объединенный
институт
ядерных
исследований
дубна

E1,2-87-567

B.Pontecorvo, S.Bilenky.

NEUTRINOS TODAY

Submitted to the "Annuario Enciclopedia
Scienza e Tecnica", Mondadori 1987, Italy

1987

Contents

1. Intermediate bosons (real and virtual).
2. Leptons, quarks and their interactions with intermediate bosons.
3. Lepton charges.
4. Lepton charge violations?
5. Neutrino masses.
6. Lepton mixing and neutrino oscillations in vacuum.
7. Neutrino mass terms.
8. The "see-saw" mechanism of neutrino mass generation.
9. A possible scheme of maximum mixing.
10. Neutrinoless double β -decay.
11. Vacuum oscillations and solar neutrinos.
12. Matter oscillations and solar neutrinos.
13. Neutrino magnetic moment and solar neutrino astronomy.
14. Neutrinos and the Universe.
15. Gravitational collapse of stars. Supernova SN 1987 A.
16. Panorama of today experimental neutrino physics.

1. Intermediate bosons (real and virtual)

Almost sixty years ago W.Pauli "invented" the neutrino. Afterwards neutrinos were discovered experimentally. Because of their amazing properties (first of all their phantastic penetrating power) they played the role of protogonist in many popular papers and books. Although for many years we have been knowing quite a lot about neutrinos, today we can write about them in a way which would not have been possible only a few years ago.

This is connected with the outstanding discovery of three new fundamental particles, the so-called charged (W^+ and W^-) and neutral (Z^0) intermediate vector bosons. These particles were discovered by C.Rubbia and others in 1983 with the help of the CERN proton-antiproton collider (see S & T 85, C.Rubbia, Osservazione sperimentale dei bosoni vettoriali intermedi W^+, W^- e Z^0).

Below we shall explain why intermediate vector bosons have such an exotic name. For the time being let us remark only that W^+, W^- and Z^0 are unstable particles with a mean life approximately equal to 10^{-24}sec and that the decay of these particles has many channels in which neutrinos are present. According to the uncertainty relation, such a mean life corresponds to a width Γ (or to an uncertainty in the mass) of about one GeV. In spite of this uncertainty intermediate bosons have a wonderful "individuality", since their width is much less than their mass (the mass of W^+ and W^- is 81.8 ± 1.5 GeV and the mass of Z^0 is 92.6 ± 1.7 GeV; upper width limits are $\Gamma_W < 6.5$ GeV, $\Gamma_{Z^0} < 4.6$ GeV). The very existence of particles with such large masses is in itself quite remarkable. From a fundamental point of view W^+, W^- and Z^0 are <u>the only neutrino sources known at present</u>. However this does not mean that for the production of neutrinos it is necessary to use extremely high energy accelerators like the CERN collider, with the help of which "real" W^+, W^- and Z^0 bosons can be produced. Neutrinos can be generated (and usually are) in low energy processes in which intermediate bosons participate as "virtual" particles. Later we shall explain the meaning of the words real and virtual.

We have already stated that the direct generation of neutrinos by <u>real</u> intermediate bosons was first observed only in 1983. This result means without any doubt that <u>virtual</u> intermediate bosons are responsible for all known "weak" processes, in which neutrinos either are produced or interact with matter. A well-known example of such processes is the β -decay of the neutron (see Fig. 1).

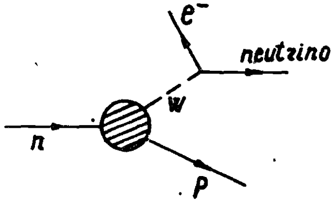

Fig. 1.

Beta-decay of the neutron - the process in which a neutron n is transformed into a proton p while an electron-neutrino pair is produced. The W-boson in this process is virtual.

Such low energy processes already in the fifties were called weak processes. According to the modern point of view they are due to the virtual production and decay of intermediate charged bosons $W^{\pm}$. Incidentally such processes are called charged current processes. The word weak is due to the fact that the effective interaction constant G_F responsible for the processes, called Fermi constant, is extremely small:

$$G_F = 1{,}44 \cdot 10^{-49}\ \mathrm{erg\ cm}^3.$$

Let us turn to Fig. 1, which is an example of the so-called Feynman diagrams. Such diagrams are quite illustrative and give us a powerful tool for the calculation of process probabilities. In Fig. 1 neutron decay is presented in the form of a two step process: first, a neutron is transformed into a proton with the emission of a virtual W-boson, second, the virtual W decays into an electron-neutrino pair.

An example of a process in which a virtual Z^0-boson participates is the scattering of a neutrino by a proton (see Fig. 2). In Fig. 2 the initial neutrino ν emits a virtual Z^0-boson and transforms into the final neutrino; the virtual Z^0 is absorbed by the initial proton which transforms into the final proton.

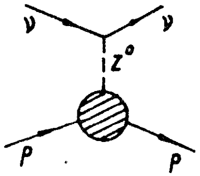

Fig. 2.

Neutrino-proton elastic scattering. The Z^0-boson is virtual.

Neutrino-proton scattering is an example of so-called neutral current processes, weak processes discovered (CERN) in 1973 (75 years after the discovery by Rutherford of the first charged current process!).

Particles with integer spin (internal angular momentum) are called bosons and particles with half integer spin are called fermions. Since the proton and the neutron are fermions from Fig. 1, for example, it follows that the W-spin is integer and consequently the W-particle is a boson. The same can be said about the Z^0-particle (see Fig. 2). Further it is clear why $W^{\pm}$ and Z^0 are called intermediate bosons: they mediate the interaction, taking part in four-fermion weak processes as virtual particles. It is well known that the γ-quantum mediates the electromagnetic interaction between charged particles; namely the analogy with electrodynamics was the starting point in the four fermion theory of β-decay (1933, E.Fermi) as well as in the intermediate boson hypothesis (1938, O.Klein).

Let us try now to explain in a simple way when particles such as $W^{\pm}$, Z^0, which mediate the interaction between fermions, are called real and when virtual. Of course we are not pretending to give a full explanation. Let us consider a free particle of mass m. Its energy E and its momentum $\vec{p}$ are related by the expression $E^2 = m^2 + \vec{p}^2$. Such particle is called real. However for a virtual particle the above expression is not valid: the energy and the momentum of virtual particles are independent. In spite of this statement, when such virtual particles are emitted or absorbed in intermediate processes, the total energy as well as the total momentum are conserved (of course and as it should be, this implies the conservation of the total energy and momentum in observable processes).

Let us consider as an example the β -decay of the neutrón. How can a neutron transform itself into a proton with the emission of a (virtual) W-boson? (see Fig. 1). The momentum conservation requires that in the rest system of the neutron, the W-boson momentum is equal to $-\vec{p}$, where $\vec{p}$ is the proton momentum. If the W-boson were real, its total energy would be equal to about 100 GeV and the neutron decay would be impossible. However the total energy of the virtual W-boson does not exceed 1 MeV, so that the process at issue is perfectly possible. Virtual particles arise as a result of the quantum nature of fields. The possibility of existence of virtual particles is deeply connected with the famous Heisenberg uncertainty relation.

The importance of the notion of virtual particles, for example W-bosons, can be appreciated even by a profane: without virtual W-boson neutrinos would be generated only in the decay of real W-bosons, for the production of which particle beams of superhigh energy are required. But we know that neutrinos do arise in plenty of low energy processes!

2. Leptons, quarks and their interactions with intermediate bosons

Neutrinos of various types are electrically neutral particles, belonging to the class of so-called leptons (fundamental fermions with spin 1/2, not undergoing the strong interaction), to which belong also electrically charged particles such as electrons, muons and taons.

The notion of electrical charge is well known to everybody. In nature there are also other charges (lepton, baryon, ...). Charges characterize internal particle properties and may take only discrete values. To every particle with charges different from zero there corresponds an antiparticle of identical mass, all the charges of which are opposite in sign to the particle charges. If all the particle charges are equal to zero such a particle is identical to its antiparticle and is called truly neutral particle (examples of which are photons and the so-called Majorana neutrinos).

The electrical charge is strictly conserved in all processes. It is not known whether lepton charges are strictly conserved. This important question will be discussed later.

All known leptons may be groupped into three generations. Every generation is consisting of one particle with electrical charge equal to zero (neutrino) and one particle the electrical charge of which is equal to -1 (in proton charge units). The electron neutrino ν_e and the electron e^- are the particles of the first generation. The second generation consists of the muon neutrino ν_μ and the muon μ^-, the mass of which is about 200 times larger than the electron mass. Finally, in the third generation the particles are the taon neutrino ν_τ and the heaviest known lepton, the taon τ^- , the mass of which is about 3500 times larger than the electron mass. Of course in addition to leptons $\nu_e e^-$, $\nu_\mu \mu^-$, $\nu_\tau \tau^-$ there exist also antileptons $\bar{\nu}_e e^+$, $\bar{\nu}_\mu \mu^+$, $\bar{\nu}_\tau \tau^+$. Let us notice that at present we do not know why there are three lepton generations. Moreover we do not know whether in nature there exist only three generations. Incidentally the last point should be clarifyed soon in e^+-e^- collider experiments. In Table 1 the values are presented of the masses, of the electrical charges and of the (currently used) lepton charges for all known leptons.

Table 1. Leptons

		Mass	Electric charge	Lepton charge		
				Electron	Muon	Taon
I generation	ν_e	< 50 eV	0	1	0	0
	e^-	0.51 MeV	-1	1	0	0
II generation	ν_μ	< 0.25 MeV	0	0	1	0
	μ^-	105.66 MeV	-1	0	1	0
III generation	ν_τ	< 70 MeV	0	0	0	1
	τ^-	1784.2 MeV	-1	0	0	1

There exists a second class of spin 1/2 fundamental fermions, undergoing the strong interaction, - the quarks. Every quark is characterised by the mass, the electrical charge and the baryon charge. Quarks are grouped also in three generations,a fact which is of great importance from the point of view of the symmetry between leptons and quarks. Every generation is consisting of quarks with electrical charges +2/3 and -1/3. The lightest quarks u and d are the particles of the first generation. The particles of the second generation are the heavier c and s quarks. Finally the most heavy t and b quarks belong to the third generation (see Table II).

Table II. Quarks

		Mass*(MeV)	Electric charge	Baryonic charge
I generation	u	4	+2/3	1/3
	d	10	-1/3	1/3
II generation	c	1500	+2/3	1/3
	s	200	-1/3	1/3
III generation	t**	> 30000	+2/3	1/3
	b	4500	-1/3	1/3

* The free quark approximate values of masses, presented as an illustration in the Table, are the so called "current" masses. The effective quark masses inside hadrons, especially in the case of light quarks, exceed the values given in the Table.

** For the time being there are no experimental proofs of the t-quark existence.

As already mentioned, leptons participate only in electromagnetic and weak interactions (as we know today, in the united electroweak interaction). Quarks participate also (and as protogonists!) in the strong interaction. According to modern ideas this is connected with the fact that the quark is carrying a supplementary quantum number called conventionally "colour", there being three colour sorts: every quark can be "green", "blue" and "red", so that in fact the quarks are three times more numerous than leptons. At a variance with the strong interaction, the electroweak interaction is not able to distinguish the colour of the quark.

Due to the strong interaction, quarks are bound in hadrons: protons, neutrons, pions, ... For example the proton is composed mainly of two u-quarks and one d-quark, the positive pion is composed mainly of one quark (u) and one antiquark ($\bar{d}$), etc. Until now quarks in a free state have not been observed, a fact anticipated by the so-called hypothesis of "quark confinement" (see S&T'84, M.Conversi, Fisica dei laboratori Sotterranei).

We will consider now the interaction of leptons and quarks with charged and neutral intermediate bosons. Let us stress right a way that intermediate bosons posses neither lepton nor baryon charges. Charged W bosons interact with pairs (currents) composed of either a neutrino and a charged lepton or a quark of charge +2/3 and a quark of charge -1/3. Notice that W-bosons interact with a combination of every quark of charge 2/3 with all quarks of charge -1/3. This fact is the so-called Cabibbo-Kobayashi-Maskawa quark "mixing". The question as to whether leptons also are mixed is open. It is one of the most important question in todays neutrino physics and will be discussed later in some detail. In Fig. 3 all possible interactions of charged W-bosons with leptons and quarks are shown . In the case of quarks the main pairs are written without brackets, whereas the pairs entering the mixture with coefficients definitely less then the main one are written in brackets.

In Fig. 4 all possible interactions of lepton and quark pairs (currents) with neutral Z^0-bosons are shown . The so-called standard model of the electroweak interaction (see, N.Cabibbo, S&T, 83, L'Unificazione delle forze fondamentali)

requires that the Z^0-boson interacts only with pairs (currents) of identical leptons and of identical quarks (i.e. there is no mixing).

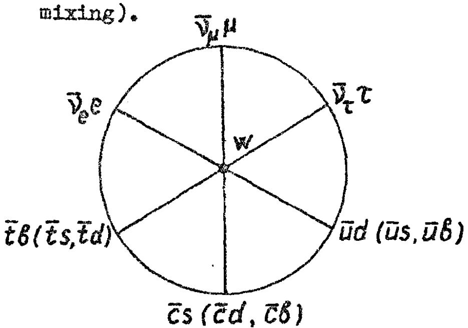

Fig. 3. Interaction of charged W-bosons with lepton and quark currents.

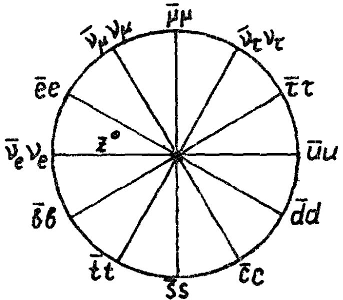

Fig. 4. Interactions of neutral Z^0-bosons with lepton and quark currents.

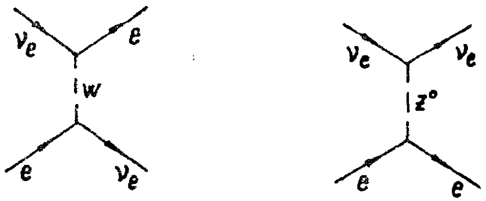

Fig.5

Diagrams of the process $\nu_e + e \to \nu_e + e$.

In Fig. 3 and Fig. 4 it is shown which pairs of fundamental fermions,either different in Fig. 3 (so-called charged currents) or identical in Fig. 4 (so-called neutral currents) the intermediate bosons are interacting with. Every current in Fig. 3

and Fig. 4 through the appropriate intermediate boson can interact either with any other current or with itself. As we have mentioned before, such four-fermion interactions, in which intermediate virtual bosons do participate, are called weak. Fig. 3 shows that there are 3 lepton decay channels and mainly 3 quark decay channels (9 if quark mixing is taken into account) of a real W-boson. Fig. 4 shows that there are 6 lepton decay channels and 6 quark decay channels of a real Z^0-boson. From Fig. 3 one can see that the number of different concrete types*) of charged current (virtual W) weak interactions is 78. From Fig. 4 one can see that the number of different concrete types*) of neutral current (virtual Z^0) weak interactions is also 78.

It is easy to verify that there are 12 different charge current (diagonal) interactions and 12 different neutral current interactions which give contributions to the same processes. A good example is the process $\nu_e + e \rightarrow \nu_e + e$ to which a contribution is given by both the virtual W and the virtual Z^0 bosons (see Fig. 5).

All processes arising from the interactions presented in Fig. 3 and Fig. 4 were surely present in the Hot Universe, but by far not all of them have been observed experimentally. For example there are expected 24 purely leptonic (charged and neutral) current x current interactions, whereas with certainty there have been observed experimentally only 8. These are listed below, each interaction being examplified in parenthesis

---

*) A type of the current x current weak interaction is fully defined if the relevant four fundamental fermions are indicated.

by one of the relevant observed processes: $(\bar{\nu}_e e)(\bar{\mu}\nu_\mu)$,
$(\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu)$; $(\bar{\nu}_e e)(\bar{\tau}\nu_\tau)$, $(\tau^+ \rightarrow e^+ \nu_e \bar{\nu}_\tau)$; $(\bar{\nu}_\mu \mu)(\bar{\tau}\nu_\tau)$,
$(\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau)$; $(\bar{\nu}_\mu \nu_\mu)(\bar{e}e)$, $(\nu_\mu e \rightarrow \nu_\mu e)$; $(\bar{e}e)(\bar{e}e)$, $(e^+e^- \rightarrow e^+e^-)$;
$(\bar{e}e)(\bar{\mu}\mu)$, $(e^+e^- \rightarrow \mu^+\mu^-)$; $(\bar{e}e)(\bar{\tau}\tau)$, $(e^+e^- \rightarrow \tau^+\tau^-)$;
$(\bar{\nu}_e e)(\bar{e}\nu_e)$ and $(\bar{\nu}_e \nu_e)(\bar{e}e)$, $(\nu_e e \rightarrow \nu_e e)$.

Let us underline here that practically all we know today about neutrinos is based on investigations of weak processes at relatively low energies. We should like to stress also that neutrinos we are detecting in the laboratory (from the β -decay of fission fragments in nuclear reactors, from decays of mesons produced in accelerators, from thermonuclear reactions producing neutrinos in the Sun, etc.) arise in processes in which virtual W -bosons *) take part.

Such type of neutrino sources may be very intense. For example, an industrial uranium reactor may emit 10^{20} neutrinos per second. In contrast with this, since the discovery of $W^\pm$ and Z^0, the overall number of neutrinos emitted by real intermediate bosons produced at the CERN p-$\bar{p}$ collider is about 10^3.

Let us discuss now the process of neutron decay and the process of neutrino-proton scattering moving from the interactions of leptons and quarks with $W^\pm$ and Z^0 bosons, presented

---

*) Neutrinos from decay of virtual Z^0-bosons as a rule are not observed. This is due to the fact that weak processes mediated by virtual Z^0-bosons are much less probable than electromagnetic processes (this is of course true at energies well below the mass of Z^0-boson). However there is an exception to this rule: neutrinos from decay of virtual Z^0-bosons play a very important role in the case of astrophysical objects such as gravitationally collapsing stars (see the last three paragraphs of the present paper).

in Fig. 3 and Fig. 4. Instead of Fig. 1 and Fig. 2 we have correspondingly Fig. 6 and Fig. 7. One of the possible diagrams of the neutron decay is presented in Fig. 6: the d-quark in the neutron emits a virtual W^--boson and transforms into a u-quark (of the proton); the virtual W^--boson decays into a $e^- - \bar{\nu}_e$ pair. One of the possible diagrams of the scattering of the neutrino by a proton is presented in Fig. 7: the initial neutrino emits a virtual Z^o-boson and transforms into the final neutrino; a u-quark of the initial proton absorbs a Z^o-boson and transforms into a u-quark (of the final proton).

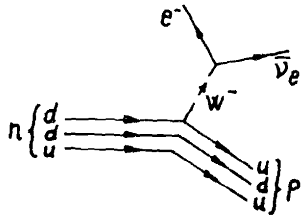

Fig. 6.

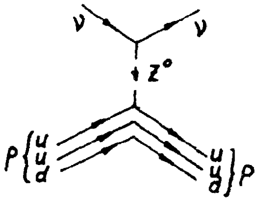

Fig. 7.

The processes of neutron decay and neutrino-proton scattering are presented from a modern point of view.

Few remarks of historical nature, mainly relevant from the point of view of the development of theoretical ideas. The first quantitative theory of the β-decay was created by E.Fermi in 1933. The theory is based on the 1930 Pauli's "invention" of neutrinos. Fermi's theory played an outstanding role in the subsequent development of elementary particle physics. According to such theory the diagram of the neutron decay is presented in Fig. 8. The idea that the four-fermion interaction is not local but is due to exchange of intermediate bosons belongs to O.Klein (1938). Fenomenologically the current x current weak interaction was introduced by Landau, Lee and Yang, Salam (1957), Feynman and Gell-Mann, Marshak and Sudarshan (1958). The electroweak theory unifying electromagnetic and weak interactions (the so-called standard theory) is associated with the names of Glashow (1961), Weinberg and Salam (1967).

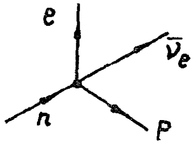

Fig. 8.

Diagram of the process $n \to p + e^- + \bar{\nu}_e$ in Fermi's theory, according to which all particles interact locally (in one space-time point). Through the discovery of $W^{\pm}$-bosons we have definitely learned that the interaction is not local.

3. Lepton charges

In paragraph 2 we introduced the notion of charges. Below we discuss lepton charges in detail. Why and how lepton charges were introduced? What is known today about their conservation?

In Table I it is seen that at present there exist three generations of charged leptons and neutrinos. Every generation is associated with a lepton charge. The lepton charges which are associated with the first, second and third generations are called correspondingly electron, muon and taon charges.

At beginning let us consider the situation when only one generation of leptons (ν_e, e) was known. The particle emitted in β^--decay together with the electron was called by convention antineutrino ($\bar{\nu}_e$). Then the particle emitted together with the positron in β^+-decay had to be called neutrino (ν_e). However the question as to whether ν_e and $\bar{\nu}_e$ are really different particles was open and had to be answered experimentally. Let us see how this came about.

Antineutrinos were first observed by Reines and Cowan in the fifties through the reaction

$$\bar{\nu}_e + p \rightarrow e^+ + n.$$

In order to detect such a reaction one needs a very intense source of antineutrinos. In the experiment of Reines and Cowan such a source was a powerful uranium reactor. The detector of $\bar{\nu}_e$ was a large scintillation counter.

The above reaction (inverse β-decay of the neutron) is due to the same interaction which is responsible for the neutron-decay. Such an interaction is also responsible for the reaction

$$\nu_e + n \rightarrow e^- + p .$$

Let us consider now the following two reactions

$$\nu_e + p \rightarrow e^+ + n$$
$$\bar{\nu}_e + n \rightarrow e^- + p .$$

They obtain from the preceeding ones through the substitution $\nu_e \rightleftarrows \bar{\nu}_e$. If ν_e and $\bar{\nu}_e$ are identical particles, the two last reactions are obviously possible. On the contrary if $\nu_e \neq \bar{\nu}_e$ the last reactions are experimentally unobservable. Thus in order to answer the question "are neutrinos and antineutrinos identical particles?", one must investigate whether the last reactions are possible. There are no sources of ν_e intense enough, whereas there exist intense $\bar{\nu}_e$ sources

(uranium reactors). Thus it is natural to fix the attention on the second of the last reactions. True, nuclei consisting only of neutrons do not exist. However it is possible to use as a target neutrons inside nuclei. For practical reasons ^{37}Cl happens to be by far the most useful nucleus, the relevant reaction being the following one:

$$\bar{\nu}_e + {}^{37}\mathrm{Cl} \rightarrow e^- + {}^{37}\mathrm{Ar} .$$

It was shown that this process does not take place. This meant that $\nu_e \neq \bar{\nu}_e$ *), i.e. there exists a lepton charge having opposite values for ν_e and $\bar{\nu}_e$. What is the nature of this charge? Let us say right away that to answer this question today is definitely more difficult than in the late fifties, when parity nonconservation in weak interactions was observed. At that time it was possible to think that the lepton charge amounts to the so-called neutrino helicity. Below we explain what we are talking about.

We have already stated that the neutrino spin is equal to 1/2. According to quantum mechanics the projection of the neutrino spin upon the direction of its momentum (helicity)**) has two possible values: ± 1.

---

*) Notice that such conclusion can be reached with a much higher degree of accuracy in experiments aimed to detect the neutrinoless double β-decay process $(A,Z) \rightarrow (A,Z+2)+e^-+e^-$, where A is the mass number, Z is atomic number (see later).

**) Let us remark that the word helicity sometimes is used (improperly) to indicate longitudinal polarization, in which case there may appear values different from ± 1.

Neutrinos with negative (positive) helicity are called left-handed (right-handed), because they remind left-handed screws (right-handed screws). Before the discovery of parity non-conservation it was naturally thought that in neutrino beams one half of the particles are left-handed and one half are right-handed. This followed from the parity conservation law, upon the validity of which physicists had no doubts before 1956. According to this law, in all phenomena there must take place a strict right-left (mirror) symmetry. As a result in nature there must not be processes in which either the right outbalances the left or viceversa. The parity conservation law, in particular, is forbidding the emission of longitudinal polarized neutrinos, i.e. of neutrinos, let us say, preferencially left-handed.

Before 1956 physicists thought also that a different symmetry must takes place - charge conjugation symmetry, according to which all physical laws are invariant when every particle is substituted by its antiparticle. Such a symmetry does not allow, for example, the polarization of neutrinos to be different from that of antineutrinos in charge conjugated processes.

Lee and Yang (1956) put forward the idea that the two above-mentioned symmetries do not take place in the case of weak interactions. As a matter of fact subsequent experiments showed that there exist phenomena in which parity (P) and charge conjugation (C) are violated, the violation of both symmetries taking place simultaneously. Then Landau as well as Lee and Yang put forward the hypothesis that the laws of nature are invariant with respect to the combined PC inversion, consisting in

the simultaneous change of right into left and of every particle into its antiparticle. From the point of view of this new symmetry neutrinos "have the right" to be polarized longitudinally. In addition if neutrinos are left-handed (right-handed) antineutrinos must be right-handed (left-handed). Such a possibility was considered by Landau, Lee and Yang and Salam (1957) in their theory of the two-component neutrino. According to this theory neutrinos must have a mass strictly equal to zero.

The predictions of the theory until now are confirmed experimentally. We know now (Goldhaber et al. 1957) that neutrinos are (at least mainly) left-handed; the degree of polarisation of neutrinos and antineutrinos is extremely high. True, experimentally it has not been demonstrated that they are totally polarized and that their masses are equal to zero, as the two-component theory requires. Summarizing it was shown experimentally that neutrinos and antineutrinos have different helicities, a good model of the neutrino (antineutrino) being a left-handed (right-handed) screw. Thus a very natural question is arising: is the difference in the helicities of neutrinos and antineutrinos the only difference among these particles? In other words is the neutrino lepton charge amounting only to its helicity? In the fifties most physicists would have answered this question positively.

The great increase in our knowledge about neutrinos which came about with the development of high energy neutrino physics, especially with the investigations of neutrinos from meson decay, rendered more subtle the question about lepton charges. Muon and taon neutrinos have been discovered. Clearly one needs something more than the helicity to distinguish, for example,

ν_e from ν_μ etc. All the experimental data can be described by the introduction of three additive lepton charges (electron, muon and taon charges), characteristic of three lepton generations (see Table I).

The question arises as to whether lepton charges are conserved exactly or not. From a theoretical point of view, present-day models of either the unified electroweak and strong interactions or models of electroweak, strong and gravitational interactions (see N.Cabibbo, S&T,83 L'Unificazione delle forze fondamentali) would suggest that lepton charges are not conserved strictly. In such models the violation is due to the finiteness of neutrino masses, the expected values of which are as low as 1 eV - 10^{-6} eV.

4. Lepton charge violation?

The question about lepton charge violations can be investigated experimentally by searching for rare lepton charge violating processes such as those presented in Table III.

As is seen in Table III, there are no experimental indications of lepton charge violations. However, from the point of view of modern ideas about neutrinos, the lepton charge conservation law is expected to be violated, true at a level of probabilities much less than the upper limits experimentally achieved today and presented as illustration in Table III. We are talking about finite neutrino masses and neutrino mixing.

Table III.

Upper limits of probabilities of some processes forbidden by lepton charge conservation

Process	Experimental data (Γ's are the relevant widths, W's are capture probabilities per unit time)
$\mu^+ \to e^+ \gamma$	$\frac{\Gamma(\mu^+ \to e^+ \gamma)}{\Gamma(\mu^+ \to all)} < 1.7 \cdot 10^{-10}$
$\mu^+ \to e^+ e^- e^+$	$\frac{\Gamma(\mu^+ \to e^+ e^- e^+)}{\Gamma(\mu^+ \to all)} < 2.4 \cdot 10^{-12}$
$\mu^- Ti \to e^- Ti$	$\frac{W(\mu^- Ti \to e^- Ti)}{W(\mu^- Ti \to all)} < 1.6 \cdot 10^{-11}$
$\mu^- \, {}^{127}I \to e^+ \, {}^{127}Sb$	$\frac{W(\mu^- I \to e^+ Sb)}{W(\mu^- I \to all)} < 3 \cdot 10^{-10}$

5. Neutrino masses

Already Fermi in 1933 pointed out that measurements of the β-spectrum of a radioelement should give information about the neutrino mass. Clearly such method should be the more sensitive the less is the total energy released in the β-decay. From this point of view the most attractive decay is

$$^3H \rightarrow {}^3He + e^- + \bar{\nu}_e + Q ,$$

where the energy release Q is only 18.6 keV. In the last few years Lubimov et al. (Moscow) and then many other groups investigated the question at unprecedent levels of accuracy with the help of magnetic and electrostatic spectrometers. The published data are summarized in Table IV.

Table IV.

Recent data on (anti)neutrino mass from the measurement of the β-spectrum of tritium

Group	Tritium source	Anti(neutrino) mass m_ν
Moscow	Valin ($C_5H_{12}NO_2$)	$14 < m_\nu < 46$ eV
Tokyo	Arachidic acid ($C_{20}H_{40}O_2$)	$m_\nu < 31$ eV
Los Alamos	<u>Free</u> tritium diatomic molecules	$m_\nu < 29$ eV
Zürich	Tritium implanted in a thin carbon layer	$m_\nu < 18$ eV

The experiments are very difficult and we take off our hat before the authors in signs of admiration. At the same time the experiments are quite "acrobatic" and in our opinion they only exclude values of the antineutrino mass larger than, let us say, 40 eV.

6. Lepton mixing and neutrino oscillations in vacuum

There is a method of getting information on neutrino masses less direct than the tritium method mentioned above, but much more sensitive. We have in mind the search for neutrino oscillations, the existence of which does imply finite neutrino masses and neutrino mixing.

If neutrino mixing does exist, the neutrinos which participate in the weak interaction (ν_e, ν_μ, ν_τ) do not possess definite masses and are not described by stationary states. We shall denote by ν_1, ν_2, ν_3 the neutrinos of definite

masses m_1, m_2, m_3. The fields of neutrinos ν_e, ν_μ, ν_τ are then combinations of the fields ν_1, ν_2, ν_3 :

$$\nu_l = \sum U_{li} \nu_i ,$$

where l stands for e, μ, τ and U is a unitary matrix.

In the simplest case of two types of neutrinos (let us say ν_e, ν_μ) we have

$$\begin{aligned} \nu_e &= \cos\theta\, \nu_1 - \sin\theta\, \nu_2 , \\ \nu_\mu &= \sin\theta\, \nu_1 + \cos\theta\, \nu_2 , \end{aligned} \tag{1}$$

where θ is the lepton mixing angle. In this example there will be oscillations in vacuum $\nu_e \rightleftarrows \nu_\mu$: if a source is emitting let us say ν_e's in a pure state, at a sufficient distance from the source the number of ν_e will decrease and there will appear ν_μ's, the total number of neutrinos being of course constant.

The probability $P_{\nu_\mu ; \nu_e}(R)$ to find ν_μ at a distance R from a source of ν_e's is

$$P_{\nu_\mu ; \nu_e}(R) = \frac{1}{2} \sin^2 2\theta \left(1 - \cos 2\pi \frac{R}{L}\right), \tag{2}$$

where

$$L = 4\pi \frac{p}{\Delta m^2} \tag{3}$$

is the oscillation length, p is the neutrino momentum, $\Delta m^2 = | m_1^2 - m_2^2 |$ is the mass squared difference. A convenient formula for the oscillation length in meters is

$$L = 2.5 \frac{p}{\Delta m^2} \text{ meters,}$$

where p is expressed in MeV and Δm^2 in eV^2 .

The probability $P_{\nu_e;\nu_e}(R)$ to find ν_e at a distance R from a source of ν_e's in the considered case of two neutrinos is obviously

$$P_{\nu_e;\nu_e}(R) = 1 - \frac{1}{2}\sin^2 2\theta\left(1 - \cos 2\pi\frac{R}{L}\right). \quad (4)$$

Clearly there are two methods of searching for neutrino oscillations. Appearance method: searching at a distance from a source of neutrinos of a definite type (let us say ν_e's) for the appearance of other type neutrinos (in our example ν_μ's). Disappearance method: searching at a distance from a source of neutrinos of a definite type (let us say ν_e's) for a decrease in the expected intensity of ν_e's.

The "philosophy" of oscillation experiments is physically very simple. If $R \ll L$, no conclusion about oscillations can be reached. If $R \gg L$ and θ is not too small, oscillation effects of the appearance and disappearance type will be observable. The cosinusoidal term in this case is not observable, as it turns to zero upon averaging over the neutrino energy spectrum, the detector and source sizes and, when needed, the distance source-detector. If $R \sim L$ and θ is sufficiently large, periodical effects will be observable, a circumstance which leads to the possibility of directly measuring squared neutrino mass differencies. The sensitivity of oscillation experiments is very high. For example in reactor experiments (for large θ) oscillation effects would be seen if $\Delta m^2 > 10^{-2}\mathrm{eV}^2$. For the Sun, which is a very favourable object due to the fact that R is as high as $150 \cdot 10^6$ km and p as low as $\sim$ 1 MeV, one can in principle see oscillation effects if $\Delta m^2 > 10^{-12}\mathrm{eV}^2$!

We remind the reader that direct measurements of the antineutrino mass give $m_\nu < 40$ eV. The fantastic sensitivity of oscillation experiments is connected with the fact that they are interference type experiments, in which an amplitude is measured and not an amplitude squared.

Presently a large number of experiments in which neutrino oscillations are searched for are being conducted at various facilities. There is no experiment in which neutrino oscillations have been definitely observed. This refers to reactor, accelerator and cosmic ray experiments (the solar neutrino experiments will be dealt with later). Experiments already performed yield only limits on the values of the parameters involved. From reactor experiments, for example, it follows

$$\Delta m^2 < 0.016 \quad (\sin^2 2\theta = 1)$$
$$\sin^2 2\theta < 0.16 \quad (\Delta m^2 > 5\ \mathrm{eV}^2)\ .$$

7. Neutrino mass terms

Neutrino mixing is due to the presence of mass terms in the Lagrangian. Let us underline that in modern theoretical models such terms arise quite naturaly. Apriori there are three types of neutrino mass terms: Majorana, Dirac, Majorana and Dirac. In order to define them let us consider for simplicity the case of one lepton generation. Let us introduce the most general Majorana and Dirac mass term, in which there are taken into account the possibilities of lepton charge violation and of existence of a right-handed neutrino field together with the usual left-handed field:

$$\mathcal{L} = -\frac{1}{2}\left[m_L (\bar{\nu}_L)^c \nu_L + m_R \bar{\nu}_R (\nu_R)^c + 2 m_D \bar{\nu}_R \nu_L\right] + h.c., \tag{5}$$

where m_L, m_R, m_D are real parameters, ν_L and ν_R are left-handed and right-handed neutrino field components, $(\nu_L)^c$ is the charge conjugated component. The case considered implies the existence of four particles: the two well-known ν_L and $\bar{\nu}_R$ and two sterile (that is not taking part in the standard weak interaction) particles ν_R and $\bar{\nu}_L$. Simple considerations show that in the general case of a Majorana and Dirac mass term, the particles with definite masses are two truly neutral particles with Majorana masses m_1, m_2 (four states as it should be).

In (5) the terms $-\frac{1}{2} m_L (\bar{\nu}_L)^c \nu_L$ and $-\frac{1}{2} m_R \bar{\nu}_R (\nu_R)^c$ stand correspondingly for the left Majorana term and the right Majorana term, the term $- m_D \bar{\nu}_R \nu_L$ stands for the Dirac term. If $m_R = m_D = 0$ there are no sterile states and there is one neutrino with Majorana mass (2 states), the corresponding mass term being defined as pure Majorana mass term. It is seen that a pure Dirac mass term is obtained when $m_R = m_L = 0$, a situation which corresponds to one (four component) neutrino with Dirac mass (four states).

Clearly in the considered case of one lepton generation, oscillations ($\nu_L \rightleftarrows \bar{\nu}_L$) may take place only if the mass term is of the Majorana and Dirac type. The Majorana masses m_1 and m_2 and the mixing angle ϑ are given by the expressions

$$m_{1,2} = \frac{1}{2}\left[(m_L + m_R) \pm \sqrt{(m_L - m_R)^2 + 4m_D^2}\right], \tag{6}$$

$$tg\,2\theta = \frac{2m_D}{m_L - m_R}. \tag{7}$$

If neutrino masses are finite, as is desirable from a theoretical point of view, they are incomparable smaller than the masses of charged fundamental fermions. Why? The following consideration might suggest the so-called "see-saw" mechanism of generation of small neutrino masses (Gell-Mann, Ramond, Slansky, 1977).

8. The "see-saw" mechanism of neutrino mass generation

In modern theories all mass terms arise from the interaction with scalar (so-called) Higgs fields through the spontaneous violation of the basic symmetry of the relevant theory. Suppose that the right Majorana term $-\frac{1}{2} m_R \bar{\nu}_R (\nu_R)^c$ in expression (5) is arising through the violation of the GUT (Grand Unified Theory of electroweak and strong interactions) symmetry and that consequently m_R has the order of magnitude of a typical GUT mass M ($M \sim 10^{14}$GeV); in the Dirac term $- m_D \bar{\nu}_R \nu_L$ it is natural to expect that m_D has the order of magnitude of a quark mass. As far as the left Majorana term $-\frac{1}{2} m_L (\bar{\nu}_L)^c \nu_L$ is concerned, let us suppose that m_L is strictly equal to zero (which is corresponding to the classical two-component neutrino a la Landau, Lee and Yang). From the expression (6) we see that such situation leads to a very heavy neutral lepton with Majorana mass $m_1 \simeq M$ and to a (very light) neutrino with a finite Majorana mass $m_2 \simeq \frac{m_D^2}{M} \ll m_D$. From expression (7) one can see that $\theta \simeq \frac{m_D}{M} \ll 1$, which means practically absence of mixing and oscillations in the case considered. As far as numerical values of neutrino masses are concerned, it should be stressed that there are many uncertainties in the estimate. Finally one gets a range 10^{-6}eV - 1 eV.

9. A possible scheme of maximum mixing

We have considered the case of one lepton generation in the presence of sterile states. Now we turn to a particular case of two lepton generations ($\nu_e e$, $\nu_\mu \mu$, for example) but without sterile states. We start again from the Majorana and Dirac mass term (5), where both ν_L and ν_R are active components (no sterile components!). It is natural in this case to change in expressions (5), (6) and (7) the notations as follows: $m_L \rightarrow m_{ee}$, $m_R \rightarrow m_{\mu\mu}$, $m_D \rightarrow m_{\mu e}$. Again the particles with definite masses are two neutrinos with Majorana masses m_1 and m_2. The striking two-component structure of the weak current is fully preserved by the Majorana character of the mass eigenstates and there arise oscillations of the type $\nu_e \rightleftarrows \nu_\mu$. If we wish to preserve the notion of lepton charge (useful even in the case considered, where it is violated) we must recognize that there is only one lepton charge which has opposite signs for e^- and μ^+. Incidentally, this is the Zeldovich-Konopinsky-Mahmoud lepton charge scheme (essentially different from the one given in Table I !) revised in connection with the assumption of lepton charge nonconservation. The considered scheme is the most economical one (for the case of two generations) *). All the four component of the neutrino field (only one!) are present in the current on the same footing.

---

*) As a matter of fact the scheme implies that two generations merge into one, the μ -e generation.

It is natural to assume that ν_L and ν_R are also entering symmetrically in the mass term (5), which should lead to the expectation of equal values of m_{ee} and $m_{\mu\mu}$. As it is seen from (7) such equality should imply $\theta = \frac{\pi}{4}$ (maximum mixing and maximum amplitude of oscillations in vacuum).

If the scheme is to be generalised to more than two generations, it would be requested that the number of generations must be even. The scheme is aesthetically so attractive that the possibility of its realization should be considered seriously.

10. Neutrinoless double β -decay

We have already underlined the high sensitivity of the neutrino oscillation method. Even if neutrino oscillations will be observed in the future, it will be practically impossible to make definite conclusions about the nature (either Majorana or Dirac) of neutrino masses. Fortunately there is a process which would take place only if neutrinos have Majorana masses, the neutrinoless double β -decay

$$(A,Z) \rightarrow (A,Z+2) + e^- + e^-.$$

In the standard weak interaction theory this is a two-step process:

I. One neutron in the nucleus decays into a proton, an electron and $\bar{\nu}_e$, the state of which is the proper superposition of states of particles ν_i, i = 1,2,... with definite masses.

II. The emitted $\bar{\nu}_e$ is absorbed by another neutron which transforms itself into a proton with the emission of a second electron. This process is forbidden if the neutrino mass is strictly equal to zero. In such a case neutrinos are completely polarized longitudinally. Then a right-handed neutrino can be emitted together with an electron by a neutron, whereas only a left-handed neutrino can be absorbed by a neutron with the emission of an electron. The situation changes if the neutrino mass is different from zero. The polarization is no more full and the process is allowed if neutrinos ν_i have Majorana masses and forbidden if ν_i have Dirac masses. This is so because a Majorana mass neutrino ν_i (which is a two component object) has no lepton charge and consequently can be emitted together with an electron as well as absorbed with production of an electron (see Fig. 9). At a variance with this the emission of a Dirac mass neutrino ν_i (which is a four-component object) together with an electron is not compatible with its absorption with the emission of an electron.

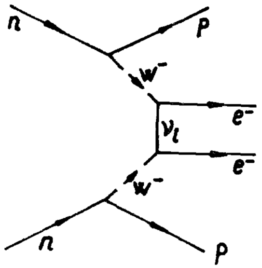

Fig. 9.

The diagram of neutrinoless double β-decay. The process may take place only if neutrinos ν_i (i = 1,2,...) have Majorana masses.

We have already mentioned that neutrinoless double β-decay cannot take place when the masses m_i of neutrinos ν_i are equal to zero. It can be shown that the process amplitude in the simple case of two neutrino types is proportional to

$$\langle m \rangle = \cos^2\theta\, m_1 + \eta \sin^2\theta\, m_2,$$

where m_1 and m_2 are Majorana masses, θ is the neutrino mixing angle and $\eta = \pm 1$ is the relative CP-parity of ν_1 and ν_2. From this formula it is seen that experiments on neutrinoless double β-decay give information on neutrino Majorana masses.

Two words about the experimental situation. First a simple remark of methodical character. Such experiments are incredibly sensitive. The background in them can be kept down, since in neutrinoless double β-decay the sum of the energies of the two emitted electrons is practically fixed.

Until now neutrinoless double β-decay has not been observed. The best result is obtained in the search for the decay

$$^{76}\mathrm{Ge} \longrightarrow {}^{76}\mathrm{Se} + e^- + e^- ,$$

for which the following limit for the half-life period was obtained (Santa Barbara-Berkeley)

$$T_{1/2} > 4 \cdot 10^{23} \text{ years} .$$

This limit implies for $\langle m \rangle$ a value as low as

$$\langle m \rangle < 2 \text{ eV} .$$

Notice that if the relative CP parity of ν_1 and ν_2 is positive ($\eta = 1$), this result means (let us say at $\theta \simeq \frac{\pi}{4}$) that m_1 and m_2 are less than about 4 eV.

On the contrary, if $\eta = -1$, there is a compensation of contributions of ν_1 and ν_2, which would imply that m_1 and m_2 could be well above 2 eV.

11. Vacuum oscillations and solar neutrinos

Solar neutrino astronomy is extremely important not only from an astrophysical point of view but also from the point of view of elementary particle physics (neutrino mixing, mass and magnetic moment). The investigation of solar neutrinos is ideally suited for the study of oscillation phenomena, because the Sun-Earth distance is enormous ($\sim 1.5 \cdot 10^8$ km) and solar neutrinos energies are relatively low (~ 1 MeV).

The very first step in solar neutrino astronomy is based on the radiochemical Cl-Ar method, whereby the reaction

$$\nu_e + {}^{37}Cl \longrightarrow e^- + {}^{37}Ar$$

is searched for, the radioactive ${}^{37}Ar$ being extracted from a large volume of C_2Cl_4 and introduced in a small proportional counter. R.Davis et al. succeeded in detecting solar neutrinos making use of such method. It was found that the rate of ${}^{37}Ar$ production by solar neutrinos is 2.0±0.3 SNU (I SNU = 10^{-36} ${}^{37}Ar$ atom/sec ${}^{37}Cl$ atom) to be compared with the value 5.8±2.2 SNU calculated by Bahcall et al. on the basis of the standard model of the Sun. The discrepancy is currently named "solar neutrino puzzle". The cause of the puzzle may well be connected with uncertainties in the predictions of the standard model. As a matter of fact the threshold of the reaction $\nu_e + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$ is considerable above the maximum energy of neutrinos emitted in the process $p+p \longrightarrow d+e^+ + \nu_e$, which is the main thermonuclear reaction in the Sun (see the last paragraph "Panorama ..." at the end of the present paper). Thus the neutrino flux (mostly from ${}^{8}B$ decay) which can be detected by the Cl-Ar method is a very small fraction ($\sim 10^{-4}$) of the total solar neutrino flux, its predicted value strongly depending upon the solar model parameters.

The solar neutrino puzzle might be due to oscillations. Anyway the only experiment made up to now certainly does not exclude oscillations and <u>might</u> be an indication of their existence. Let us assume that the solar neutrino puzzle is really connected with vacuum neutrino oscillations. Such assumption would imply that the difference of the neutrino masses squared $\Delta m^2 \gtrsim 10^{-12} eV^2$!!

The importance of possible vacuum neutrino oscillations in neutrino astronomy was pointed out in Dubna before the first solar neutrino observations were performed. The Cl-Ar method gives the possibility of detecting only ν_e. Thus if there are vacuum oscillations $\nu_e \rightleftarrows \nu_\mu$, $\nu_e \rightleftarrows \nu_\tau$, ... the intensity of ν_e (averaged over the ν_e-producing region of the Sun, the Sun-Earth distance and the neutrino energy) may be as low as 1/N of the averaged intensity I_o expected in the absence of oscillations, N being the number of lepton generations. If there are oscillations also into sterile states ($\nu_e \rightleftarrows \nu_\mu$, $\nu_e \rightleftarrows \nu_\tau$, $\nu_e \rightleftarrows \bar{\nu}_{eL}$, $\nu_e \rightleftarrows \bar{\nu}_{\mu L}$, ...) the averaged intensity of ν_e may be as low as $\frac{1}{2N} I_o$. In both cases such maximum reduction is achieved at maximum mixing. Thus it is seen that a reduction of the ν_e intensity by the "neutrino puzzle factor" ($\sim 1/3$) would be easily understood in terms of vacuum oscillations with substantial mixing and three lepton generations *).

A substantial lepton mixing is generally not considered likely (by analogy with quark mixing). True, earlier we presented some aesthetic arguments in favour of a scheme with maximum mixing. Be that as it may, we have discussed until now vacuum oscillations. In other words we have not taken into account the presence of matter. Recently it was shown (Miheev, Smirnov, Wolfenstein, MSW) that matter effects may substantially change the picture of neutrino oscillations.

12. Matter oscillations and solar neutrinos

The neutrino Hamiltonian in matter is the sum of the free Hamiltonian and the interaction Hamiltonian. The interaction of a neutrino beam with matter can be effectively described in terms of a refraction index, which is determined by the amplitude of the forward neutrino elastic scattering and by the matter density. The reason why oscillations in matter may be different from vacuum oscillations is that the ν_e -e scattering amplitude is different from the ν_μ-e (ν_τ-e, ...) scattering amplitude (ν_e -e scattering is due to W as well as Z^o exchange, whereas ν_μ-e, ... scattering is due to Z^o exchange only). Thus the mixing angle θ_m and the oscillation length L_m in matter are different from the values θ and L in vacuum. One gets for the simplest case of two neutrino types (ν_e, ν_μ):

$$\sin 2\theta_m = \frac{\Delta m^2 \sin 2\theta}{A}, \quad \cos 2\theta_m = \frac{\Delta m^2 \cos 2\theta - 2\sqrt{2}\, G_F N_e p}{A}, \qquad (8)$$

$$L_m = \frac{L \Delta m^2}{A},$$

where

$$A = \sqrt{(\Delta m^2 \cos 2\theta - 2\sqrt{2}\, G_F N_e p)^2 + (\Delta m^2 \sin 2\theta)^2}. \qquad (9)$$

Here $\Delta m^2 = m_2^2 - m_1^2 > 0$ is the vacuum oscillation parameter supposed to be positive, m_2 and m_1 are the masses of ν_2 and ν_1 (in vacuum), G_F is the Fermi constant, N_e is the electron density and p is the neutrino momentum. The expressions for the transition probability $\nu_e \to \nu_e$ in matter is identical to the vacuum oscillation expression (4) in which the $\theta \to \theta_m$, $L \to L_m$ substitutions are made:

$$P^m_{\nu_e;\nu_e}(R) = 1 - \frac{1}{2}\sin^2 2\theta_m \left(1 - \cos 2\pi \frac{R}{L_m}\right). \qquad (4a)$$

It is seen from (8) that there might be oscillations in matter only if there is lepton mixing, that is if θ and Δm^2 are not equal to zero. The most noteworthy feature in (8) is that for arbitrary (but finite) values of θ and Δm^2 the matter mixing angle θ_m is equal to $\pi/4$ (maximum amplitude of matter oscillations) provided the resonance condition

$$\Delta m^2 \cos 2\theta = 2\sqrt{2}\, G_F N_e p \qquad (10)$$

is fulfilled.

---

*) We are not considering here the accidental possibility that the oscillation length is of the order of the Sun-Earth distance, in which case the term cos $2\pi R/L$ in (4) might survive averaging, with the result of a large reduction factor (and may be of time variations of the ν_e intensity, as first noticed by Pomeranchuk).

When the resonance condition is satisfied, however, the oscillation length in matter L_m is connected to the vacuum oscillation length L by the relation

$$L_m = \frac{L}{\sin 2\theta} \quad , \tag{11}$$

which implies that for the relevance of matter oscillations θ must not be too small.

The resonance condition may be written as follows

$$\Delta m^2 \cos 2\theta = 0.65 \cdot 10^{-7} \rho p \quad , \tag{10a}$$

where Δm^2 is given in units eV^2, ρ is the matter density in g/cm^3 and p is the neutrino momentum in MeV. Having in mind applications to the Sun let us take $\rho \simeq 10^2$ g/cm^3 (typical for the Sun central region) and $p \simeq 1$ MeV. The resonance condition in such a region is satisfied at values $\Delta m^2 \cos 2\theta$ as low as $\simeq 10^{-5} eV^2$.

Until now we have discussed the situation in which the matter density is constant. In such a case matter neutrino oscillations, but for different values of oscillation amplitudes and lengths, are similar to vacuum oscillations, in the sense that we are confronted in both cases with a periodical phenomenon. A different situation is arising when the matter density is not constant. We shall briefly discuss below this case having in mind the Sun.

The matter density obviously decreases from its maximum value ρ_{max} at the center of the Sun. The minimum neutrino momentum for which the resonance condition (10a) is fulfilled is

$$p_{min} = 1.5 \cdot 10^{7} \frac{\Delta m^2 \cos 2\theta}{\rho_{max}} .$$

For neutrinos of momentum $p < p_{min}$ the resonance condition cannot be fulfilled. On the contrary all neutrinos of momentum $p > p_{min}$ on their way from the central region of the Sun to its surface pass through matter of "resonance density" ρ_R for which $\theta_m = \frac{\pi}{4}$.

Let us suppose now that the vacuum mixing angle θ is small. Then from expressions (8) it follows that in the high density region ($\rho > \rho_R$), where ν_e are generated, the matter angle θ_m is approximately equal to $\frac{\pi}{2}$, which means that the ν_e-state practically coincides with the heavier of the two eigenstates of the neutrino Hamiltonian in matter, the other eigenstate practically coinciding with the ν_μ-state. When the neutrino is passing from the region of high density ($\rho > \rho_R$) through the resonance region ($\rho = \rho_R$) to a small density region ($\rho < \rho_R$), the matter angle θ_m is changing from $\frac{\pi}{2}$ to 0 (through the resonance value $\frac{\pi}{4}$). This implies that at low densities the heavier eigenstate is practically the ν_μ-state, the lightest one being practically the ν_e-state. This picture is correct if the spatial change in density is slow enough. This condition (so-called adiabatic condition) can be formulated as follows: the effective change of the density in the resonance region must take place over lengths greater than the matter oscillation length at resonance.

Under the assumptions made above we get finally the following picture: the ν_e's with momentum larger than p_{min} generated in the center regions of the Sun passing through the resonance region, emerge as ν_μ's (or ν_τ's, ...), that is as particles which cannot be detected in the radiochemical experiments of the Davis type. Incidentally, the periodicity characterizing neutrino oscillations in vacuum (see (4)) and in a medium with constant density is entirely lost through the effect of changing density. This very interesting effect may be a solution of the solar neutrino puzzle. If we assume that the explanation is right, there arise two possible solutions for the fundamental vacuum parameters Δm^2 and $\sin^2 2\theta$*):

1. $\Delta m^2 \simeq 10^{-4} eV^2$, $\sin^2 2\theta > 10^{-3}$,

2. $\Delta m^2 \sin^2 2\theta \simeq 3 \cdot 10^{-8} eV^2$.

The future of experimental solar neutrino astronomy is quite bright. With respect to the Davis observations, improvements are expected in experiments being prepared now in which:

1) there will be detected low energy neutrinos ($E < 0.4$ **MeV** from the main $pp \to de^+\nu_e$ reaction) the flux of which is predictable in an almost model independent way if there are no oscillations (Ga-Ge radiochemical method)

2) electronic methods of detecting neutrinos will be used, suitable for giving some information on the neutrino energy, for proving that the neutrinos come from the Sun direction and also for detecting (through neutral current reactions) not only ν_e but also ν_μ and ν_τ . Some information on such developments can be found in the **paragraph "Panorama of today** experimental neutrino physics" at the end of the present paper.

---

*) Of course in principle there exists the old solution of a completely different type: the large amplitude vacuum oscillation solution, which implies $\Delta m^2 \gtrsim 10^{-12} eV^2$.

In conclusion we would like to notice that matter oscillations may play a relevant role not only in the passage of neutrinos through the Sun, but also in the passage of neutrinos through the Earth and in the gravitational collapse of stars, ...

13. Neutrino magnetic moment and solar neutrino astronomy

The solar neutrino puzzle might be explained not only by the presence of neutrino oscillations. A number of different explanations of the possible lack of detectable solar neutrinos has been suggested in terms of either particle physics or astrophysics. Below we discuss one explanation which is connected with possible finite values of the neutrino magnetic moment.

If massive neutrinos are four-component (Dirac) particles, they might posses finite magnetic moments. The existence of a large enough magnetic neutrino moment μ would have important astrophysical consequences. In particular, it might lead to a decrease of the detectable solar neutrino flux. As a matter of fact a left-handed solar neutrino passing through a region where a strong enough magnetic field is present, becomes in part sterile (right handed) due to the precession of the magnetic moment. If the neutrino magnetic moment were the cause of the solar neutrino puzzle, the magnetic moment should turn out to be $\mu \gtrsim (0.3-1) \cdot 10^{-10}$ Bohr magnetons *). In such a case as recently suggested in Moscow, one would expect to

---

*) Incidentally, a value by many orders of magnitude larger than the value predicted by the standard model.

observe, among other things, 11 year period variations of the detectable solar neutrino flux, which are connected with the variations of the solar magnetic activity.

14. Neutrinos and the Universe

In general, because of their properties, mainly low masses (if any) and an enormous penetrating power, neutrinos are of extreme importance in astrophysics, cosmology and astronomy. Noteworthy are:

1) the appearance of a new page in astronomy - the solar neutrino astronomy;

2) the participation of neutrinos in hydrogen burning termonuclear reactions, whereby hydrogen is finally transformed into helium ($4H \rightarrow {}^4He + 2e^+ + 2\nu_e + 26$ MeV), resulting for the Sun case in a flux at the earth surface equal to $\sim 6 \cdot 10^{10}$ /cm^{2}sec (the neutrino luminosity of the Sun being only $\sim$ 2% of its photon luminosity, a proportion typical for all stars slowly evolving while hydrogen burning thermonuclear reactions take place in their central regions);

3) the today presence, inferred by big-bang cosmology, of a relict radiation of neutrinos of all types, whose last interactions took place only $\sim$ 1 sec after the big-bang, that is much earlier than the last relict microwave radiation interactions, having taken place $\sim 10^6$ years after the big-bang;

4) the possible contribution of neutrinos to the mass of dark matter (that is the bulk of matter in the Universe which is not luminous and is revealed only through gravitation), as well as their possible importance in the formation of galaxies;

5) the remarkable fact that cosmological, astrophysical and astronomical data are giving some information on neutrino properties (number of neutrinos, masses, mixing, magnetic moments, ...);

6) the fantastically large ($\sim 10^{58}$!) number of neutrinos of all types with average energy $\sim$ 10 MeV radiated by a gravitationally collapsing star during $\sim$ 20 sec;

7) the variety in the star evolution of neutrino emission processes, which rapidly increase in importance while the nuclear fuel is being consumed in the star central regions, insure the neutrino luminosity to dominate over the photon one at temperatures $T > 10^8$K, lead to a considerable shortening in the time scale of the late stages in the evolution of massive stars, eventually entirely define the star collapse dynamics: in order of relevance, starting back from the collapse phase and high temperatures down to relatively small temperatures, the processes are: 1) one neutrino processes in which the charge W boson is involved - $e^-p \rightarrow \nu_e n$, $e^+n \rightarrow \bar{\nu}_e p$ (Urka), 2) neutrino pair processes in which the W and/or the neutral Z^0 are involved - $e^+e^- \rightarrow \nu_e\bar{\nu}_e, \nu_\mu\bar{\nu}_\mu, \nu_\tau\bar{\nu}_\tau$ (electron positron), plasmon $\rightarrow \nu_e\bar{\nu}_e, \nu_\mu\bar{\nu}_\mu, \nu_\tau\bar{\nu}_\tau$ (plasma), $\gamma e \rightarrow e\nu_e\bar{\nu}_e, e\nu_\mu\bar{\nu}_\mu, e\nu_\tau\bar{\nu}_\tau$ (photo), $eZ \rightarrow e\nu_e\bar{\nu}_e Z, e\nu_\mu\bar{\nu}_\mu Z, e\nu_\tau\bar{\nu}_\tau Z$ (bremstrahlung), 3) neutrino pair processes in which only Z^0 is involved - $A^* \rightarrow A\nu_e\bar{\nu}_e, A\nu_\mu\bar{\nu}_\mu, A\nu_\tau\bar{\nu}_\tau$ (neutrino radioactivity from excited nuclei);

8) the importance in nucleosynthesis, especially in the efficient production of by-passed (neutron poor) isotopes, of neutrinos from the collapsing steller core, which produce (in the matter of the star envelope to be thrown out) such

isotopes in agreement with observed galactic abundancies;

9) the rise, to be covered below, of a new era in astronomy, marked by experimental searches for, and investigation of, neutrinos associated with gravitationally collapsing stars.

15. Gravitational collapse of stars. Supernova SN 1987 A

On February 24, 1987 the supernova now called SN 1987 A, resulting from the collapse and successive explosion of the star Sanduleak (69-202) was optically discovered by Shelton and Jones in the Large Magellanic Cloud, a nearby galaxy. The event is providing and will provide unique astrophysical information because

1) the supernova is an enormously bright object, many millions of times brighter than the Sun,

2) the distance of the Supernova from the earth, only about 160000 light years, is well known,

3) detailed and comprehensive observations of the initial explosion stages are being made for the first time,

4) the dependence of the supernova SN 1987 A luminosity upon time is rather unexpected, the fact that the presupernova star was much heavier than the Sun being almost beyond question,

5) also for the first time a supernova is observed at a moment when theoretical understanding of supernovas, and in general of the star gravitational collapse, is serving as a guide to physicists, astrophysicists and astronomers, in particular through the outstanding prediction that a few tens of second long burst of $\simeq 10^{58}$(!) neutrinos of average energy $\simeq 10$ MeV should accompany the collapse, preceding somewhat in time the emission of visible supernova light,

6) last but not least the supernova has appeared at a time when in various sites a number of large electron detectors suitable for the registration of ~ 10 MeV neutrinos were found to be in working conditions.

Naturally all the groups working with large electron detectors carefully inspected their records before and after the 24 of February. During the last few years they created the necessary apparatus suitable to observe an event just of the type considered (neutrino burst from gravitational collapse) and they were more or less ready (see also the paragraph "Panorama..." at the end of the present paper). The detectors with the help of which collapse neutrinos were observed on February 23, as it was announced, are

i) The ~ 100 ton liquid scintillator (antineutrino) detector (Italy-USSR) placed in the Mont-Blanc tunnel: during 7 seconds there were registered 5 pulses ($\bar{\nu}_e p \to e^+ n$?) above the 7 MeV energy threshold (on February 23, about 1 day before the first optical sighting)

ii) The several thousand ton H_2O Cerenkov detector Kamiokande II (Japan): during 13 seconds there were registered 11 electron pulses in the energy interval 7.5 - 36 MeV (on February 23, also before the optical sighting, but 4.5 hours after the Mont-Blanc burst). Two electrons (from neutrino-electron scattering?) point to the Large Magellanic Cloud with angles 18±18 and 15±27 degrees. The other tracks ($\bar{\nu}_e p \to e^+ n$?) are distributed random. The discrepancy in time of the Mont-Blanc and the Kamiokande II signals is not explained. The

Kamiokande II signal is may be the more convincing experimental evidence for a correlation between the Supernova SN 1987 A and a neutrino burst.

iii) The several thousand ton H_2O Cerenkov detector (Irvine-Michigan-Brookhaven): during six seconds there were registered 8 electron pulses in the energy range 20-40 MeV at a time coinciding with the Kamiokande time to an accuracy of ±1 min. The discrepancy with the Mont-Blanc event time is not explained. Also not sufficiently well explained is the absence of a signal at the Mont-Blanc time in the Kamiokande detector, which makes it difficult to think in terms of two distinct neutrino bursts.

vi) The ∼3000 liquid scintillators (of total weight ∼ 300 ton) at the Baksan Observatory (USSR); some indications of a neutrino signal were suggested at the Kamiokande - time.

The question as to whether a neutrino burst connected with the light emission from the Supernova SN 1987 A has been actually detected seems to us, under the circumstances, not essential.

There are many unclear points in evaluating a posteriori probabilities of accidental coincidences. And yet all the groups have open a new era in astronomy. The study of the light from SN 1987 A and the search for, as well as the investigation of, neutrinos connected with star gravitational collapse constitute a sort of dress rehearsal of an international enterprise (especially associated with the name of

G.Zatsepin), and as such are of utmost importance. The enterprise has been prepared in the course of the last ten years and will certainly be very active in the future. It is already clear that there is a lot of room for improvement, especially the necessity of unambiguous universal time measurement and of registering star collapse neutrinos independently of supernova light.

The international collaboration program should include the permanent operation at various sites of apparatus suitable for the observation of visible light from the supernova, of radio waves from its possible remnant neutron star (pulsar), of neutrinos and gravitational waves. At the moment there exist sensitive cryogenic antennas for gravitational radiation, but unfortunately on February 23, 1987 only a room temperature resonance antenna (Rome) was in operation. The relatively low sensitivity of the antenna gave little hope of detecting gravitational waves; it was not claimed by the authors that gravitational radiation has been detected, although there was an indication of a positive signal coinciding in time with the Mont-Blanc neutrino burst. However the record of the data from such antenna was published mainly with the aim of showing "the kind of analysis involved on occasion of events of this and similar types".

The star gravitational collapse is a quite complex phenomenon. However some of its features, of great importance from the point of view of the possibility of observing the neutrino burst and also of getting information on neutrino properties (mass, lifetime, ...), are almost model independent. The energy of neutrinos ($\sim 3 \cdot 10^{53}$ erg) emitted in the gravitational collapse of a star (the collapsing mass of which is, for example $\simeq 2\ M_{Sun}$) can be estimated simply: neutrino emission is the only effective way of cooling the star and therefore the gravitational mass defect of the remaining star is emitted almost entirely in form of neutrinos. The neutrino energy is estimated to be 10-15 MeV, which correspond to 10^{58} neutrinos of all types (ν_e , $\bar{\nu}_e$, ν_μ , $\bar{\nu}_\mu$, ν_τ , $\bar{\nu}_\tau$)*). The time in which neutrinos are emitted is expanded to 20 sec due to the opacity of the collapsing star to neutrinos. These considerations directly suggest the experimental requirements to a detector suitable for revealing a gravitational collapse taking place, let us say, in our galaxy: one must be able to register with efficiency 100% the passage through the detector of $\sim 10^{12}\,\nu/\mathrm{cm}^2$ during $\sim$ 20 sec. An underground detector of weight $\sim$ 100 tons (either CH_2 scintillator or H_2O Cerenkov counter) is sufficient to fix (well above the background) $\gtrsim$ 10 interacting neutrinos (neutrino burst), especially if several detectors are working at various sites.

Information on neutrino masses can in principle be obtained in the following ways:

1) if gravitational radiation is detected, the delay of the antineutrino signal ($\bar{\nu}_e p \to e^+ n$) together with the measurement of the positron energy yields direct information on the $\bar{\nu}_e$ - mass.

2) if neutrino have finite masses, neutrinos of higher energy arrive to the detector earlier than neutrinos of lower energy; thus the study of the time of arrival of neutrinos together with measurements of their energy gives information on neutrino masses *).

As far as the stability of neutrinos is concerned, it is clear that the very observation of neutrino bursts would permit to get information on neutrino life-times. For example the Kamiokande II observation of the neutrino burst implies that the life-times of ν_e and $\bar{\nu}_e$ are larger than 10^5 years.

Thus all over the world there are now a number of permanently working stations, well communicating between themselves, led by physicists, astronomers and astrophysicists, who are expecting the great event, the collapse. How long will they have to wait?

The gravitational collapse, a fantastically rapid (free fall) implosion of the star or of the central star region in which the nuclear fuel has been consumed**), may be accompanied by a supernova explosion, when the star envelope is thrown out and there appears a fantastic show whereby a single star has

---

*) The intense emission of $\nu_\mu \bar{\nu}_\mu$, $\nu_\tau \bar{\nu}_\tau$ pairs is due to neutral current processes ($e^+ e^- \to \nu_\mu \bar{\nu}_\mu$, $\nu_\tau \bar{\nu}_\tau$) involving the Z^0-boson. Because the photon mean free path is incomparably smaller than the neutrino mean free path, electromagnetic processes are no more competing with processes involving the virtual Z^0. Thus, as stated in §2, collapsing stars are practically the only example (we are able to give) of a neutrino source in which neutrinos arise in the decays of virtual Z^0-bosons.

*) If a neutrino burst has really been detected in the Kamiokande II experiment, one can get an upper value of the electron neutrino mass $m_{\nu_e} < 10$ eV from an analysis of the time distribution of pulses in the burst.

**) One would expect that the result of the collapse is either a neutron star (pulsar) or a black hole.

the luminosity of a galaxy. Of course supernovas have been observed for a long time. They are quite rare in our galaxy. Their number in hundred years may be as small as one and as high as 6: supernovas may not be visible, as their light is absorbed by intersteller dust.

Gravitational collapse may take place without the star envelope being thrown out. The number of such events is estimated to be comparable with, but larger than, the number of supernovas. Thus the number of neutrino bursts might be an order of magnitude larger than the number of observable supernovas.

Best wishes to the international community of brave scientists!

16. Panorama of today experimental neutrino physics

Neutrino type	Typical neutrino energies and intensities	Neutrino source. Facilities	Neutrino detector type and size	Main significance
1	2	3	4	5
$\bar{\nu}_e$	0 - 7 MeV. The total flux at several meters from reactor center is 10^{13}-$10^{14}cm^{-2}s^{-1}$	Powerful ($>10^6$kW) fission reactors (Grenoble, Gosgen, Bugey, Savannah River, Rovno)	Liquid scintillator (200-400 liters) registering the reaction $\bar{\nu}_e p \to e^+ n$.	Particle physics: search for neutrino oscillations. Reactor physics: burning rate of ^{235}U, production rate of ^{239}Pu, neutrino external control of reactors, ...
$\nu_\mu, \bar{\nu}_\mu, \nu_e$	30 MeV (ν_μ) <53 MeV ($\bar{\nu}_\mu, \nu_e$) The total flux for every indicated neutrino type is $\sim 10^7 cm^{-2}s^{-1}$ at a distance ~ 10 m from beam dump place.	Meson factory, where 800 MeV protons produce π^+ which are brought at rest, the neutrinos originating in the decays $\pi^+ \to \mu^+ \nu_\mu, \mu^+ \to e^+ \nu_e \bar{\nu}_\mu$ (Los Alamos, in future Moscow meson factory)	Water Cerenkov counter of weight ~ 6 tons, scintillator system of weight ~ 15 tons.	Particle physics: search for oscillations, $\nu_e - e$ scattering.

1	2	3	4	5
$\nu_\mu, \bar{\nu}_\mu$	10-200 GeV (CERN), 2-30 GeV (Protvino), 1-15 GeV (Brookhaven), 20-400 GeV (Batavia). The fluxes of ν_μ at the detector in the wide band beam at CERN, for example, are $10^9 GeV^{-1}m^{-2}$ per accelerator pulse at 20 GeV and $10^6 GeV^{-1}m^{-2}$ per pulse at 180 GeV.	In <u>accelerators</u> of protons to energies 400, 70, 30, 1000 GeV (CERN, Protvino, Brookhaven, Batavia, correspondingly) there are generated pions and kaons, the decay of which in turn generates ν_μ or $\bar{\nu}_\mu$. The decay is taking place in the facility containing a decay region (see for example in Fig.10 a CERN facility) (300 m, 140 m, 60 m, 400 m) and a shield for muons and hadrons (400 m Fe, 62 m Fe, 30 m Fe, 1000 m earth + Fe).	Electronic detector - calorimeter with magnetic spectrometer for muons (see for example in Fig.11 the IHEP-JINR neutrino detector): CERN-CDHS ~ 1000 tons, CHARM ~100 tons, IHEP-JINR ~ 200 tons, Batavia ~ 4000 tons. Large bubble chambers: CERN Gargamelle, 5 m^3 CF_3Br, BEBC 20 m^3 H_2, D_2+Ne; Protvino SKAT, 4.5 m^3 CF_3Br; Batavia 15'FNAL, 20 m^3 H_2+Ne; Brookhaven 12'ANL, 16 m^3 H_2, D_2 7'BNL, 6 m^3 H_2, D_2.	Particle physics: discovery $\nu_e \neq \nu_\mu$, discovery of neutral currents (reactions $\nu_\mu e \to \nu_\mu e, \nu_\mu + N \to \nu_\mu + \cdots$), quark structure of nucleons by investigating the reactions $\nu_\mu + N \to \mu + \cdots$, elastic $\nu_\mu - p$ scattering, measurements of Weinberg angles, production of charmed particles by neutrinos ($\nu_\mu + N \to \mu^- + \mu^+ + \mu^- + \cdots$), search for neutrino oscillations. Practical applications of neutrino beams from future accelerators: prospecting for oil etc., neutrino tomography of the Earth.

1	2	3	4	5
$\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu$ (not from pion and kaon decays).		<u>High Energy accelerators</u> generate charmed particles the decay of which originates "direct" or prompt neutrinos - CERN, Protvino, Batavia.	Electronic detectors - calorimeters and bubble chamber BEBC.	Particle physics: study of the production of charmed particles in collision of protons with nuclei by investigating the decay of charmed particles with emission of neutrinos.
$\nu_\mu, \bar{\nu}_\mu$	1-100 GeV	Atmospheric neutrinos from decay mesons generated by <u>cosmic ray protons in the atmosphere</u>	Underground scintillation telescope, mass~300 tons (Baksan), water Cerenkov detectors ~3000 tons (Kamioka mine and Morton-Thiokol mine)	Search for neutrino oscillations and for neutrino decay.
Tagged $\nu_\mu, \nu_e, \bar{\nu}_\mu, \bar{\nu}_e$	Average energies of ν_e and ν_μ, for example, are 12 GeV and 23 GeV, correspondingly.	<u>Proton accelerator</u> (70 GeV) generating $K^\pm$ beams of energies ~30 GeV, the registration of	Liquid argon calorimeter (~600 tons) and muon spectrometer	Particle physics: test of $\mu - e$ universality, search for neutrino oscillations, $\nu_e - e$ scattering.

1	2	3	4	5
	Total tagged neutrino intensity ~ 10^8 per accelerator pulse.	muons, electrons and photons from $K^+\to\mu^+\nu_\mu$, $K^+\to\pi^0 e^+\nu_e$, $K^-\to\mu^-\bar{\nu}_\mu$, $K^-\to\pi^0 e^-\bar{\nu}_e$ tagging the neutrinos (Protvino, future).		
ν_e, may be ν_μ, ν_τ et al., if oscillations play a role.	Expected maximum energies and fluxes are correspondingly 0.42 MeV, $6\cdot10^{10}cm^{-2}s^{-1}$ from reaction $pp\to de^+\nu_e$; 1.44 MeV (monochromatic) $1.5\cdot10^8cm^{-2}s^{-1}$ from $pep\to d\nu_e$; 0.86 MeV, $5\cdot10^9cm^{-2}s^{-1}$ from $^7Be\to{}^7Li e^+\nu_e$; 14 MeV, $5\cdot10^6cm^{-2}s^{-1}$ from $^8B\to{}^8Be e^+\nu_e$.	Sun	Underground radiochemical detectors: $\nu_e{}^{37}Cl\to e^-\,{}^{37}Ar$, threshold 0.81 MeV, $4\cdot10^5$ liters C_2Cl_4, South Dacota and $2\cdot10^6$ l C_2Cl_4 Baksan (future); $\nu_e{}^{71}Ga\to e^-{}^{71}Ge$, threshold 0.23 MeV 50 tons metallic Ga (Baksan, future) and 30 tons Ga in form $GaCl_3$ (Gran Sasso, future). Underground Cerenkov detector, $\nu_x e\to\nu_x e$, $x=e,\mu,\tau$, 3000 tons H_2O, Kamioka mine, capable of detecting ^8B solar ν's of energy > 9 MeV and of measuring their energies and directions. Underground Cerenkov detector of charged and neutral current type ($\nu_e d\to ppe^-$, $\nu_x e\to\nu_x e$, $\nu_x d\to\nu_x pn$), 1000 tons D_2O, Sudbury Observatory suitable for measuring ^8B ν_e-flux, direction and energy (future). Liquid argon time projection chamber Icarus, Gran-Sasso, 6500 tons Ar, suitable for detecting ν_e through $\nu_e{}^{40}Ar\to e^-K^*$ (threshold 5.9 MeV), all neutrinos through $\nu_x e\to\nu_x e$ and of measuring their energies and directions (future).	Particle physics (are leptons mixed?) and astrophysics.
$\nu_e,\bar{\nu}_e,\nu_\mu,\bar{\nu}_\mu$, $\nu_\tau,\bar{\nu}_\tau$	Average energies ~10 MeV, total number of neutrino emitted ~10^{58} within a few tens of seconds.	Supernovas, stellar gravitational collapse.	Water Cerenkov detectors ~3000 tons (Kamioka mine and Morton Thiokol mine). Liquid scintillation detectors (see for example in Fig. 12 the Baksan scintillation detector): ~100 tons (Mont Blanc, Artemovsk, Homestake mine). Underground scintillation telescope, ~300 tons (Baksan).	Neutrino properties: masses, life-times, mixings, magnetic moments. Astrophysics: mechanism of supernova explosions.

1	2	3	4	5
$\nu_\mu, \bar{\nu}_\mu$	10^2-10^5 GeV	Supernovas (?), Nuclei of active Galactics, Bright stage of Universe.	Deep underwater Cerenkov detector ($\sim 3\cdot10^7 m^3$ H_2O), Baikal (future). Pacific ocean (?).	Particle physics: search for new particles, investigation of neutrino interactions at very high energies, search for neutrino oscillations. Astrophysics: investigation of active processes in the Universe.
$\bar{\nu}_e$		**Tritium**	Spectra of electrons from $^3H \overset{\circ}{\rightarrow} {}^3He\, e^- \bar{\nu}_e$ are measured near the end point with the help of β-spectrometers.	Attempts to measure directly $\bar{\nu}_e$ mass (see Table IV).

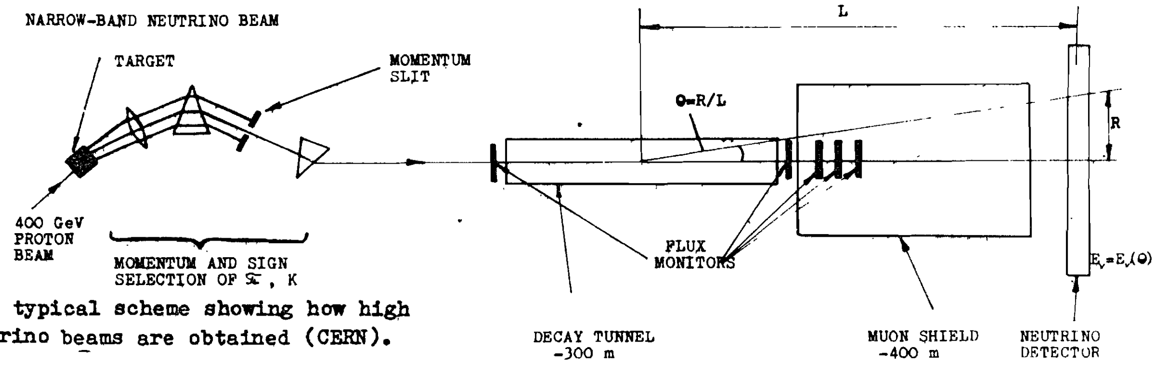

Fig. 10. A typical scheme showing how high energy neutrino beams are obtained (CERN).

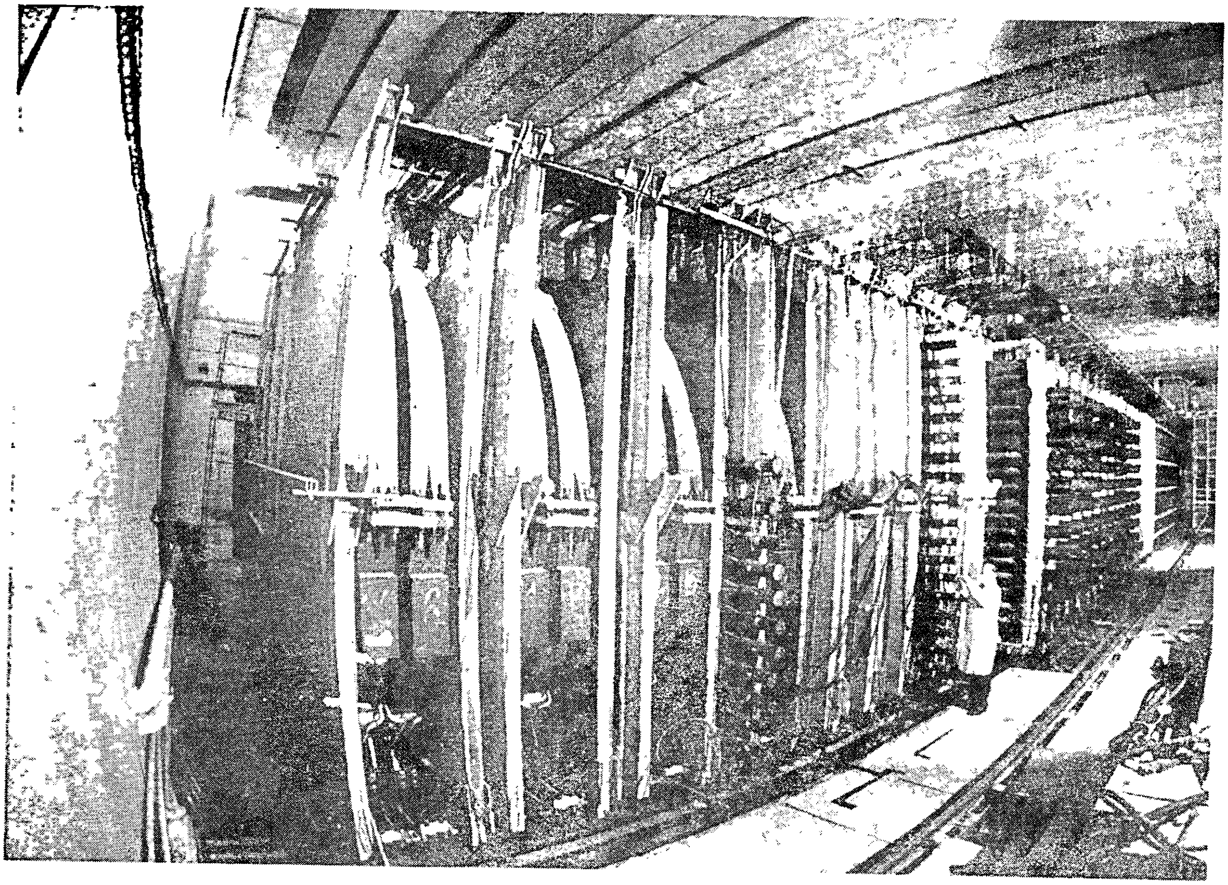

Fig. 11. The photograph is showing the IHEP-JINR neutrino detector.

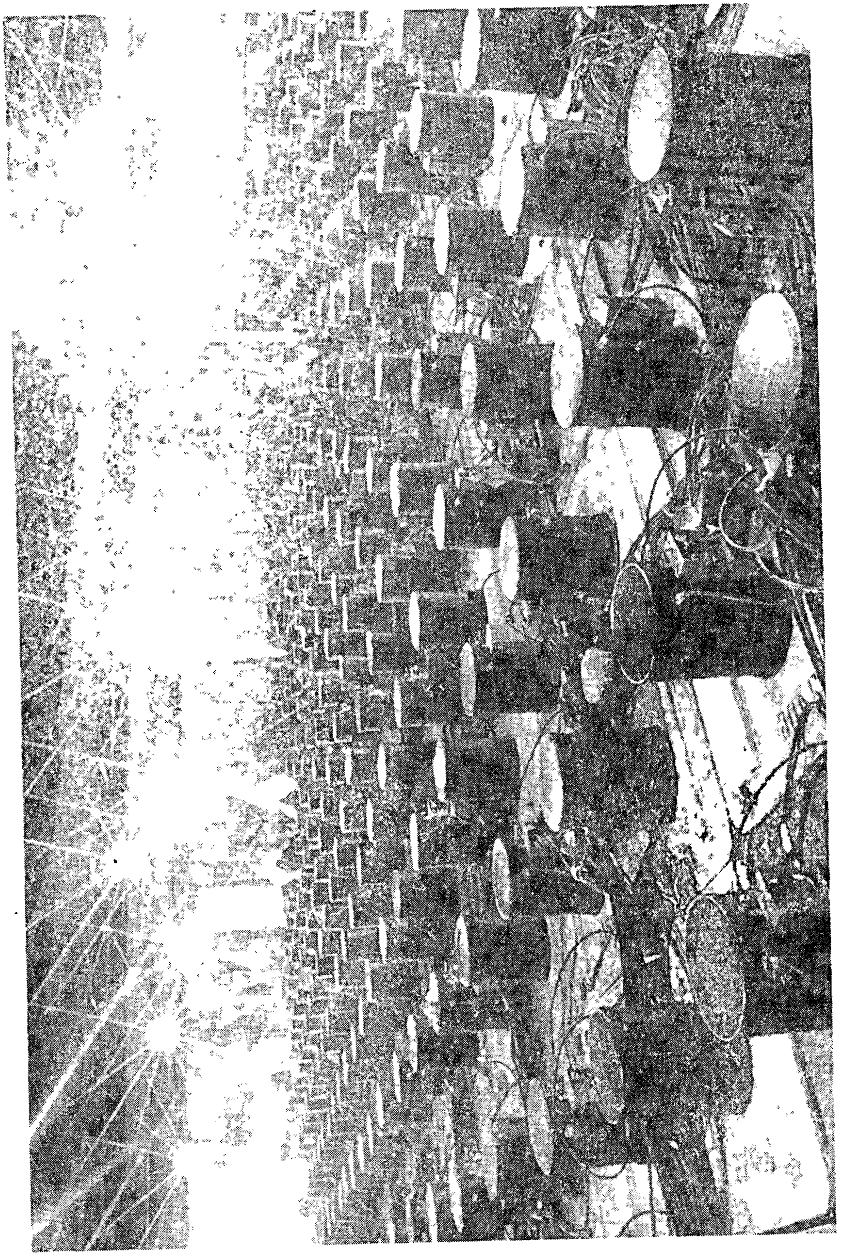

Fig. 12. The photograph is showing the Baksan observatory neutrino telescope (~ 3000 liquid scintillators of total weight ~ 300 tons).

Received by Publishing Department
on July 20, 1987.

Биленький С.М., Понтекорво Б.М. E1,2-87-567
Нейтрино Сегодня

После открытия промежуточных $W^{\pm}$, Z^0-бозонов /1983/ можно с уверенностью утверждать, что W, Z^0-бозоны ответственны за образование нейтрино и их взаимодействия. Физика нейтрино рассматривается с этой точки зрения в первых четырех вводных, совсем элементарных, параграфах. Следующие семь параграфов менее элементарны. Они посвящены вопросу масс и смешивания нейтрино, являющемуся самым актуальным вопросом современной физики нейтрино. Рассматриваются осцилляции нейтрино в вакууме, в веществе и процесс безнейтринного двойного бета-распада. Физика солнечных нейтрино подробно обсуждается с точки зрения осцилляций нейтрино в вакууме и веществе. Кратко обсуждается роль, которую играет нейтрино во Вселенной. В последнем параграфе речь идет о вероятном наблюдении различными группами нейтрино, связанных с суперновой 1987 А: первое наблюдение нейтрино от гравитационного коллапса звезды /по крайней мере, генеральная репетиция такого наблюдения/ открывает новую эру в астрономии. "Панорама" сегодняшней экспериментальной физики и астрофизики нейтрино представлена в конце статьи в виде таблицы.

Работа выполнена в Лаборатории ядерных проблем и Лаборатории теоретической физики ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна 1987

Bilenky S.M., Pontecorvo B.M. E1,2-87-567
Neutrinos Today

After the famous 1983 discovery of intermediate W , Z^0 bosons it may be stated with certainty that W , Z^0 are entirely responsible for the production of neutrinos and for their interactions. Neutrino physics notions are presented from this point of view in the first four introductory, quite elementary, paragraphs of the paper. The following seven paragraphs are more sophisticated. They are devoted to the neutrino mass and neutrino mixing question, which is the most actual problem in today neutrino physics. Vacuum neutrino oscillations, matter neutrino oscillations and neutrinoless double -decay are considered. Solar neutrino physics is discussed in some detail from the point of view of vacuum and matter neutrino oscillations. The role played by neutrinos in the Universe is briefly considered. In the last paragraph there is discussed the probable observation by different groups of neutrinos connected with the Supernova 1987 A: the first observation of gravitational star collapse (at least the general rehearsal of such observation) opens up a new era in astronomy. A "panorama" of today experimental physics and astrophysics is presented at the end of the paper in the form of a Table.

The investigation has been performed at the Laboratory of Nuclear Problems, JINR.

Preprint of the Joint Institute for Nuclear Research. Dubna 1987