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*THE NEUTRINO AND ITS ROLE IN ASTROPHYSICS**

BRUNO PONTECORVO

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I wish to show in my report that neutrinos must in all probability play an important part in macroscopic phenomena. I must warn you, however, that in the physics of neutrinos there are a number of questions of a qualitative sort to which we cannot even give a "yes-or-no" answer. I shall tell about these problems, how they have arisen, and in what ways physics is preparing to answer them experimentally. Before proceeding to this discussion, however, allow me to give a brief and elementary survey of the main known properties of neutrinos.

1. KNOWN PROPERTIES OF THE NEUTRINO

In various decay processes of elementary particles it is often the case that the total energy and momentum of the particles in the initial state are not equal to the total energy and momentum of the particles in the final state. In such cases, as we now know very well, the apparent violation of the conservation laws is caused by the emission of neutrinos.

Most of the neutrino's properties became known about 30 years ago, immediately after Pauli theoretically "invented" it for the precise purpose of explaining the apparent violation of the energy and momentum conservation laws. The only process studied at that time was that of the β decay of certain radioactive elements, and it was known that the spectrum of the electrons is continuous. In this connection it must be said that the "invention" of the neutrino to explain the apparent disappearance of energy in the β-decay process required a great deal of imagination. As we already know now, the continuous nature of the β spectrum is due to the fact that in the final state there are three particles—the electron (e), the neutrino (ν), and the final nucleus. After a number of new elementary particles had been discovered, two-particle decay processes were found, in which the energy that "disappears" always has the same magnitude; for example, in the process of π—μ decay, 28 MeV always disappears. In muon capture by the process $\mu^- + He^3 \rightarrow H^3 + \nu$, which was discovered at the Joint Institute for Nuclear Research in 1960, 100 MeV disappears. Figure 1 shows an example of this reaction, obtained with a diffusion cloud chamber filled with He^3: the recoil triton always has a definite range. If two-particle processes involving neutrinos had been known earlier, there might have been no need for Pauli's genius to "invent" this particle.

For completeness we shall list practically all of the observed decay processes in which neutrinos are involved: $n \rightarrow p + e^- + \tilde{\nu}$ (β decay); $\mu^- + p \rightarrow n + \nu$

FIG. 1. Typical photograph of the reaction $\mu^- + He^3 \rightarrow H^3 + \tilde{\nu}$.

*Lecture delivered at the School of Astrophysics in Tartu (July, 1962).

(μ capture); $\mu \to e + \nu + \tilde{\nu}$ (μ decay); $\pi \to \mu + \nu$ (π—μ decay); $\pi \to \pi^0 + e + \nu$; $K \to \mu + \nu$, $K \to \mu + \nu + \pi$, $K \to e + \nu + \pi$; $\Lambda^0 \to p + e^- + \tilde{\nu}$.

The main properties of the neutrino are fixed, we may say, by definition: the charge is zero, the mass must be much smaller than that of the electron, the spin is one-half, and the penetrating power is enormous. Let us see what it can be. In matter there must occur neutrino collisions caused by the interaction which is responsible for the β decay of nuclei. In other words, there must, for example, be processes of the type

$$\tilde{\nu} + p \to e^+ + n, \qquad (1)$$

which are inverse to the ordinary process of β decay of the neutron,

$$n \to p + e^- + \tilde{\nu}.$$

A maximum value for the cross section for process (1) can be obtained from dimensional arguments:

$$\sigma \leqslant \frac{1}{\tau}\frac{\lambda}{c}\lambda^2.$$

Here τ is a typical time characteristic of β decay (tens of seconds, when the electron energies are ~1 MeV), and λ is the wavelength of the neutrino, the largest length we are concerned with in this process. We find that $\sigma \sim 10^{-43}$ cm^2 for neutrinos of energy ~1 MeV; this corresponds to a mean free path for the neutrino of about 10^{16} km of solid matter!

Processes which involve neutrinos are called slow processes, since they have small probabilities. They are due to the so-called weak interaction. Although all other particles are also subject to the weak interaction—the most widespread of all types of interaction—neutrinos are correctly regarded as the main actors in weak interactions. The point is that neutrinos are involved in only the weak interaction, whereas all other particles are subject not only to the weak interaction, but also to the electromagnetic or to the strong interaction, or else to both. If we recall that the intensities of strong, electromagnetic, and weak interactions, which are proportional to the squares of the coupling constants, are, roughly speaking, in the ratios $1 : 10^{-2} : 10^{-12}$, the fact that the neutrino is unique among elementary particles in its penetrating power is readily understood.

It must be stated at once that "free" neutrinos, i.e., neutrinos far from the source, have been observed recently in experiments done by Reines and Cowan. Their interaction with matter corresponds roughly to the mean free path to be expected from the dimensionality arguments mentioned above. Experiments with free neutrinos will play a very important part in solving the problems which we shall discuss later.

Since up to the present only a few experiments with free neutrinos have been done, I shall give a brief account of the very first work of this sort.

These experiments were done with the beam of $\tilde{\nu}$ from a reactor, i.e., antineutrinos with energies of the order of several MeV. The flux of antineutrinos from a very powerful reactor (with a power, let us say, of several hundred thousand kilowatts), which can be obtained beyond the shield, under conditions such that the antineutrino beam is sufficiently free from neutrons and γ rays, is approximately 10^{-3} cm^{-2} sec^{-1}.

In the experiments of Reines and Cowan the detector for the antineutrinos was a liquid scintillation counter of volume ~ 1 m^3. In the registration of the reaction (1) the positron energy was measured, the two quanta from the annihilation of the positron were distinguished, and after the slowing down of the neutron the γ rays corresponding to its capture by a nucleus were registered. Thus to decrease the background full use was made of the remarkable succession of events which is characteristic of reaction (1). Several events per hour were registered. The great significance of this experiment is of course that for the first time effects were observed which were due to neutrinos but independent of the process in which they were produced; this freed the neutrino from its mystical character. The accuracy of these measurements was sufficient to verify the fact that the cross section for reaction (1), in agreement with the theory of the longitudinal neutrino (see below), has a value twice that to be expected if parity were conserved. We shall speak later about parity nonconservation.

I shall now say a few words about the fact that the neutrino and antineutrino are not identical. That neutrinos and antineutrinos are different particles was recently proved by means of a rather difficult experiment. I shall speak briefly about this experiment, since it is important not only in showing that ν and $\tilde{\nu}$ are not identical, but also for the determination of the flux of cosmic neutrinos, in particular of neutrinos from the sun (by the way, the neutrinos from the sun have not yet been detected).

We have defined the antineutrino as the particle emitted in the β-decay of the neutron and the neutrino as that emitted in the β^+ decay of the proton, leaving open the question as to whether these particles are identical. We know that the reaction (1) has the expected value of the cross section. The reaction

$$\nu + n \to p + e$$

is brought about by the same interaction as the reaction (1). Therefore it can be used for the detection of neutrinos. Since, however, there are no free-neutron targets, one can use complex nuclei, for example deuterium or heavier elements. The reaction

$$\nu + Cl^{37} \to Ar^{37} + e \qquad (2)$$

is very convenient for technical reasons (CCl_4 is a cheap substance, and furthermore tiny amounts of radioactive A^{37} can be separated from large masses

Table I. Some properties of the neutrino

	According to the theory of the longitudinal neutrino	According to experiment
Electric charge	0	0
Mass	0	< 250 eV
Spin	$^1/_2 \hbar$	$^1/_2 \hbar$
"Neutrality"	$\nu \neq \tilde{\nu}$	$\nu \neq \tilde{\nu}$
Helicity	Complete longitudinal polarization	Degree of polarization $> 97\%$, ν — left-handed $\tilde{\nu}$ — right-handed
Magnetic moment	0	$< 10^{-9} \mu_B$ *)

*μ_B is the Bohr magneton.

of CCl_4). As for the reaction

$$\tilde{\nu} + Cl^{37} \rightarrow Ar^{37} + e^-, \qquad (3)$$

one cannot predict beforehand whether it will be observable or not. It depends on whether or not ν and $\tilde{\nu}$ are identical. The experiment shows that the cross section for reaction (3) is less than 5 percent of the expected cross section for reaction (2). It follows from this that $\nu \neq \tilde{\nu}$. What is the difference between ν and $\tilde{\nu}$? We now know that neutrinos are longitudinally polarized. The neutrino is a left-rotating object, and the antineutrino is a right-rotating object. Thus it would seem that the difference between ν and $\tilde{\nu}$ is the different direction of the "helicity." It must be pointed out, however, that we do not know as yet whether or not the difference in the directions of the "helicities" is the only thing distinguishing neutrinos from antineutrinos. It may be noted here that the behavior of neutrinos which is described by the theory of the longitudinal neutrino, according to which neutrinos are completely polarized along the direction of the momentum, serves as a prototype, so to speak, for the behavior of all other particles (we are speaking, of course, of their weak interactions). The known properties of the neutrino are listed in Table I.

As for the longitudinal character of the neutrino, we here encounter an obvious case of parity nonconservation and of noninvariance under charge conjugation (replacement of particles by antiparticles). I shall say a few words about this so that astrophysicists can get an idea (I do not know whether or not a correct idea) that parity nonconservation could also have macroscopic consequences. I would like them to think about this question.

The law of invariance under space inversion P (change of sign of all the coordinates) can be formulated in the following way: any mirror image of a physical process is an actually existing physical process. Therefore any correlation $\sigma \mathbf{p}$ of spin and momentum is incompatible with the law of conservation of parity, since in the mirror image σ does not change sign, but p changes sign. In particular, longitudinal polarization of elementary particles, for example the longitudinal character of the neutrinos and electrons in β decay, is incompatible with parity conservation.

Similarly, the concept of the left-handed neutrino and the right-handed antineutrino is clearly incompatible with invariance under the operation of charge conjugation C. If, on the other hand, the laws of nature are invariant under Landau's operation of "combined inversion" PC, i.e., the operation in which each particle is replaced by its antiparticle and at the same time all coordinates change sign, then the longitudinal neutrino is an entirely legitimate object. What sort of macroscopic effects can arise from the longitudinality of particles? I shall first indicate a simple example.

Let a thin layer of β-radioactive material be glued to an aluminum plate and suspended freely from a thin fiber (Fig. 2). Electrons emerge only upward, since when they are emitted downward they are absorbed by the aluminum. Since they are longitudinally polarized the system will rotate. It is very hard to realize this experiment practically, but we know that

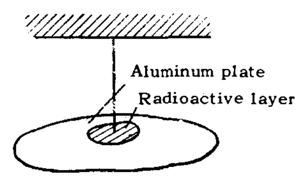

FIG. 2. Ideal experiment for detection of a macroscopic consequence of parity nonconservation.

in nature and in the universe phenomena which appear insignificant in the laboratory are of great importance. The most striking example of this is gravitation. I am not at all convinced that there are macroscopic effects of parity nonconservation, but it seems to me that it would be worth while to give some attention to this question.

2. THE PHYSICS OF HIGH-ENERGY NEUTRINOS

I shall now pass on the question of the unsolved problems of neutrino physics which are of great interest for the theory of elementary particles. In recent years a new branch of elementary-particle physics has appeared—the physics of high-energy neutrinos. If we are to give an exact definition of this field, we could say that all neutrino processes except β decay belong to high-energy neutrino physics. It is now agreed, however, to include in high-energy neutrino physics mainly the processes of interaction of high-energy neutrinos with other particles. Various experiments have been suggested and a number of theoretical predictions have been made in this new branch of physics. It now seems very likely that the experimental results which will be obtained in this field can play a decisive role in the construction of the future theory of elementary particles.

I shall list a number of questions of this sort, giving special attention to the aspects of the problem which are associated with experiments with free neutrinos.

3. IS THE FOUR-FERMION INTERACTION A PRIMARY INTERACTION?

It is well known that all weak processes can be "explained," at least phenomenologically, in terms of an interaction between four fermions. The question at once arises, however, is the four-fermion interaction a primary interaction? In the first papers of Yukawa on nuclear forces an attempt was made to interpret the β decay of nuclei in terms of the virtual emission of a meson by a nucleon and subsequent decay of this meson.

Let us denote by B the intermediate boson which is assumed to be the carrier of the weak interaction. (A spin value of unity is of course required for the B meson.) Let g_B be the constant for the coupling of the B meson with nucleons and with fermions in general. Then the four-fermion weak interaction is not a primary interaction, but is already characterized by a phenomenological Fermi constant

$$G = \frac{10^{-5}}{M^2} \quad (\hbar = c = 1),$$

where M is the mass of the nucleon. In this case it is an interaction of second order with respect to the constant of the primary interaction of the B meson, which is of "intermediate" intensity. Since g_B, like e and g_π, is a dimensionless constant, it is obvious from dimensional considerations that $G \sim g_B^2/M_B^2$, where M_B is the mass of the intermediate boson. Therefore, if $M_B \sim M$, $g_B^2 \sim 10^{-5}$. This quantity is to be compared with $e^2 = 1/137$ and $g_\pi^2 \sim 10$. The B particle will decay with the characteristic time

$$\frac{1}{\tau} \sim g_B^2 M_B \sim 10^{18}\ \mathrm{sec}^{-1}$$

by the channels

$$\begin{aligned} B &\to \pi + \pi, \\ &\to K + \pi, \\ &\to e + \nu, \\ &\to \mu + \nu \end{aligned} \quad \text{and so on.}$$

When the energy of a weak-interaction process is insufficient for the actual production of a B, the nonlocal effects associated with the existence of the B meson are small and hard to observe. But if B can actually be produced, this will lead to perceptible effects. This is due to the fact that once a B has been produced it must decay, and in particular must decay by lepton channels. It follows that if $M_B \sim M$, then in nuclear reactions at high energies we must observe the emission of leptons from "stars." The number of leptons is $\sim 10^{-5}$ per star. This is a relatively large quantity. The difficulty of observing leptons from "stars" is not due to the small number of events. The difficulty is rather due to the processing of a large number of events. In any case, it would be extremely interesting to establish that leptons are emitted (or that they are absent) in "stars."

Another very interesting possibility for detecting B mesons consists of bombarding nuclei A with high-energy neutrinos:

$$\left.\begin{aligned} \nu + A \to B &+ \left\{ \begin{matrix} \mu \\ e \end{matrix} \right\} + A, \\ &\to \mu + \nu, \\ &\to e + \nu. \end{aligned}\right\} \quad (4)$$

From dimensional arguments the cross section for this process is

$$\sigma \sim Z^2 e^4 \frac{g_B^2}{M_B^2}$$

(cf. diagram, Fig. 3).

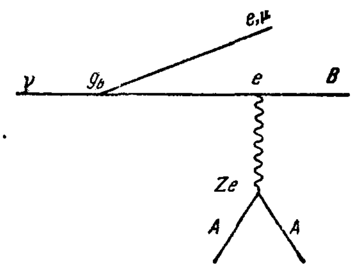

FIG. 3. Diagram of process (4).

For neutrinos with energies of several BeV and for $M_B = M$ we have $\sigma \sim 10^{-37}$ cm²/nucleon (in the case of Fe). This is larger than the cross sections obtained for the case of the local weak interaction, when, of course, the nucleon form-factor is taken into account. The cross section of reaction (4) increases rapidly with the neutrino energy and decreases with increase of M_B. In this connection we must note that:

1. The mass of the B meson must obey the relation $M_B \geq M_K$, so that the process $K \to B + \pi$ cannot occur.

2. In the reaction (4) there is a possibility of observing the "unnatural" pair μe. The appearance of such an "unnatural" pair is very typical of reactions in which B mesons are produced by means of high-energy neutrinos.

High-energy neutrinos are obtained from the decay of π mesons in flight. Since the spectrum of neutrinos from pion decay is a step function extending from zero to a maximum energy of 0.42 E_π, the energy of the neutrinos produced is rather small, and for the search for B mesons it is particularly important to have proton synchrotrons of the highest possible energy.

The intensity of the neutrino beams which can be obtained from 30 BeV accelerators of the type of those at CERN and Brookhaven at a distance of ~100 m from the internal target is 10^3—10^4 per cm^2 per pulse for neutrinos of energies larger than 1 BeV. If we compare the conditions of experiments with high-energy neutrinos from an accelerator with those of experiments with neutrinos from a reactor, it can be seen that the absolute number of events is several orders of magnitude larger in the latter case than in the former. Background conditions, however, are much more favorable in the experiments with high-energy neutrinos, especially because of the pulsed operation of the accelerator. We shall speak a bit later about the state of the search experiments being made with high-energy neutrinos.

4. ARE ν_e AND ν_μ IDENTICAL PARTICLES?

It is entirely unknown whether the neutrino emitted in β decay and the neutrino emitted in π—μ decay are the same particle. We define the electron neutrino (ν_e) and the muon neutrino (ν_μ) by the following reactions

$$e^- + p \rightarrow n + \nu_e, \quad \mu^- + p \rightarrow n + \nu_\mu,$$

leaving open the question as to the identity of ν_e and ν_μ; which can be settled only by experiment. The idea that ν_e and ν_μ are not identical arose in connection with the fact that some decay processes, for example $\mu \rightarrow e + \gamma$ and $\mu \rightarrow e + e + e$ are absent (at least they have not been observed so far). This leads to the idea that $\mu \rightarrow e$ transitions are forbidden by the existence of certain quantum numbers (or "charges") whose conservation is required by the laws of nature. If this is true, ν_μ has a muon "charge" and ν_e does not have such a charge.

The idea of the experiment designed to settle the question of the identity of ν_e and ν_μ is reminiscent of the idea of the experiment with Cl^{37}, about which we spoke in discussing the question of the identity of neutrino and antineutrino. Let us consider the reaction

$$\tilde{\nu}_\mu + p \rightarrow n + e^+.$$

The cross section for this reaction is zero if $\nu_e \neq \nu_\mu$, but if $\nu_e = \nu_\mu$ we can calculate the cross section. For neutrinos with energy 2 BeV the cross section is $(0.4—0.8) \times 10^{-38}$ cm^2 and is approximately equal to the cross section for the reaction

$$\tilde{\nu}_\mu + p \rightarrow n + \mu^+.$$

At the present time experiments to settle this question are being done at the Brookhaven laboratory. A definite answer to the question is expected in the very near future (see note added in proof at end of article).

The device used to detect the charged leptons from the reaction caused by the neutrinos is a large spark chamber with aluminum plates about 2.5 cm thick. The total weight of aluminum used is about 10 tons. It is expected that there will be several events per day per ton of material. To decrease the background owing to cosmic rays, it has been possible to make the duration of the synchrotron pulse about 35 μsec. Besides this, the beam has a fine structure: every 200 nsec there is a burst of duration about 10 nsec. With these conditions the difference between the times of flight of neutrons and neutrinos can be used to obtain a marked lowering of the neutron background.

5. IS THERE AN ANOMALOUS ν_μ—N INTERACTION?

This question has been discussed from the theoretical point of view by Kobzarev and Okun'. Let us assume that there are two types of neutrinos. Various experiments, for example that on the determination of $g - 2$ for the muon, or the experiment in which a search was made for large-angle scattering of muons by nuclei, do not exclude a relatively strong anomalous (i.e., nonelectromagnetic) interaction of the muon.

If we express the anomalous interaction in terms of a four-fermion interaction with the constant F, the maximum value F_{max} compatible with the determination of $g - 2$ is given by $F_{max} < 10^{-1}/M^2$. It can be seen that F_{max} is four orders of magnitude larger than G, the weak-interaction constant.

If muon neutrinos and nucleons are also subject to an anomalous interaction, then according to the ideas of Okun' and Kobzarev it is reasonable to look for a process of scattering of neutrinos by nucleons (ν_μ—N scattering). At an energy of 2 BeV the maximum admissible cross section reaches a value of 10^{-31} cm^2. As can be seen, the existing experimental information leaves plenty of room for the possible existence of an anomalous interaction.

Experiments have been made with the proton synchrotron at the Joint Institute for Nuclear Research to look for anomalous scattering of muon neutrinos by protons. Since the maximum admissible value of the cross section for this process is several orders of magnitude larger than the cross section from the weak interaction, it was possible to make the experiment with a beam with a relatively small intensity of high-energy neutrinos and with a neutrino "detector" of comparatively small mass. The experiments showed that the cross section for ν_μ—N scattering is smaller than 10^{-32} cm^2. A study of the intensity of cosmic rays at large depths in the earth gives even more accurate information, namely $\sigma_{\nu_\mu N} < 10^{-34}$ cm^2. This greatly reduces the probability of the existence of an anomalous interaction.

The experiments are of interest from a purely phenomenological point of view, apart from the work of Okun' and Kobzarev. Actually there do not exist any data on ν—N scattering, which has no connection with the known weak interaction, and therefore calls for independent investigation.

6. IS THERE A ν—e INTERACTION?

The theory gives a positive answer to this question, but it is clear that an experimental investigation is necessary, We are of course speaking about ν—e scattering in first order in the weak-interaction constant. In principle the experiments can be made with low-energy neutrinos (for example, neutrinos from reactors, with energies about 1 MeV). Reines is now planning such an experiment. On the other hand, these experiments can obviously also be done with high-energy neutrinos.

The main difficulties in making the experiments with low-energy neutrinos are due to the presence of background. Reines intends to make this experiment by means of several hundred "anticoincidence" NaI scintillation counters with a total weight of about two tons. The calculated cross section of the process $\nu + e \rightarrow \nu + e$ is 8×10^{-42} E cm^2, where E is the neutrino energy in BeV.

Instead of a reactor one can use monoenergetic neutrinos from a reaction produced by stopped mesons, such as

$$\pi^+ \rightarrow \mu^+ + \nu,$$
$$\mu^- + A \rightarrow A' + \nu.$$

The neutrino from the first of these reactions has an energy of 28 MeV, and that from the second, about 100 MeV. The accelerator used here can be a cyclotron with a spatially varying magnetic field, which can give a proton current close to a milliampere. The use of monoenergetic neutrinos offers a possibility of using kinematical features of the reactions being studied to diminish the background.*

7. ARE THERE NEUTRAL CURRENTS IN THE WEAK INTERACTIONS?

The most popular form of theory of the weak interactions, proposed by Feynman and Gell-Mann, assumes that there are only "charged" currents: the form of the Lagrangian is such that a four-fermion weak interaction requires the interaction of a charged pair of fermions with itself or with another charged pair. The possibility is not excluded a priori that there are also "neutral" currents of the types (ee), ($\mu\mu$), ($\nu\nu$), (pp), (nn), ($\Lambda\Lambda$), (μe), (Λn). It is true that no current (μe) can exist because its presence means a relatively large probability for the process $\mu \rightarrow e + \gamma$, which has very small probability according to the experimental data. Therefore Feynman and Gell-Mann have assumed that there are no neutral currents at all. The absence of the current (μe) does not, however, mean that all of the possible neutral currents are absent. The question of the symmetric neutral currents (ee), ($\mu\mu$), ($\nu\nu$), (pp), (nn), ($\Lambda\Lambda$) is quite a live one. There is actually not a single experimental result that contradicts the hypothesis of symmetric neutral currents. Moreover, the small probability of the process $\mu \rightarrow e + \gamma$ could be due to the existence of such currents. The presence of these currents would have the following consequences:

1. There must exist weak processes of interaction, for example scattering of electrons by protons and by electrons without conservation of parity. There are no experimental data on this problem, and it would be very difficult to obtain any.

2. Excited nuclei must emit $\nu\tilde{\nu}$ pairs. This effect is practically undetectible under laboratory conditions because of its small probability in comparison with the probabilities of ordinary electromagnetic processes. In astrophysics, however, there would be important consequences of the existence of symmetric neutral currents, and that is why I mention these processes in my report.

3. In experiments with high-energy neutrino beams there must be observable neutrino-nucleon scattering events (and stars in complex nuclei) which are not accompanied by charged leptons. A search for these processes with cross sections of the order of 10^{-38} -10^{-40} cm^2/nucleon could answer the question of the existence of neutral currents in the weak interactions.

8. SOME REMARKS ON MACROSCOPIC EFFECTS ASSOCIATED WITH NEUTRINOS

I shall briefly mention some data which show that neutrinos must necessarily play a part in phenomena on a macroscopic scale.

First of all, it must be said (and a more detailed discussion will be given in the next section) that inside stars neutrinos are produced in great numbers in nuclear reactions, in particular in the β decays of various unstable nuclei. As we have already seen, neutrinos have an enormous penetrating power. To sense it, think of an iron plate of thickness billions of times the distance from the earth to the sun. This is the mean free path of a neutrino of energy about 1 MeV! Naturally neutrinos will not have the slightest difficulty in emerging from, say, the sun. The energy transfer associated with the flux of solar neutrinos to the earth's surface amounts to several percent of the solar constant.

One more example of a macroscopic effect: An uranium reactor with a power in the hundreds of

*Since the demonstration that there are two kinds of neutrinos this way of doing the experiment is impossible: scattering of muon neutrinos by electrons will not occur in first order in the weak-interaction constant (see note added in proof at end of article).

thousands of kilowatts "loses" tens of thousands of kilowatts in the form of neutrinos.

I think these examples are enough to show the importance of neutrinos in the macroscopic world. Rather often, however, there is a situation in which one cannot estimate the quantitative importance of neutrinos in a phenomenon because of the absence of information about certain properties of the neutrino; the answers to rather delicate questions in elementary -particle physics (for example, the existence of an $e\nu$ interaction or the existence of neutral currents in weak interactions) have far reaching astrophysical consequences. On the other hand there are also cases in which we can assert that neutrinos would have enormously important effects in stars under definite conditions of density and temperature but it is not known whether these conditions actually exist.

9. NEUTRINOS AND THE SUN

Although much remains unknown about the problem of the production of neutrinos in stars, still some definite assertions about this question can be made. For example, the flux of neutrinos from the sun is known and is of the order of 10^{11} neutrinos per cm^2 and sec at the surface of the earth. We can also definitely assert that the sun emits neutrinos, and not *antineutrinos*. This is because of the types of nuclear reactions that can occur in stars (as contrasted with antistars, if these latter exist).

As is well known, the energy of the sun and other stars is released in the hydrogen and carbon cycles, in which hydrogen is converted into helium; in this process about 5 percent of the energy of the sun and

Table II. Processes responsible for energy release in the sun

		Character of neutrino spectrum	Neutrino energy, MeV
	Hydrogen cycles		
a)	$^1H + {^1H} \to {^2H} + e^+ + \nu$	Continuous	$E_{max} \sim 0.4$
	$^2H + {^1H} \to {^3He} + \gamma$		
	$^3He + {^3He} \to {^4He} + {^1H} + {^1H}$		
b)	$^3He + {^4He} \to Be^7 + \gamma$		
	$^7Be + e^- \to {^7Li} + \nu$	Monochromatic	$E \sim 0.9$
	$^7Be + e^- \to {^7Li^*} + \nu$	Monochromatic	$E \sim 0.4$
	$Li^{7*} \to Li^7 + \gamma$		
	$Li^7 + {^1H} \to {^4He} + {^4He}$		
c)	$^7Be + {^1H} \to {^8B} + \gamma$		
	$^8B \to {^8Be^*} + e^+ + \nu$	Continuous	$E_{max} \sim 14$
	$^8Be^* \to {^4He} + {^4He}$		
	Carbon cycle		
	$^{12}C + {^1H} \to {^{13}N} + \gamma$		
	$^{13}N \to {^{13}C} + e^+ + \nu$	Continuous	$E_{max} \sim 1.2$
	$^{13}C + {^1H} \to {^{14}N} + \gamma$		
	$^{14}N + {^1H} \to {^{15}O} + \gamma$		
	$^{15}O \to {^{15}N} + e^+ + \nu$	Continuous	$E_{max} \sim 1.7$
	$^{15}N + {^1H} \to {^{12}C} + {^4He}$		

of main-sequence stars is radiated in the form of neutrinos (Table II).

The relative importances of the cycles are unknown, however. We know only that the sun and the "cold" stars work mainly on the hydrogen cycle, whereas the carbon cycle predominates in the hotter stars. The carbon cycle evidently is also realized in the central part of the sun. As for the various channels of the hydrogen cycle, practically nothing is known.

As can be seen from Table II, the neutrinos emitted by the sun and other main-sequence stars have various spectra. In particular, there are intense monochromatic neutrinos from the electron-capture process. We shall speak later about the possibility of registering neutrinos from the sun and about the significance of such researches. Here we only note that the various mechanisms of emission of neutrino-antineutrino pairs which are associated with the electron-neutrino interaction process are not important in the sun and in stars of low temperature and density.

10. EMISSION OF NEUTRINO-ANTINEUTRINO PAIRS OWING TO ELECTRON-NEUTRINO INTERACTION

As we have seen (Section 6), the most widely used form of the theory of weak interactions assumes that the reaction $\nu + e \to \nu + e$ occurs with a probability comparable to those of other weak-interaction processes. I wish to emphasize that there is no experimental proof of this. If, however, we assume that it is true, then there are very interesting consequences for astrophysics.

If follows from the electron-neutrino interaction that electron-positron annihilation can occur with the emission of a neutrino-antineutrino pair ($\nu + e \to \nu + e$, and therefore $e^+ + e^- \to \nu + \tilde{\nu}$). Consequently, in electromagnetic processes it is possible to have emission of a pair $\nu\tilde{\nu}$ (via a virtual pair e^+e^-) instead of the emission of a photon. This fundamental relation between electromagnetic phenomena and lepton processes follows directly from the electron-neutrino interaction (when there are only charged currents). It is true that the emission of a $\nu\tilde{\nu}$ pair in an elementary act of interaction is very improbable in comparison with the emission of a photon, but the enormous penetrating power of neutrinos forces us to think about the possibility of effects associated with the neutrino-electron interaction in large bodies at high temperatures. It turns out that at a certain stage of the evolution of stars the energy radiated into space in the form of neutrino-antineutrino pairs is comparable with that radiated in the form of photons. As the stars evolve further their neutrino luminosity greatly exceeds the photon luminosity. I shall take time only for some conclusions from a study of the neutrino luminosities of stars owing to the electron-neutrino interaction.

1. The mechanisms of neutrino luminosity considered here, which are due to the electron-neutrino interaction, imply the emission of neutrino-antineutrino pairs, and not the separate emission of neutrinos which occurs in the nuclear reactions characteristic of the sun.

2. The effects caused by the electron-neutrino interaction are important only in stars with large densities and temperatures, when the light elements have already practically all burned up ($Z \geq 10$). Therefore they are of no importance in the energy balance of the sun. The predominance of neutrino luminosity over photon luminosity for large Z is due to the fact that when Z is increased the range of the gamma quanta is diminished, at the same time that the cross section for the production of $\nu\tilde{\nu}$ pairs is increased.

3. The electron-neutrino interaction causes several processes whose importance depends on the temperature and density of the star. The following are the main processes:

$e^- + Z \to e^- + Z + \nu + \tilde{\nu}$ — neutrino deceleration radiation,
$\gamma + e^- \to e^- + \nu + \tilde{\nu}$ — photoneutrino effect on an electron,
$\gamma + Z \to Z + \nu + \tilde{\nu}$ — photoneutrino effect on a nucleus,
$e^+ + e^- \to \nu + \tilde{\nu}$ — neutrino annihilation of electron-positron pair.

4. The neutrino luminosity becomes comparable with the photon luminosity for $T \sim 10$ keV, $\rho = 2$—3×10^3 g cm^{-3} (Z = 12). For denser and hotter stars the photon luminosity is already quite negligible in comparison with the neutrino luminosity. For stars with density $\rho \sim 10^4$ g cm^{-3} the energy $q_{\nu\tilde{\nu}}$ released by 1 cm^3 of the stellar matter owing to the eν interaction is in the range 10^4—10^{14} erg cm^{-3} sec^{-1} for the temperature range 10—100 keV. The fractional contribution of the neutrino processes listed above depends on T. If we fix Z = 12 and $\rho = 10^4$ g cm^{-3}, then at low temperatures ($T < 10$ keV) the process that predominates is that of neutrino deceleration radiation, then up to T = 50 keV, photoneutrino effects, and for $T > 50$ keV, the neutrino annihilation of electron-positron pairs.

5. Neutrino processes arising from the electron-neutrino interaction must play a very great role in the evolution of white dwarf stars. They must decidedly affect the dynamics of the explosions of supernovae.

In conclusion we note that under the conditions of very large densities and temperatures the process of "pumping-over" of energy into the neutrino-antineutrino component is a rather general property of matter.

11. THE URCA PROCESS

There is one other process which under favorable conditions can contribute to the neutrino luminosity. For reasons which are not very clear it has come to have the name of urca process in the literature.

In this process the $\nu\tilde{\nu}$ pair is not emitted owing to eν interaction, but the particles are produced separately (i.e., a ν and then a $\tilde{\nu}$) from the catalytic action of electrons:

$$\begin{cases} e^- + Z \to (Z-1) + \nu, \\ (Z-1) \to Z + e^- + \tilde{\nu}. \end{cases}$$

The process occurs because at high temperatures electrons can cause inverse β processes with the production of ν's and radioactive nuclei, which then decay with the emission of $\tilde{\nu}$'s.

The urca process differs fundamentally from the mechanisms of emission of $\nu\tilde{\nu}$ pairs that are based on the eν interaction. The latter are processes without thresholds, and the urca process is an effect with a definite threshold. For this reason the importance of the urca process depends strongly on the chemical composition of the stars, and it is difficult to estimate.

12. NEUTRAL CURRENTS IN ASTROPHYSICS

We have seen that it has not yet been proved that there are no neutral currents of the types (ee), ($\nu\nu$), ($\mu\mu$), (pp), (nn) in the weak interactions. If there are neutral currents, processes of emission of $\nu\tilde{\nu}$ pairs from excited nuclei are possible. These processes are analogous to the processes of β radioactivity of nuclei: instead of an electron and a neutrino, a $\nu\tilde{\nu}$ pair is emitted. This neutrino radioactivity is not connected with electromagnetic processes and differs from the emission of $\nu\tilde{\nu}$ pairs caused by the electron-neutrino interaction in that it is a process of order G^2, and not G^2e^4. Therefore it is clear that neutrino radioactivity can be very important for astrophysics if neutral currents actually exist in nature.

13. THE NEUTRINO AND COSMOGONY

Recently a number of papers have appeared which discuss the possible role of the neutrino in cosmogony. It would require a great deal of time to explain the application of the neutrino to cosmogony, and therefore I shall confine myself to listing some very interesting questions. The relevant literature will be given more completely, however.

As is well known, the accepted explanation of the red shift is that it is a consequence of an expansion of the universe. According to the general theory of relativity the "homogeneous" Friedmann model leads to different cosmogonic possibilities, depending on the value of the (average) density $\bar{\rho}$ of matter in the universe. If $\bar{\rho}$ is less than a critical value ρ_{cr}, which is estimated to be about 2×10^{-29} g cm^{-3}, the universe will continue to expand without limit (open model). If, on the other hand, $\bar{\rho} < \rho_{cr}$ (closed model) then the expanding universe will sometime cease to expand and begin to contract, and afterwards will again go over into an expanding phase (pulsating universe).

The order of magnitude of the average density of nucleons ρ_N in the universe is 10^{-29} g cm^{-3} $\sim 10^{-2}$ MeV cm^{-3}. Its value is not known accurately enough for us to say whether it is larger or smaller than ρ_{cr}.

The question arises: cannot the energy density of the neutrinos and antineutrinos in the universe be comparable with or even larger that the energy density ρ_N of hydrogen? The question of a large density of neutrinos and antineutrinos arises naturally in the discussion of the PC asymmetry of the world and the hypothesis of the existence of antiworlds. There have been repeated discussions in the literature on the possibility of the existence of antiworlds arising as the result of fluctuations of a charge-symmetric universe. Although at present there is no experimental evidence for the existence of antiworlds, it must be noted that the fluctuation hypothesis requires that there must exist in the universe (now or at some time in the past) a large charge-symmetric "background." This background would in principle have to consist to a large extent of ν's and $\tilde{\nu}$'s, existing with equal densities.

What is known about the energy density of neutrinos? In the range of neutrino energies $\gtrsim 1$ BeV measurements of cosmic-ray intensities underground have shown that the energy density of neutrinos is at least three orders of magnitude smaller than ρ_N. As for the range of energies of the order of a few MeV, the experimental data (obtained from an analysis of the experiments of Reines and Cowan and of Davis based on the hypothesis that the "background" in their apparatus was caused by cosmic neutrinos) do not exclude the existence of an energy density of neutrinos and antineutrinos considerably in excess of ρ_N.

If, however, we consider the gravitational consequences for neutrinos of arbitrary energy, as applied to the expanding universe, we can show that the maximum neutrino energy density $\rho_{\nu\tilde{\nu}}$ cannot be much larger than ρ_N ($\bar{\rho} \approx \rho_N + \rho_{\nu\tilde{\nu}} < 10\,\rho_N$). We note that in this case ($E_\nu \lesssim 1$ MeV) the nuclear-physics experiments give less information than the estimate based on the gravitational action of the neutrinos. However that may be, it turns out that the energy density of ν's and $\tilde{\nu}$'s is at present not large in comparison with the energy density of hydrogen. At first glance this contradicts the fluctuation hypothesis, since it would seem that there is not enough "background" for fluctuations to arise from. This contradiction can be solved in a natural way, however.

It follows from the equations of the general theory of relativity that the average energy of relativistic particles (neutrinos in our case) falls off in proportion to the curvature of space a^{-1} (the energy density of the particles varies as a^{-4}). In other words, in the past the average energy of neutrinos must have been larger than the present density to the same extent that the curvature was larger. Therefore in the past, when the matter density was enormous, the energy density of neutrinos (and of photons—the total density of "symmetrical" energy not associated with rest mass) could have been many orders of magnitude larger than the total energy density of the nucleons. These could be the conditions under which the fluctuations occurred. The mechanism of the fluctuations is of course not discussed, and the question as to whether the neutrino-antineutrino pairs are actually primeval remains open. We can only remark here that the mechanism discussed above of a "pumping-over" of energy into the neutrino-antineutrino component owing to the scattering of neutrinos by electrons should assure predominance of the "symmetrical form" of energy in $\nu\tilde{\nu}$ pairs over other symmetrical forms of energy (thermal energy, energy of photons, and so on).

Thus also independently of the fluctuation hypothesis it seems rather probable that the dynamics of the universe, if it is actually pulsating, is determined by the energy density of the ν's and $\tilde{\nu}$'s, at least in the contracted phases. In such a phase the neutrinos have very high energy.

14. EXPERIMENTAL NEUTRINO ASTRONOMY

a) Introduction. By neutrino astrophysics and astronomy we mean the science of the description of numerous phenomena in which neutrinos play a primary part. Neutrino astrophysics has two aspects.

First, neutrinos are involved in processes occurring in the interiors of stars and in the cosmos in general. Therefore, as theoretical sciences, astrophysics and cosmology must take into account the role of these particles in dynamical processes in stellar interiors and in the cosmos. The foregoing sections have been devoted to this aspect of the science.

Second, the neutrinos coming from the stars and from cosmic space can be registered in experiments made on the earth or on space ships, for the purpose of getting valuable information about the universe. This aspect of neutrino astronomy as an experimental science, about which I wish to speak briefly, is particularly alluring. The point is that up to now there has been accessible to us essentially only a single type of radiation coming to the earth from cosmic space—electromagnetic waves. True, I said "essentially only one" type of radiation, since in recent times cosmic rays have been studied from the point of view of astrophysics. But I do not want to go into this.

When we secure the possibility of registering the intensity, energy, and direction of the neutrinos and antineutrinos coming from individual stars and from cosmic space, we shall have in our hands powerful means for the solution of astrophysical problems.

Let us note in particular that when astronomers register electromagnetic waves they are not "looking" deep inside the stars, because these waves come out only from the surface layer of a heavenly body. Because of the enormous penetrating power of neutrinos, registering them will provide possibilities for looking very deep inside stars. This highly interesting possibility is a very real one only for the study of nuclear reactions inside the sun, and will be discussed later.

Now let me engage in fantasy, i.e., let me speak of things that are less real. I shall indicate some possibilities for experimental neutrino astronomy that exist in principle. It can be stated at once that practical realizations of these possibilities are very far off, and perhaps will never be at all.

After the neutrino fluxes from the sun have been registered, it will be necessary to take the next step—to measure the neutrino fluxes from cosmic space (we have already seen how important this problem is), and from individual galaxies. For this it is necessary to increase the sensitivity of present methods of registration by a factor of more than a million. Therefore I shall not go into these matters in detail, but shall illustrate only one prospect for neutrino astronomy which is possible in principle. This bears on the problem of antiworlds—worlds constructed entirely of antiparticles.

Can observations on the earth tell us whether or not there are antiworlds? Suppose we see some heavenly body and want to know: is it made of matter, or of antimatter? We say at once that observation of light and electromagnetic radiation in general cannot possibly answer this question. The light emitted, say, by a hydrogen atom, is identical with that emitted by an atom of antihydrogen (for photons are genuinely neutral particles—they have no sort of charge and differ in no way from their antiparticles).

But how is it in the case of neutrino radiation? We have already seen that the sun emits neutrinos, and not antineutrinos. This will be true of any star where the main source of energy is the thermonuclear reaction of conversion of hydrogen into helium. Imagine an antisun with internal processes analogous to those in the sun. This means that its source of energy is the conversion of antihydrogen into antihelium. The light given by such antisuns is indistinguishable from that from our sun. But they will emit antineutrinos, not neutrinos! Thus we see what prospects open up before neutrino astronomy. True, I must warn you against a too optimistic idea about the possibility of settling this question. It is not only that one is concerned with extremely small intensities of neutrinos and antineutrinos. The greatest difficulty is that we do not know how to make an effective neutrino telescope. In order to establish that neutrino radiation comes from a definite heavenly body it is necessary to measure the angular distribution of the products of disintegrations caused by the neutrinos. It turns out that the angular distribution is quite insensitive to the direction of the incident beam (in the case of neutrinos with energies of a few MeV or less). This difficulty is so great that I am not sure that the problem mentioned above will ever be solved. The very possibility is interesting, however.

The problem of constructing a neutrino telescope is much simpler for high-energy neutrinos ($E_\nu \gtrsim 1$ BeV). We shall talk about this a bit later.

b) The neutrino intensity of cosmic rays under the ground. The determination of the intensity of high-energy cosmic neutrinos and of their direction is of great interest. As a detector for the neutrinos one can use a complicated apparatus of scintillation counters placed at a great depth and registering the muons produced by the neutrinos in reactions of the type

$$\nu + N \rightarrow \mu + N'.$$

According to M. A. Markov the underground installation will react to the muons from neutrinos coming from the lower hemisphere—that is, passing through the whole earth. This is possible, of course, since the mean free path of neutrinos is incomparably larger than the diameter of the earth. In this way one can eliminate the background of muons not of neutrino origin, since charged particles cannot pass through the earth. In principle one can register, first, the "atmospheric" neutrinos, i.e., the neutrinos from the decay of pions produced in collisions of the proton component of the cosmic rays in the atmosphere. This research is more interesting from the point of view of elementary-particle physics than from that of astronomy. Second, it is not excluded that one may study the directions in space of localized sources of cosmic neutrinos; if these exist, this could open up new horizons for astronomy. Experimental neutrino astrophysics is a very young science. It may even seem to you that it is not born yet, indeed I have constantly been speaking in the future tense. Experiments have already been done, however, which give information about cosmic neutrino fluxes. True, the neutrinos have not been detected so far, and the results are of a negative nature. It has been found that the energy density of the high-energy neutrinos ($E_\nu \gtrsim 1$ BeV) is less than 10^{-5} MeV cm^{-3}, i.e., at least three orders of magnitude smaller than the energy density of hydrogen in the universe. It is remarkable that this result is obtained from an analysis of brilliant measurements of underground cosmic-ray intensities, which did not have the purpose of getting information about neutrinos.

c) Solar experimental neutrino astrophysics. We have seen (Table II) that the various reactions that are sources of the sun's energy are accompanied by the emission of neutrinos of various intensities and spectra. A question of primary theoretical interest is: just what kind of nuclear reactions occur in the central part of the sun? Since the probability of interaction (and therefore the sensitivity for registration) of neutrinos depends strongly on their energy, we have here a unique possibility for getting valuable information about the sun. It is clear that a primary problem for neutrino astronomy is to register solar neutrinos. How? We are already acquainted with the reaction of the interaction of neutrinos with the Cl^{37} nucleus: $\nu + Cl^{37} \rightarrow A^{37} + e^-$. The threshold for this reaction, i.e., the threshold for this neutrino detector, is about 0.8 MeV, so that registration of solar neutrinos is impossible if the only source of these neutrinos is the reaction $p + p \rightarrow d + e^+ + \nu$ (see Table II). On the other hand, in the decay reactions

$$^{13}N \rightarrow {}^{13}C + e^+ + \nu,$$
$$^{15}O \rightarrow {}^{15}N + e^+ + \nu$$

and especially in the process

$$^{8}B \rightarrow {}^{8}Be + e^+ + \nu$$

neutrinos are produced with energies above the detector threshold energy.

So far we know only one method for registering neutrinos with energies of a few MeV—the use of the reaction $\nu + {}^{37}Cl \rightarrow {}^{37}A + e^-$. This method is just sensitive enough for the registration of solar neutrinos to be possible, though extremely difficult, at present. It is not excluded that in the future a new efficient method for registering megavolt neutrinos will be devised.

To complete the picture I mention that a good method for registering megavolt antineutrinos is the Reines-Cowan reaction $\tilde{\nu} + p \rightarrow n + e^+$. As for ν and $\tilde{\nu}$ with energy $\ll 1$ MeV, there are unfortunately no methods at all for their registration.

SUMMARY

The known properties of neutrinos are given in Table I. Some of the properties of neutrinos are still unknown; in particular, it is not known whether or not there is a neutrino-electron scattering process, which is very important for astrophysics.

The most characteristic feature of neutrinos is their immense penetrating power; the cosmic role of neutrinos is due to this property. The sun and the main-sequence stars emit neutrinos, and not antineutrinos. The energy that such stars emit in the form of neutrinos makes up several percent of the energy they release.

In heavy ($\overline{Z} \sim 12$) stars with high temperatures ($T > 10$ keV) and densities ($\rho > 3 \times 10^3$ g/cm^3) the neutrino luminosity exceeds the photon luminosity. These objects emit neutrino-antineutrino pairs owing to various mechanisms (neutrino deceleration radiation, photoneutrino effects, neutrino annihilation of electrons and positrons) which have one common property: they are all due to a neutrino-electron interaction of first order in the weak-interaction constant. Neutrinos and antineutrinos evidently play a large part in the evolution of white dwarf stars and in the dynamics of the explosion of supernovas.

It is very probable that neutrinos play a large part in cosmogony.

Experimental neutrino astrophysics is a very primising science which is still only being born. Its primary problem is to register neutrinos from the sun in order to look into its central part.

Note added in proof. The news has just arrived of the completion, at the Brookhaven laboratory in the U.S.A., of an experiment designed to settle the question whether muon and electron neutrinos are identical particles. The experiment showed that electron and muon neutrinos are different particles.

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Translated by W. H. Furry