 m.w.e. are recoil protons from neutrino-nucleon scattering ($E_\nu \gtrsim 1$ GeV), one finds:

$$I\sigma_{\nu N} N R_{\mathrm{nucl.}} \lesssim 1.6\times10^{-10},$$

where $I \sim 2\times10^{-2}$ $\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}\,\mathrm{sr}^{-1}$ is the vertical intensity of atmospheric neutrinos [9] and $R_{\mathrm{nucl.}}$ is the absorption mean free path of protons ($\sim$150 gr cm^2).

In this way the upper limit for the high energy neutrino-nucleon cross-section is

$$\sigma_{\nu N} < 10^{-34}\ \mathrm{cm}^2\ .$$

From this an upper limit for the constant F of the effective four-fermion neutrino-nucleon interaction can be found

$$F < \frac{3 \times 10^{-3}}{M^2},$$

which is only by two orders of magnitude greater than the weak interaction constant G.

Clearly, underground measurements decrease greatly the possibility of the existence of the anomalous interaction.

SUMMARY

An analysis of recent data on the intensity of cosmic rays at great depths allows us to make the following conclusions:

(1) The energy density of high energy neutrinos ($E_\nu \gtrsim 1$ GeV) in the universe is at least less by three orders of magnitude than the total energy density of nucleons.

(2) The neutrino-nucleon scattering cross-section ($E_\nu \gtrsim 1$ GeV) is smaller than 10^{-34} cm^2.

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DISCUSSION

HAYAKAWA: In deducing the 10^{-3} factor what cross-section did you use?

OKUN: 8×10^{-38} cm^2.

HAYAKAWA: That is an upper limit?

OKUN: That is a reasonable figure.