THE NEUTRINO AND THE DENSITY OF MATTER IN THE UNIVERSE

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The possibility that the energy density of the neutrino and antineutrino in the Universe is comparable to or greater than the energy density due to the rest mass of hydrogen is considered. The assumption of a large neutrino and antineutrino energy density is not inconsistent with the available experimental data. Some methods of verifying this assumption, which arises as a result of discussion of PC-asymmetry of the world together with the hypothesis of existence of anti-worlds, are discussed. The importance of the Fermi $(e\nu)(e\nu)$ interaction which ensures transfer of energy to the $\nu\bar{\nu}$ component is emphasized. It is shown that the small magnitude of the "visible" kinetic energy density (which is much smaller than the energy density due to the rest mass of the nucleons) is not in contradiction with the hypothesis of separation of matter from anti-matter as a result of fluctuations in a charge symmetric universe. The fluctuation hypothesis merely requires that sometime in the past the neutrino and antineutrino energy density exceeded the nucleon energy density by several orders of magnitude.

INTRODUCTION

Up to this time there does not exist a well-founded estimate of the density of neutrinos and antineutrinos in space. Since these particles are hardly at all absorbed by dense matter, and since the manner of their production in the past is unknown, their number could attain large magnitudes. Although it is generally accepted that the matter in the Universe consists in essence of hydrogen a natural question arises: could not the energy contained in the neutrinos and antineutrinos in the Universe be comparable to or even larger than that contained in hydrogen?

CHARGE ASYMMETRY OF THE WORLD AND THE FLUCTUATION HYPOTHESIS

The assumption of a large number of ν and $\bar{\nu}$ in the universe arises, for example, in the discussion of the question of charge (more precisely, PC) asymmetry of the Universe. The possibility of existence of anti-worlds, resulting from fluctuations in a charge symmetric Universe, has been repeatedly discussed in the literature. Although at this time there are no experimental grounds for supposing that anti-worlds really exist, it seems of interest to us to note that the fluctuation hypothesis requires the existence in the Universe (now, or sometime in the past) of a large charge symmetric "background." Such a background should in principle consist to a large extent of ν and $\bar{\nu}$, whose densities are equal. Therefore the fluctuation hypothesis in principle leads to a conclusion which can be verified under "earthly" conditions. We note immediately that should this background exist today a measurement of the flux and energy of ν and $\bar{\nu}$ would give the value of a very important parameter—the average energy density in the Universe. At present the energy density of the Universe is estimated from the "smear-out" of galaxies. All astronomical estimates at this time agree that the average density of such "smeared-out" galaxies does not exceed 10^{-29} g/cm^3 (10^{-2} Mev/cm^3) or is less than 10^{-5} protons in 1 cm^3.[1] *

It follows from the equations of the general theory of relativity, that the average energy of relativistic particles (in our case neutrinos) falls in direct proportion to the curvature of the space a^{-1} (the energy density of such particles falls as a^{-4}). In other words, the average energy

*The question of the matter density in the Universe is particularly important for deciding on a cosmogonic model of the world. The magnitude of the average density coresponding to a flat Universe (passage from a closed to an open model) is $\sim 5 \times 10^{-29}$ g/cm^3.[2] In connection with the fact that recently the scale of cosmic distances was increased by more than a factor of two this number should be decreased to approximately 2×10^{-29} g/cm^3, which is close to the quoted estimate of the density. The size of the neutrino component may, therefore, turn out to be decisive.

of the neutrino in the past should be larger than its present energy by as many times as the curvature was larger in the past. Therefore in the past, when the density of matter was colossal, the neutrino energy density may have been larger than the nucleon energy density by many orders of magnitude. These may have been the conditions under which fluctuations took place. We have nothing to say about the mechanism of the fluctuation, in particular the question of "primordialness" of $\nu\bar{\nu}$ pairs is left open. We shall only remark that from our point of view the presence of anti-matter in our galaxy is by no means excluded.

Obviously the estimate of ν and $\bar{\nu}$ energy density in the Universe depends strongly on the concrete cosmogonic model. Let us emphasize once more that the fluctuation hypothesis requires the existence of a large symmetric background of neutral particles now or sometime in the past.

If today the energy density of ν and $\bar{\nu}$ should turn out to be small in comparison with nucleon energy density (as is quite likely), this would in no way contradict the fluctuation hypothesis.

At the same time the existing experimental data, discussed below, do not exclude the possibility of even large (i.e., in comparison with nucleon energy density) values for the energy density of ν and $\bar{\nu}$, and furthermore large values ($\gtrsim$ 100 Mev) for the average energy are not a priori excluded either. It is therefore of importance to verify whether the contribution of neutrinos to the general energy density in the Universe is substantial also at the present time (from a different point of view the importance of this problem was indicated by Kharitonov[3] and Marx and Menyhard[4]).

THE UNIVERSAL WEAK INTERACTION AND THE ENERGY TRANSFER INTO THE $\nu\bar{\nu}$ COMPONENT

If the possibility of existence of energy density of ν and $\bar{\nu}$ comparable to 10^{-2} Mev/cm^3 is seriously considered then one is confronted in a natural way by the question: why are there not in the Universe intense fluxes of γ rays with energy and energy density comparable to the energy of the proposed lepton flux? One can answer right away that the energy of annihilation photons (from the decay of pions) will be naturally degraded under conditions of substantial matter density because of their interaction, and this then explains the absence of high energy photons. However, such "degraded" energy cannot disappear but should, at first glance, appear in the Universe in the form of thermal energy, photonic energy, etc., in quantities no smaller than the energy connected with the nucleon rest mass. It is known, however, that the density of thermal and photonic (i.e., "symmetric") energy in the Universe is small in comparison with the density ("nonsymmetric") of energy connected with rest mass; this is difficult to explain (if the ν and $\bar{\nu}$ density is today comparable with the nucleon density). This objection can be eliminated if neutrino-electron scattering exists (as predicted, for example, in the Fermi universal weak interactions theory). Then it is possible in electromagnetic processes to emit in place of photons $\nu\bar{\nu}$ pairs (via a virtual or real e^+e^- pair[5]). At very high temperatures and densities (and even more so under conditions that now interest us) the emission of $\nu\bar{\nu}$ pairs becomes the sole effective mechanism for radiation of energy by dense bodies.[5-8]

EXISTING INFORMATION ON THE ν AND $\bar{\nu}$ ENERGY DENSITY

Let us discuss now the experimental data on the ν and $\bar{\nu}$ energy density in space. Direct information on maximum densities of ν and $\bar{\nu}$ may be obtained from the assumption that in the experiments of Reines and Cowan[9] and Davis,[10] performed with the help of a reactor, the effect observed with the reactor turned off was due in its entirety to neutral leptons from cosmic space. In the Reines and Cowan experiment antineutrinos of energy 3 — 10 Mev could be registered; it follows from the experiment that the flux of antineutrinos from cosmic space with energies from 3 to 10 Mev cannot be significantly in excess of 10^{13} cm^{-2} sec^{-1}. This corresponds to a maximum value of the order of 10^3 Mev/cm^3 for the energy density of 3 to 10 Mev antineutrinos.

As far as high energy antineutrinos are concerned, no information can be deduced from the Reines and Cowan experiment, in which by selecting events of the type $\bar{\nu} + p \rightarrow n + e^+$ detection of $\bar{\nu}$ with energies $\gg$ 10 Mev was made impossible.

In the experiments of Davis it was shown that

$$c\int_0^\infty \rho(E)\sigma(E)\,dE \lesssim 1.1\cdot 10^{-33}\ \mathrm{sec}^{-1},$$

where $\rho(E)$ is the density of cosmic neutrinos with energy E (including neutrinos from the sun) in units of Mev^{-1} cm^{-3} and $\sigma(E)$ is the cross section for the reaction $\nu + Cl^{37} \rightarrow Ar^{37} + e^-$. Roughly speaking, this cross section is proportional to the neutrino energy squared in the region from several Mev to several tens of Mev. It follows from an analysis of the Davis experiment that the energy density of cosmic space neutrinos with an energy of a few Mev cannot exceed several tens of Mev per cm^3. About a neutrino whose energy is of the order of 1 Bev, which makes it capable of disintegrating the argon nucleus, the Davis experiment clearly says nothing. An estimate of the energy density of neutrinos with energies up to a 100 Mev can be obtained by assuming that the detector in the Davis experiment was irradiated by monoenergetic neutrinos of energies equal to the maximum energy for which nucleon recoil does not prevent the formation of Ar^{37} (let us say, $E \sim 70$ Mev). Even in this extreme case the maximum (i.e., permissible by the experiment) energy density of these neutrinos is of the order of a few Mev per cm^3 and significantly exceeds W_H^{max}—the maximum hydrogen energy density in the Universe ($W_H^{max} \sim 10^{-2}$ Mev/cm^3).

Let us discuss now the information that could be obtained from experiments carried out underground. At large depths the neutrinos and antineutrinos from cosmic space will produce charged leptons distributed isotropically with an intensity independent of the depth. If their energy is significantly in excess of the rest energy of the muon, then the ν and $\bar{\nu}$ will effectively produce muons. The latter should be slowed down and stopped and under equilibrium conditions the number of muons created and stopped should be equal. It follows from measurements[11] at a depth of 6000 g/cm^2 that the number of muons stopped in emulsions, reaching the emulsion from the lower hemisphere, is $\sim 10^{-8} sec^{-1} cm^{-3}$. This number can be viewed as the maximum possible number of muons produced by cosmic neutrinos (since muons entering the emulsion from the lower hemisphere could be products of the decay of pions emitted from stars produced by the penetrating component). From here it follows that

$$c \int_0^\infty \rho(E)\, \sigma(E)\, dE \lesssim 10^{-32} sec^{-1},$$

where $\sigma(E)$ is the neutrino-nucleon cross section. For neutrinos and antineutrinos with energies of ~ 1 Bev the value of σ lies between the limits $10^{-38} - 10^{-39}$ cm^2,[12] so that underground measurements of slow muon intensity require that the energy density of ~ 1 Bev neutrinos and antineutrinos be $\lesssim 10^{-1}$ Mev/cm^3. This number is rather near to the magnitude of W_H^{max}.

An even lower limit for the possible energy density of 1 Bev neutrinos and antineutrinos is obtained, if one takes as the starting point the results of the experiments performed[13] with the help of telescopic counters at a depth of $\sim 10^5$ g-cm^{-2}. These data, however, are difficult to interpret from our point of view, so that one may only conclude that the maximum energy density of ν and $\bar{\nu}$ with energy equal to or larger than 1 Bev cannot be greatly in excess of W_H^{max}, and is probably less than W_H^{max}. In any event under the existing conditions of experimental techniques it is fully realistic to attempt to detect neutrino and antineutrino fluxes of the order of 10^5 cm^{-2} sec^{-1} and with energies of ~ 1 Bev. This problem is considerably less complicated than the problem of detecting neutrinos from an accelerator; the latter problem has been lately widely discussed (in particular at the conferences on high energy physics at Kiev and Rochester). Such a flux would produce inside the Earth between 10 and a 100 isotropically distributed charged particles (electrons and muons) daily per ton of matter.

It is necessary to emphasize that for ν and $\bar{\nu}$ energies of the order of or less than $m_\mu c^2$ production of muons by neutrinos is impossible; the underground measurements in no way exclude energy densities of ν and $\bar{\nu}$ larger than W_H^{max}.

Experiments on detection of ν and $\bar{\nu}$ in cosmic rays were discussed previously,[14] under the assumption that these particles were produced in collisions of "cosmic-radiation protons" with the earth's atmosphere or with interstellar matter. It is obvious that in that case the number of neutrinos is very small; this can be seen right away from, for example, the extremely low intensity of high-energy γ rays from π^0 decay.

CONCLUSION

It follows from what has been said above, that it is not possible to exclude a priori the possibility that the neutrino and antineutrino energy density in the Universe is comparable to or larger than the average energy density contained in the proton rest mass. This should be tested experimentally.

In conclusion we note that under conditions of very high densities and energies the predominance of the "symmetric" type of energy in the form of $\nu\bar{\nu}$ pairs over other symmetric energy forms is a rather general property, connected with the scattering of neutrinos by electrons, and may be of interest also apart from its connection with the fluctuation hypothesis. In general the mechanism responsible for the "transfer" of energy into the neutrino component could lead to a substantial density of ν and $\bar{\nu}$ in the Universe. The existence of this mechanism will put into doubt estimates of matter density in the Universe, based on "visible" forms of matter only.

It should be emphasized that experimental disproving of the hypothesis on the existence of a given neutrino and antineutrino energy density $\int \rho(E)\,E\,dE$ in the Universe becomes more difficult with decreasing average energy. Roughly speaking, the ν and $\bar{\nu}$ energy density that can be experimentally detected is inversely proportional to the square of the energy of the neutral leptons for energies larger than a few Mev. At lower energies the difficulties in detection are colossal. Thus, for example, the hypothesis on the existence of ν and $\bar{\nu}$ density equal to or larger than W_H^{max} can be easily tested experimentally (it has, perhaps, already been disproved by the existing data on underground muon intensity), if the neutrino energy is $\gtrsim 1$ Bev. If, however, the ν and $\bar{\nu}$ have an energy of ~ 100 Mev then a test of the hypothesis is realistic but involves considerable difficulties. For neutrinos with energy of ~ 1 Mev it is difficult to disprove experimentally ν and $\bar{\nu}$ energy densities even many orders of magnitude larger than W_H^{max}.*

The most convenient method for measuring fluxes of neutral leptons of 1 Bev energy consists of detecting the secondary muons produced by the neutrinos.[14,15] For ν and $\bar{\nu}$ energies in the region between several Mev and several hundreds of Mev the Reines-Cowan and Davis experiments are fully applicable. Regarding detection of ν and $\bar{\nu}$ with energies $\lesssim 1$ Mev it seems to us that electron-neutrino scattering provides the sole detection possibility. Unfortunately today this possibility exists in principle only.

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*However, a neutrino density $W \gg H$ is in contradiction with cosmological data.[15]

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