RESULTS FROM NEUTRINO EXPERIMENTS

Alexei Yu. Smirnov

International Centre for Theoretical Physics, I-34100 Trieste, Italy

ABSTRACT

Recent (first or/and the best) results from the neutrino experiments are reviewed and their implications for the theory are discussed. The sense of the experiments is the searching for neutrino masses, mixing and interactions beyond the standard model. Present laboratory experiments give upper bounds on the masses and the mixing which are at the level of predictions of the “electroweak see-saw”. Positive indications of nonzero lepton mixing follow from studies of the solar and atmospheric neutrinos.

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†On leave from Institute for Nuclear Research, Russian Academy of Sciences, 117312 Moscow, Russia. e-mail: smirnov@ictp.trieste.it
INTRODUCTION

A “Zoo” of the neutrino experiments includes: direct measurements of the neutrino masses, double beta decay searches, oscillation experiments, searches for the neutrino decays, “peaks and kinks” (in energy spectra of charged leptons from the weak decays), detection of the atmospheric neutrinos, spectroscopy of the neutrinos from Sun. The main goal (or one of the main goals) of these experiments is searching for the neutrino masses and mixing. Moreover, the results of the experiments can be presented as certain regions (excluded, unexcluded, favoured, disfavoured, etc.) on the unique plot of the mass and mixing parameters (say, $\Delta m^2$ and $\sin^2 2\theta$ in two neutrino case). Another goal is searching for neutrino interactions beyond the standard model (e.g., neutrino-Majoron coupling, electromagnetic interactions due to large magnetic moment of neutrino, etc.).

An important information on the neutrino properties follows from “non-neutrino” experiments, (e.g., LEP measurements of the width of the $Z^0$-boson), as well as from the astrophysics and cosmology (evolution of stars, neutrino burst from SN1987A, primordial nucleosynthesis, large scale structure of the Universe).

In a number of experiments a neutrino is used as the “probe” particle for studies of structure and interactions of other particles (measuring the structure functions of the nucleons, determination of the electroweak mixing angle and the weak neutral currents of the electrons, etc.)

In present review we will consider the experiments which give the information on the neutrino properties, and first of all, on the neutrino masses and mixing.

FLAVORS AND MASSES

1. There are three neutrinos. Measurements of the invisible width of the $Z^0$ boson at LEP give the number of light ($m < 50$ GeV) neutrino species with usual weak interactions:

$$N_\nu = 2.98 \pm 0.03, \quad 90\% C.L., \quad (1)$$

(combined result of four collaborations\(^1\)). With statistics increase, $N_\nu$ continuously converges to 3. The bounds on ($N_\nu$ - 3) have a number of applications to the neutrino physics.
The upper bound gives, e.g., the restriction on the admixture of the $SU_2$-nonsinglet state in the Majoron field and consequently on the neutrino - Majoron coupling. The lower bound restricts the admixture of heavy ($m > m_Z$) neutral lepton, etc..

Three neutrinos correspond to three charged leptons and the correspondence (i.e., flavor of neutrino) is established by the charged current weak interactions. Mass and flavor states may not coincide. In the direct searches for the neutrino masses the data are fitted under assumption that flavor state has a definite mass or that in flavor state only one mass component dominates. Let us describe the data.

2. Electron (anti)neutrino: the bounds on mass obtained from tritium experiments\(^2\)\(^–\)\(^8\) are shown in fig.1. The best limit was announced by Mainz group\(^3\). The result of measurements, \(m^2 = -39 \pm 34 \pm 15\) eV\(^2\) (1\(\sigma\)), gives

\[
m(\bar{\nu}_e) < 7.2\text{ eV}, \quad 95\% \text{ C.L.}\ .
\] (2)

The value of \(m^2\) is about 1\(\sigma\) below zero which may testify for some undiscovered systematic error, especially in view of the fact that all other experiments also give negative values of \(m^2\). (For discussion of this problem see\(^8\)). In this connection, the discrepancy was pointed out\(^3,6\) between the data and the spectrum expected from the theoretical final state distribution. In 1993, Mainz group has taken new data for 3 months and it is expected that statistics accumulated can considerably improve the limit (2), as well as can help to understand possible systematic errors. Also for this purpose the measurements are performed with conversion electrons from \(^{83m}\)Kr.

3. Muon neutrino: the best limit on the mass follows from study of the pion decay \(\pi^+ \rightarrow \mu^+\nu_\mu\) at the rest. Two values are involved: the momentum of the muon which has been measured recently with better precision at PSI\(^9,10\) and from independent measurements of the pion mass. Method of \(m_\pi\) determination has an ambiguity: two different values of \(m_\pi\) where obtained. One value results in strongly negative \(m^2(\nu_\mu)\) (about 5\(\sigma\) below zero), another one gives \(m^2(\nu_\mu) = -0.002 \pm 0.030\) MeV\(^2\) in agreement with zero. The latter corresponds to a new upper bound\(^10\)

\[
m(\nu_\mu) < 220\text{ kev}, \quad 90\% \text{ C.L.}\ .
\] (3)

2
4. **Tau neutrino.** The invariant masses of five pions in the decay $\tau \rightarrow 5\pi \nu_\tau$ are measured and an upper bound on the tau neutrino mass follows from spectrum of the invariant masses near the end point:

$$m(\nu_\tau) < \begin{cases} 
31 \text{ MeV} & 95\% \text{ C.L.} \quad \text{ARGUS}^{11} \\
32.6 \text{ MeV} & 95\% \text{ C.L.} \quad \text{CLEO}^{12} 
\end{cases}.$$ (4)

The electromagnetic calorimetry allows CLEO to detect the decays with neutral pions: $\tau \rightarrow (3h)^{-2}\pi^0 \nu_\tau$. As much as 53 events of such a type have been found. A sample analyzed includes also 60 events with 5 charged pions. The limit is determined, actually, by a few events near the end point. ARGUS group detecting only charged pions is lucky: the limit was obtained with just 20 events; the probability to get such a limit is\(^{11}\) $p \approx 0.04\%$. The probability of CLEO limit is 13.9 %.

5. **Strong bounds on tau neutrino mass follow from a primordial nucleosynthesis\(^{13-16}\) (fig.2).** At the epoch of nucleosynthesis the neutrinos with masses $m > 0.1$ MeV were non-relativistic (in appreciable part of spectrum). Their contribution to the energy density in the Universe is characterized by $N_{\text{eff}}$ – the effective number of the relativistic neutrinos giving the equivalent amount of energy. The contribution of massive neutrinos is the interplay of two factors: $\Delta N_{\text{eff}} \propto m \cdot n(T)$ – the mass, and the concentration, $n(T)$; the latter is exponentially suppressed at temperatures $T < m$. As the result of the interplay the energy density, has a maximum at $m = (4 - 6)$ MeV, and in maximum: $\Delta N_{\text{eff}} \cong (4 - 5)$. Total effective number of the relativistic neutrinos, $N_{\text{eff}}$, is restricted by present $^4\text{He}$ abundance. The limit $N_{\text{eff}} < 3.4$ was used in original paper\(^{13}\) and the regions of masses of the Majorana neutrino (0.5 - 25) MeV and (0.5 - 32) MeV were excluded for the neutrino lifetimes larger than 1 s and $10^3$ s correspondently. Recently the bounds have been refined. In\(^{14}\) using even weaker restriction, $N_{\text{eff}} < 3.6$, the region 0.5 - 35 MeV was excluded for $\tau > 10^2$ s. The limit $N_{\text{eff}} < 3.3$ forbids\(^{15,16}\) the interval 0.1 - 40 MeV for $\tau_\nu > 10^3$ s. Consequently, for stable neutrinos there is no gap between the laboratory (4) and NS bounds and the upper limit is pushed down to

$$m(\nu_\tau) < 0.1 \text{ MeV}, \quad (\tau > 10^3 \text{s}).$$ (5)

Fast decay $\nu_\tau \rightarrow \nu' + \chi$, where $\chi$ is the Majoron, can relax the bound. It has been found\(^{16}\) that the gap appears for $\tau_\nu < 10^2$ s. For $m = 30$ MeV the lifetime $10^2$s corresponds to the
nondiagonal neutrino-Majoron coupling constant \( g'_\chi \sim 10^{-12} \). At \( \tau_\nu < 10^{-2} \) s the mass region 3 - 30 MeV is not excluded. The gap for stable neutrinos appears if one admits \( N_{\text{eff}} > 4 \).

6. The above result has a number of implications. A relatively stable tau neutrino should be appreciably lighter than the electron; there is no decay \( \nu_\tau \rightarrow e^+ e^- \nu' \). If the mass of \( \nu_\tau \) is generated by the see-saw mechanism, the corresponding Majorana mass of the right handed component should be of the order of \( m_\tau^2 / m(\nu_\tau) \approx 3 \cdot 10^4 \) GeV, which is appreciably larger than the electroweak scale, i.e., the electroweak see-saw does not work, etc..

It is important to strengthen the laboratory upper bounds: the discovery of the tau neutrino mass in the region about 30 MeV will mean either that the neutrino is unstable, and moreover, the invisible modes (like the Majoron one) should dominate, or that present picture of the primordial nucleosynthesis is incorrect.

The above nucleosynthesis limit is applied also to the muon neutrino.

7. Let us define the following mass scales:

\[
m_1 = \frac{m_e^2}{M} \equiv 3.2 \text{ eV} \frac{m_W}{M}, \quad m_2 = \frac{m_\mu^2}{M} \equiv 135 \text{ keV} \frac{m_W}{M}, \quad m_3 = \frac{m_\tau^2}{M} \equiv 39 \text{ MeV} \frac{m_W}{M},
\]

where \( m_e, m_\mu, m_\tau \) and \( m_W \) are the masses of the electron, muon, tau lepton and W-boson correspondently. Such relations can arise from the see-saw mechanism of mass generation with Majorana mass of the right handed neutrinos \( m(\nu_R) = M \). At \( M = m_W \) the masses in (6) coincide (up to the factor of 2) with present upper bounds on the neutrino masses (2 - 4). This means that the sensitivity of present searches is at the level of the electroweak see-saw (\( M = 30 - 300 \) GeV). (Although it is unclear how the singlet \( \nu_R \) “feels” this scale).

Physics of solar neutrinos determines another scales:

\[
m_\odot = (10^{-5} - 3 \cdot 10^{-3}) \text{eV},
\]

which imply much higher values of \( M \).
DOUBLE BETA DECAY SEARCHES

1. Two neutrino double beta decay, \((\beta\beta)_{2\nu}\): \(Z \rightarrow (Z + 2) + e^- + e^- + \bar{\nu} + \bar{\nu}\) was observed already for five nuclei: \(^{76}\text{Ge}\), \(^{100}\text{Mo}\), \(^{130}\text{Te}\), \(^{82}\text{Se}\), \(^{238}\text{U}\). Its study gives to some extend the “calibration” of nuclear matrix elements. Searches for the neutrinoless mode, \((\beta\beta)_{0\nu}\), \(Z \rightarrow (Z + 2) + e^- + e^-\) are sensitive, in particular, to the effective Majorana mass of the electron neutrino:

\[
m_{ee} \equiv \sum_i \eta_i^{CP} |U_{ei}|^2 m_i,
\]

where \(U_{ei}\), \(m_i\), and \(\eta_i^{CP}\) are the admixture in the electron neutrino state, the mass and the CP-parity of the i-component of neutrino \((m_i < 30\text{ MeV})\). (In case of opposite parities the cancellation in (8) allows even for lightest component to have a mass above the upper bound on \(m_{ee}\)). The Majoron mode of the decay, \((\beta\beta)_{0\bar{\nu}\chi}\), \(Z \rightarrow (Z + 2) + e^- + e^- + \chi\), being a signature of the spontaneous violation of the lepton number symmetry, determines the neutrino Majoron - coupling, \(g_\chi = m(\nu)/\sigma_0\), where \(m\) is the neutrino mass and \(\sigma_0\) is the scale of lepton number violation.

Let us describe the results of experiments.

2. Heidelberg - Moscow Collaboration (Gran Sasso underground laboratory)\(^{17-19}\) performed the experiments with three \(^{76}\text{Ge}\) - detectors. Total active mass of the enriched (86\%) isotope is 6.01 kg; total exposure time is 6.2 kg\cdot y (70.75 mol\cdot y). (Fourth detector with mass 2.88 kg is available).

In a study of the \((\beta\beta)_{2\nu}\) -mode the Collaboration used the data taken by the detector \# 2 (2.6 kg) from September 1991 to August 1992. In the interval 800 - 1500 kev after background subtraction (the model of the background build from measured quantities) more than 4100 events have been prescribed to \((\beta\beta)_{2\nu}\) decay. The energy distribution of two electrons as well as the half life, \(T_{1/2} = (1.42 \pm 0.03 \pm 0.13) \cdot 10^{21} y\), (90\%C.L.) agree with expectations, and the error bars reflect the amusing progress in the field.

In searches for the neutrinoless mode all the exposure time was used and the best limit\(^{17}\) has been obtained

\[
T_{1/2} > 1.5 (2.4) \cdot 10^{24} y, \quad 90(68)\%C.L. .
\]
It corresponds to the effective Majorana mass

\[ m_{ee} < 1.3 \text{ eV}, \quad 90\% \text{ C.L.} \]  

(10)

for “Heidelberg” nuclear matrix element. These results, however, were not changed practically during last year although the exposure time has increased appreciably. The reason is the appearance of the excess of events at the end point. The following features of the excess are remarked: (1) it has a shape of the peak at the energy \( E = 2040 \text{ kev} \) which coincides with the end point; (2) the width of the peak \( \Delta E = 4.4 \text{ kev} \) corresponds to the energy resolution of the detector, 3.7 kev; (3) the increase of the number of events in the peak with time can be described by linear dependence; (4) the number of the events in the peak \( (\Delta E = 8.8 \text{ kev}) \) equals \( N_p = 28 \), whereas the expected number of the background events (extrapolation of the signal from the regions outside the peak) is \( N_b = 15 \). The peak can be explained as 2.7\( \sigma \) fluctuation of the background; the fit of the data by using the hypothesis “background plus peak” gives 1.5\( \sigma \) significance of the peak. In August’93 new sample of the data has been analyzed\(^\text{19}\), exposure time has reached 83.03 mol\(^*\)y. Since the background increased more fastly than the peak did, the significance of the excess has decreased from 2.7 to 2.2\( \sigma \). The interpretation of the effect is still unclear, but the excess is strong enough to be proved or disproved within reasonable time scale (\( \sim 1 \) year).

The Majoron mode of the decay was searched\(^\text{18}\) in energy “window” 1100 - 2050 kev (71\% of all expected events). Total number events, 208, has been found, whereas the background model gives \( N_o = 92.5 \) events. Thus the 2.25\( \sigma \) excess has been observed, but the energy distribution of events has a “wrong shape”\(^\text{17}\). The limit \( T_{1/2}(0^\nu) > 1.7(1.9) \cdot 10^{22} \text{ yr} \) (90 (68) \% C.L.) has been obtained which gives the restriction on the Majoron coupling: \( g_{\chi} < 1.8 \cdot 10^{-4} \), 90\% C.L. .

3. Neuchatel-Pasadena-PSI Collaboration (Gottard underground laboratory) has published\(^\text{20}\) the results of study of the \(^{136}\)Xe decay with xenon time projection chamber. Active volume is 180 liters of the enriched (62.5\%) Xe at 5 atm.. Data taking for 6830 h gives the bound on half-life for neutrinoless (mass) mode: \( T_{1/2}(0^\nu) > 3.4 \) (6.4) \( \cdot 10^{23} \text{ years} \), 90\% (68\%) C.L. . This corresponds to the upper bound \( m_{ee} < 2.8 - 4.3 \text{ eV} \). The estimations of the nuclear matrix elements for \(^{136}\)Xe have no large spread, in contrast with case of \(^{76}\)Ge. For the Majoron mode the limit \( T_{1/2}(0^\nu\chi) > 4.9 \cdot 10^{21} \text{ years} \) has been obtained; it gives for the Majoron
coupling: $g_\chi < 2.4 \cdot 10^{-4}$. Collaboration plans to reduce the background and to reach the sensitivity $\sim 10^{24}$ yr for $(\beta\beta_{0\nu})$ mode.

4. *NEMO* Collaboration (Frejus underground laboratory) has published first results of searching for the double beta decay of the $^{100}$Mo with the detector NEMO-II$^{21}$. The detector consists of tracking volume (frames of Geiger cells); the source foil placed in central frame has two parts: one contains 172 g of enriched (98.3 %) isotope $^{100}$Mo, and second one – 163 g of natural (9.6%) isotope. On the opposite sides of the tracking volume there are two scintillator walls which allow to make the energy and the time flight measurements. The data where collected from December 92 to May 93 with total exposure time 2485 h. The subtraction of the results (enriched - natural) has been done to remove the external background. After the subtraction the sample consists of 454 events; their energy distribution is perfectly described by the expected one from the $2\nu$ decay. The obtained lifetime: $T_{1/2} > (1.0 \pm 0.08 \pm 0.2) \cdot 10^{19}$ years, agrees with previous results. No events have been observed above 2600 kev (the end point is 3030 kev) which gives the upper bounds on the neutrinoless mode: $T_{1/2}(0\nu) > 3.8 \cdot 10^{21}$ yr, as well as on the Majoron mode: $T_{1/2}(0\nu\chi) > 5 \cdot 10^{20}$ yr (90 % C.L.). The latter result corresponds to rather strong limit on the Majoron coupling: $g_\chi < 1.8 \cdot 10^{-4}$. At present (October’93)$^{22}$ the exposure time has increased up to 6140 h (1.2 mol*yr) which gives the upper bounds on the neutrinoless mode: $T_{1/2}(0\nu) > 3.8 \cdot 10^{21}$ yr, as well as on the Majoron mode: $T_{1/2}(0\nu\chi) > 5 \cdot 10^{20}$ yr (90 % C.L.). The latter result corresponds to rather strong limit on the Majoron coupling: $g_\chi < 1.8 \cdot 10^{-4}$. The data where collected from December 92 to May 93 with total exposure time 2485 h. The subtraction of the results (enriched - natural) has been done to remove the external background. After the subtraction the sample consists of 454 events; their energy distribution is perfectly described by the expected one from the $2\nu$ decay. The obtained lifetime: $T_{1/2} > (1.0 \pm 0.08 \pm 0.2) \cdot 10^{19}$ years, agrees with previous results. No events have been observed above 2600 kev (the end point is 3030 kev) which gives the upper bounds on the neutrinoless mode: $T_{1/2}(0\nu) > 3.8 \cdot 10^{21}$ yr, as well as on the Majoron mode: $T_{1/2}(0\nu\chi) > 5 \cdot 10^{20}$ yr (90 % C.L.). The latter result corresponds to rather strong limit on the Majoron coupling: $g_\chi < 1.8 \cdot 10^{-4}$. At present (October’93)$^{22}$ the exposure time has increased up to 6140 h (1.2 mol*yr) which gives the upper bounds on the neutrinoless mode: $T_{1/2}(0\nu) > 3.8 \cdot 10^{21}$ yr, as well as on the Majoron mode: $T_{1/2}(0\nu\chi) > 5 \cdot 10^{20}$ yr (90 % C.L.). The latter result corresponds to rather strong limit on the Majoron coupling: $g_\chi < 1.8 \cdot 10^{-4}$. At present (October’93)$^{22}$ the exposure time has increased up to 6140 h (1.2 mol*yr) which gives the upper bounds on the neutrinoless mode: $T_{1/2}(0\nu) > 3.8 \cdot 10^{21}$ yr, as well as on the Majoron mode: $T_{1/2}(0\nu\chi) > 5 \cdot 10^{20}$ yr (90 % C.L.). The latter result corresponds to rather strong limit on the Majoron coupling: $g_\chi < 1.8 \cdot 10^{-4}$. At present (October’93)$^{22}$ the exposure time has increased up to 6140 h (1.2 mol*yr) which gives the upper bounds on the neutrinoless mode: $T_{1/2}(0\nu) > 3.8 \cdot 10^{21}$ yr, as well as on the Majoron mode: $T_{1/2}(0\nu\chi) > 5 \cdot 10^{20}$ yr (90 % C.L.).

$LBL-MHC-UNM-INEL$ Collaboration$^{23}$ has improved their limit on the half life of the neutrinoless double beta decay of $^{100}$Mo by factor of 11. The Si(Li) detector is used; the mass of isotope is 60.63 g; 3849.5 h of exposure time give $T_{1/2}(0\nu) > 0.44 \cdot 10^{23}$ years which corresponds to $m_\nu < 6.6$ eV 68% C.L. .

5. *Washington-Tata* group has studied the double beta decay of $^{128}$Te and $^{130}$Te (Te $\rightarrow$ Xe) by the geochemical method$^{24}$. The ancient Te - ores (10$^9$ years) were used and the Xe-atoms produced in the decay were detected by the ion-counting mass spectroscopy. The double beta decay is considered to dominate in the production of Xe in ores. Thus the
measured ratio of \(^{128}\)Xe and \(^{130}\)Xe concentrations gives the ratio of the half lifes:

\[
\frac{T_{1/2}(^{130}\text{Te})}{T_{1/2}(^{128}\text{Te})} = (3.52 \pm 0.11) \cdot 10^{-4},
\]

(11)

and this ratio agrees well with two neutrino decay mode. Using Pb-dating one finds the absolute value of the half life for \(^{130}\)Te: \(T_{1/2}(^{130}\text{Te}) = (2.7 \pm 0.1) \cdot 10^{21}\) yr, and consequently, using the result (11): \(T_{1/2}(^{128}\text{Te}) = (7.7 \pm 0.4) \cdot 10^{24}\) yr. The ratio (11) allows also to get the upper bounds on the neutrinoless modes, and consequently, on the Majorana mass: \(m_{ee} < (1.1 - 1.5)\) eV. Suggesting that all the \(^{128}\)Te - decays are due to the Majoron mode one gets the bound on the Majoron coupling \(g_\chi < 3 \cdot 10^{-5}\).

6. Let us comment on the implications of the results. The bounds on \(m_{ee}\) and \(g_\chi\) from the discussed experiments are summarized in (12)

| Experiment                  | Element | \(m_{ee} <\), eV, 90 % C.L. | \(g_\chi \cdot 10^4 <\) |
|------------------------------|---------|-----------------------------|--------------------------|
| Heidelberg-Moscow           | \(^{76}\)Ge | 1.3                         | 1.8                      |
| Neuchatel-Pasadena-PSI      | \(^{136}\)Xe | 2.4 - 4.3                   | 2.4                      |
| NEMO-II                     | \(^{100}\)Mo | 7                           | 1.8                      |
| Tata-Washington             | \(^{130}\)Te | 1.1 - 1.5                   | 0.3                      |
| Nucleosynthesis             | -       | -                           | 0.09                     |

(12)

Present limits on the effective Majorana mass are at the level (1 - 2) eV. In future Heidelberg-Moscow Collaboration will perform the experiment with 20 kg of the enriched \(^{76}\)Ge; a similar amount of the enriched \(^{76}\)Ge will be used in IGEX experiment\(^{25}\); NEMO collaboration intends to use 10 kg of the enriched \(^{100}\)Mo (also the experiments with other enriched isotopes are planed). The sensitivity of these experiments to the neutrino mass will reach 0.1 - 0.2 eV, and the mass interval \(m_{ee} = 0.1 - 1\) eV will be “observable”.

7. What are the implications of new searches? A straightforward interpretation of the positive signal in \(\beta\beta_0\nu\) is that the electron neutrino consists mainly of the lightest mass eigenstate, \(\nu_1\), having the mass in the indicated region. The mass \(\sim 1\) eV can arise from the see-saw mechanism at the electroweak scale. For masses of two other components one predicts then \(m_2 = (1 - 100)\) kev and \(m_3 = (1 - 30)\) MeV. However, this scenario does not allow to solve the solar and atmospheric neutrino problems by the neutrino oscillations or resonant
conversion. The conversion $\nu_e \rightarrow \nu_\mu$ of solar neutrinos implies $m_2 \approx m_\odot \approx 3 \cdot 10^{-3}$ eV, then according to the see-saw the mass of third neutrino can be in the region $(1 - 30)$ eV. But its admixture to the $\nu_e$ state is typically predicted to be very small $\left( |U_{e3}|^2 < \frac{m_1}{m_3} < \frac{m_\odot}{m_3}\right)$, and consequently, the contribution to the effective Majorana mass is negligible: $m_{ee} \sim m_\odot$. There are several ways to reconcile the “observable” Majorana mass and the neutrino physics solution of the $\nu_\odot$-problem\textsuperscript{26}. The admixture of the $\nu_3$ in the $\nu_e$ state can be enhanced so that the effective Majorana mass is due to admixture of the third neutrino: $m_{ee} = |U_{e3}|^2 m_3$ (fig. 3). The enhancement can be obtained by the see-saw mechanism with certain structure of mass matrix of the RH neutrinos. In turn, this structure can be a consequence of certain family symmetry at high mass scales and it implies a strong mass hierarchy of the RH neutrinos.

Another extreme case corresponds to strongly degenerate spectrum: $m_1 \approx m_2 \approx m_3 \sim m_{ee}$. Small mass splitting $(m_2 - m_1)/m_{ee} \sim m_\odot^2/m_{ee}^2$ allows to solve the solar neutrino problems, and for larger splitting $m_3 - m_2$ – to solve the atmospheric neutrino problem. The degeneracy can follow from horizontal symmetry, whereas small splitting and mixing result\textsuperscript{26} from radiative corrections or from the see-saw contribution or from Planck scale effects (see below and\textsuperscript{90,91}).

8. Direct searches give the upper bound on the Majoron coupling at the level $(1-2) \cdot 10^{-4}$; more strong bound follows from the geochemical experiment: $g_\chi < 0.3 \cdot 10^{-4}$. Primordial nucleosynthesis gives even more strong restriction\textsuperscript{27}. The contribution of Majorons to the energy density in the Universe has been calculated and the upper bound on number of the relativistic degrees of freedom, $N_{\text{eff}} < 3.3$, allows one to get $g_\chi < 0.09 \cdot 10^{-4}$. These results strongly disfavour the interpretation of the excess of events observed in the experiments with three different nuclei\textsuperscript{28} in terms of usual Majoron decay.

9. It is possible to construct the models\textsuperscript{29} with large neutrino-Majoron coupling $(10^{-5} - 10^{-4})$ which do not contradict to LEP bound (1). But in this case the upper bound on $m_{ee}$ implies that the scale of lepton number violation is as small as $\sigma_0 = 10 - 100$ kev. Such a scale can be naturally protected by some kind of supersymmetry\textsuperscript{30}.

The double beta decay with emission of massless scalar particle may take place without
lepton number violation, so that scalar carries double lepton charge and the Majorana neutrino mass is zero\textsuperscript{31}. Such a scalar may appear as the Goldstone boson at spontaneous violation of some new symmetry which is not related to the lepton number. The scale of violation can be as large as 100 MeV which allows one to escape from the Nucleosynthesis bound. The double beta decay with “charged Majoron” has more soft energy spectrum of two electrons than the standard Majoron decay\textsuperscript{31}.

It was argued that all global symmetries are broken by gravity (Planck scale interactions) which means that massless Majoron does not exist at all\textsuperscript{32,33}. At low energies the effects may be described by nonrenormalizable effective interactions with can drastically change the picture of the lepton number violation for small scales $\sigma_0$. For example, the term $\lambda \frac{\Phi^4}{M_{Pl}} + \ldots$, where $\Phi$ is the usual Higgs doublet with vacuum expectation $v$, could generate the mass $m_\chi^2 \sim \frac{v^4}{M_{Pl}\sigma_0} \sim 1$ MeV of the order of the energy release in the $\beta\beta$ decays.

“KINKS, PEAKS, DECAYS”. OSCILLATIONS

1. Vacuum mixing implies that flavor neutrino states are composed of several states with definite masses, e.g., the electron neutrino is $\nu_e = \sum_i U_{ei} \nu_i$. Mixing has a number of consequences: kinks on the Kurie plot of beta decays, additional peaks in energy distributions of charged leptons from two body decays, for example, $\pi \rightarrow \mu \nu$, neutrino decays, oscillation of neutrinos, etc..

2. Kinks. No kinks on the Kurie plots have been found in recent high statistics and high precision experiments\textsuperscript{34–38} in kev region. This gives the upper bound on mixing parameter $|U_{ei}|^2$ as function of neutrino mass

| Experiment | Isotope | $U_{eh}^2$ | C.L. | mass, kev |
|------------|---------|------------|------|-----------|
| INS Tokyo\textsuperscript{34} | $^{63}Ni$ | 0.073 % | 95% | 17 |
| -”- | $^{63}Ni$ | 0.15 % | 95% | 10.5 - 25 |
| Zürich\textsuperscript{35} | $^{63}Ni$ | 0.11 % | 95% | 17 |
| Argonne\textsuperscript{36} | $^{35}S$ | 0.25 % | 95% | 10 - 45 |
| Princeton\textsuperscript{37} | $^{35}S$ | 0.29 % | 95% | 17 |
| Oklahoma\textsuperscript{38} | $^3H$ | 0.24 % | 99% | 17 |
As it was noted by A. Hime\textsuperscript{39}, these recent experiments “definitely ruled the presence of a 17 kev neutrino and circumvent the criticisms applicable to earlier “null” results”. More subtle question is what is the origin of spectra distortion in the “non null” experiments? Recent studies (see for review\textsuperscript{39}) show among the reasons, e.g., the electron scattering effect on the way from the source to detector. Nevertheless the kev region is interesting. The electroweak see-saw gives the mass of the second neutrino in this region. Mixing parameter could be as small as 0.1 - 1 \%. Models developed in context of the 17 kev neutrino (in particular with radiative generation of masses) predict more naturally smaller mixing than it was found in the “positive” experiments (0.8 - 1.2 \%). One may keep in mind |U_{eh}|^2 \approx m_e/m_\tau \approx 0.03\% or (m_\mu/m_\tau)^2 \approx 0.25\%, etc..

2. Neutrino decays. If the electron neutrino has an admixture U_{eh} of state \nu_h with mass m_h > 1 \text{ MeV}, the decay \nu_h \rightarrow e^+e^-\nu_e takes place. The bound on the lifetime of \nu_h, and consequently, on U_{eh} has been improved recently by Munich-Annecy-Marseille group\textsuperscript{40}. The decay was searched for in the antineutrino beam from the reactor BUGEY. The detector placed at distance 18.6 m from the core of reactor consists of the He-filled decay volume \sim 2 \times 2 \times 2 \text{ m}^3 and the electrons are detected by position sensitive multiwire proportional chambers, placed at the opposite (to reactor) side of the detector. No decays have been observed during the run of the experiment in 1991. The upper bound on the decay rate (\text{ < 0.012 s}^{-1}, 90 \text{ \% C.L.}) gives the best limit |U_{eh}|^2 < 2 \cdot 10^{-4} (90 \text{ \% C.L.) in the region (3 - 6) MeV. This results improve the previous limits from “Gösgen-87” and “Rovno-90” by factor of 3. The analysis of results from next run of the experiment will allow to improve the limit up to (5 - 7) \cdot 10^{-5}.

Some remarks are in order. The \nu_h could be a main component of the tau neutrino. In this case the region of sensitivity of the BUGEY experiment, m_h \sim 1 - 10 \text{ MeV}, is strongly disfavoured by Nucleosynthesis, unless the neutrino has some other decay mode like a Majoron one with \tau < 1 \text{ s}. The \nu_\tau as the Dirac neutrino is excluded by data from SN87A\textsuperscript{41} (the upper bound is about 20 - 30 kev). If \nu_\tau is the Majorana particle, then strong bound on mixing follows from the \beta\beta_{0v} searches: |U_{e\tau}|^2 < m_{ee}/m_h < 2 \cdot 10^{-6}(m_h/\text{MeV})^{-1}, where for m_{ee} the upper bound (10) is used. The bound is much stronger than the existing and planning limits. To avoid it one should suggest strong cancellation of the contributions in m_{ee}. The possibility of \nu_h to be a sterile neutrino is disfavoured by the primordial nuc-
osynthesis consideration.

3. **L-3 collaboration** (LEP) searches for isosinglet neutral heavy lepton, $N$, that mixes with active neutrino states. If $m_N < 90$ GeV then $Z^0$ decays into $\nu N$, and $N$, in turn, decays into $l\bar{q}$, $\nu q\bar{q}$, $\nu l\bar{l}$. A signature, e.g., of the first mode is missing energy, charged lepton, and two jets. The data are compared with Monte Carlo predictions. No excess of the events above the background has been found which gives the upper bound on $|U_{th}|^2$ as function of the lepton mass. Preliminary result for the $N$ admixture in, e.g., the $\nu_\tau$ is: $|U_{\tau h}|^2 < (0.7 - 1.0) \cdot 10^{-4} (m_h = 5 - 60$ GeV) (90 \% C.L.).

The result is important for the electroweak see-saw. If the mass of the right handed neutrino is $\sim 60$ GeV, then its admixture in the tau neutrino state may be as large as $(m_\tau/m_N)^2 \sim 10^{-3}$.

4. **Oscillations.** The reactor experiment **BUGEY-III** is essentially accomplished, and the data are analyzed. Preliminary results of measurement of the $\bar{\nu}_e$ spectra at the distance 95 m from the reactor are published. During the run of 1992, about 1200 neutrino events have been detected and no effects of oscillations have been found. In particular, the ratio of signals measured by the same detector from two different reactors (95 m/15 m) does not depend on the neutrino energy. New regions of the neutrino parameters can be excluded in comparison with the existing results (fig. 3). Thus G"osgen bound on $\sin^2 2\theta$ will be improved up to the factor of 1.5 - 3 in the region $\Delta m^2 = (3 \cdot 10^{-2} - 5 \cdot 10^2)$ eV$^2$. These new limits follow mainly from a comparison of spectra from two distances 15m/40m (the same detector) and from measuring of signal at 15 m.

5. **CHARM-II** collaboration has published the limit on $\nu_\mu - \nu_\tau$ oscillations. In the detector $\nu_\tau$ would produce the $\tau$-leptons that decay, in particular, as $\tau \rightarrow \nu_\tau \pi$. No excess of the events with single pion has been observed. The limit on $\sin^2 2\theta$ is only factor of two weaker than the best limit on this mode from E531.

There are new results from E645 oscillation experiment at meson factory LAMPF. For “non-exotic” mode $\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e$ the upper bounds have been found $\Delta m^2 < 0.14$ eV$^2$ at maximal mixing and $\sin^2 2\theta < 0.024$ for large $\Delta m^2$. 

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Essential progress in the field will be related to new high precision experiments CHORUS\textsuperscript{46} and NOMAD\textsuperscript{47} at CERN which will start next year, as well as to long base line experiments.

6. It has been argued in\textsuperscript{48} that for the $\nu_\tau$ mass in the cosmologically interesting domain 2 - 30 eV the strong restrictions on the $\nu_\tau - \nu_e$ mixing can be obtained from Supernova. Such a mixing will induce the resonant conversion of the $\nu_\tau$ in the $\nu_e$ near the core of the star thus producing $\nu_e$ with high energies (original $\nu_\tau$ have about two times higher average energies than $\nu_e$). High energy electron neutrinos will strongly suppress r-processes. If supernovae are produce r-process heavy elements, then region $\sin^2 2\theta > 10^{-4} - 10^{-5}$ is excluded.

**ATMOSPHERIC NEUTRINOS**

The atmospheric neutrinos are formed in the decays of pions: $\pi \rightarrow \mu \nu_\mu \rightarrow e \nu_\mu \nu_e \nu_\mu$ (and, in a smaller part, of kaons). Pions, in turn, are generated in interactions of cosmic rays with nuclei of atmosphere.

Several types of events induced by the atmospheric neutrinos are studied in the underground detectors (for details see\textsuperscript{49}). *Contained events:* neutrinos interact in a fiducial volume of detector producing in quasielastic scattering the electrons and muons; (also in some part of events pions are produced). The electrons and muons show up as the “$e$-like” (diffuse rings, showers) and “$\mu$-like” events (sharp rings, tracks) correspondently. The trajectories of the secondary particles are contained completely or partly in the detector. The energies of these events are 0.2 - 1.5 GeV.

*Upward going muons:* Muon neutrinos produce the muons in the rock that surrounds the detector. The time and the angular resolution of detectors allow to pick up the muons arriving from the down semisphere (also horizontal muons were studied). These events, in turn, are divided into two categories: *stopping upward going* muons (muons decay in the detectors) and *through going* muons.

Typical energies of the original neutrinos are: 5 - 10 GeV, 20 - 100 GeV, and 50 - 300 GeV for contained events, stopping muons, and through going muons correspondingly.
2. The atmospheric neutrino problem is formulated as the deviation (smallness) of the double ratio

$$R(\mu/e) = \frac{(\mu - \text{like})/(e - \text{like})_{\text{data}}}{(\mu - \text{like})/(e - \text{like})_{M-C}}$$

for the contained events measured by water Čerenkov detectors Kamiokande and IMB from 1 \textsuperscript{49-52} \cite{ref}: $R(\mu/e)$ is about 0.6. The results are summarized in fig. 4.

The latests Kamiokande results further confirm the smallness of $R(\mu/e)$. The data correspond to the observation up to July ’93: total exposure time is 6.18 kt*y. For visible energies $E_{\text{vis}} < 1.33$ GeV, 557 fully contained single ring events have been observed\textsuperscript{50,51}. Among them there are 191 $\mu$-like and 198 e-like events. The ratio $\mu/e = 0.96$ should be compared with 1.60 - 1.63, predicted by different groups. As the result for the double ratio one finds

$$R(\mu/e) = (0.59 - 0.60) \pm 0.06(\text{stat}) \pm 0.05(\text{syst}), \quad (1\sigma). \quad (15)$$

The absolute number of the observed events is (0.74 - 1.12) of the predicted value. The shape of energy distribution of the events is in agreement with expectation. (Although one can remark the excess of the events in the the energy bit 0.4 - 0.5 GeV and the deficit in the bin 0.5 - 0.6 GeV both in e- and in $\mu$- spectra).

It is of great importance for implications to study the effect at higher energies. For $E_{\text{vis}} > 1.33$ GeV Kamiokande has 110 fully contained events (7.33 kt*y) and 89 vertex contained events. Among them there are 116 $\mu$-like and 83 e-like events and it seems the ratio $\mu/e$ is smaller than expectation too\textsuperscript{51}.

Similar results have been obtained for the contained events by IMB Collaboration\textsuperscript{52}.

There is a consensus that the uncertainties in the predictions of the ratio $(\mu - \text{like})/(e - \text{like})$ are smaller than 5%. (The spread of values predicted by different authors is even smaller). The misidentification of the events in water Čerenkov detectors has been discussed as one of possible reasons of small double ratio. But well identified events with muon decays (signal from decay electrons is detected) confirm the deficit of muon neutrinos. Moreover, the calibration experiment is planning at KEK\textsuperscript{53} to check possible methodical effects.

3. Iron calorimeters Frejus\textsuperscript{54} and NUSEX\textsuperscript{55} do not show the anomaly (see fig.4). Mea-
sured value of the double ratio agrees with 1, although the errors are rather large. Does this testify for methodical origin of the atmospheric neutrino problem? In this connection new results of SOUDAN-II Collaboration are of great interest.

SOUDAN-II detector is the iron calorimeter with tracking drift chambers. The experiment had been started in April 1989 with 275 tons and then the mass of the detector was increased, being 680 t in August 91, and 900 t since July 93; a complete mass, 950 tons, is planning to be in fall of 1993. First publication corresponds to 0.5 kt*y recorded up to August '91. Now an additional 0.5 kt*y has been analyzed\textsuperscript{56,57}. The total sample (∼ 1 kt*y) consists of 579 fully contained events. After energy cut ($E > 200$ MeV) one finds 98 candidates 72\% of which are quasielastic events (one charged lepton). These raw data contain 34 tracks (µ-like) and 32 showers (e-like events). The correction due to shield inefficiency gives 33.5 track and 33.3 showers. This should be compared with predictions (Monte Carlo): 42.6 tracks and 29.1 showers. The double ratio (“provisional” result) is

$$R(\mu/e) = 0.69 ± 0.19({\text{stat}}) ± 0.09({\text{syst}}), \quad 1\sigma$$

which is larger than the result from the first 0.5 kt*y: $R(\mu/e) = 0.55 ± 0.27(\text{stat})$. The ratio is close to that seen by Kamiokande and IMB, thus confirming the problem, but $R(\mu/e) = 1$ is also not excluded: the probability to be in agreement with 1 is about 11\%.

Some remarks are in order. The data show the deficit of the µ-like events whereas e-like events are in a good agreement with predictions. However, for second 0.5 kt*y only, one finds 22.5 tracks which coincides with predicted value 22.1 track, i.e., there is no deficit of muon neutrinos. The respective increase of the number of events could be related to the increase of mass of the detector in second series (680 - 750 tons), and therefore to the increase of the acceptance to muons. The double ratio in second series is $R \approx 0.77$ – more close to 1. All these features can be a result of statistics and more data are needed to make a firm conclusion.

4. The fluxes of the upwardgoing muons do not show a deficit of muon neutrinos. The corresponding data from Kamiokande\textsuperscript{58}, IMB\textsuperscript{59} and Baksan\textsuperscript{60} are in agreement with predictions. In particular, the flux measured by Kamiokande\textsuperscript{51}: $F = (2.04 \pm 0.13) \cdot 10^{-13}$ cm$^{-2}$s$^{-1}$st$^{-1}$ should be compared with expected value $F = (2.0 - 2.45) \cdot 10^{-13}$ cm$^{-2}$s$^{-1}$st$^{-1}$. However, in this analyses the absolute value of the neutrino flux is used which has an un-
certainty up to 30\%. There are new calculations of $\nu_\mu$-flux at high energies. In\textsuperscript{61} the largest flux has been found and it is claimed that the deficit of upwardgoing muons exists too. On the contrary, the estimations in\textsuperscript{62} result in smallest $\nu_\mu$-flux, but in the same time it is claimed that the uncertainties (following from the $K/\pi$- ratio, hadron interaction cross sections, neutrino cross-sections) are underestimated. The realistic value ($\sim 40\%$) admits different interpretations of the results.

5. The uncertainties in the absolute fluxes are cancelled when one compares the number of stopping and through going muons (small uncertainty is related to energy dependence of flux). The ratio (stopping/through going) = $0.16 \pm 0.02$ measured by IMB\textsuperscript{59} is in excellent agreement with prediction: $(0.163 \pm 0.05)$. Since stopping and through going muons correspond to different intervals of neutrino energies, the ratio is sensitive to the energy dependent effects like the neutrino oscillations.

6. The deficit of $\nu_\mu$-flux can be explained by the oscillations $\nu_\mu - \nu_e$ or $\nu_\mu - \nu_\tau$ or $\nu_\mu - \nu_s$\textsuperscript{63}, where $\nu_s$ is the sterile neutrino, although the last possibility is disfavoured by the nucleosynthesis consideration. Negative results give the exclusion region of the neutrino parameters which however does not cover all the region of positive results (fig.5). Such a reconciliation is still possible due to relatively large error bars in the Frejus data and large uncertainties in the results on the upwardgoing muons. Note that the most conservative limit is given by Kamiokande, where the angular distribution of the muons was studied. The IMB and Baksan strongly restrict the region. Moreover, Baksan data with flux calculated by Volkova exclude all the region of the positive results (but see discussion in\textsuperscript{49}). Also one should mention the fact that the upwardgoing muons correspond to higher neutrino energies and the oscillations $\nu_\mu \leftrightarrow \nu_e$ can be suppressed by matter effect in the Earth at high energies more strongly than at low energies. The survival domains are

$$\Delta m^2 = (0.3 - 3) \cdot 10^{-2} \text{ eV}^2, \quad \sin^2 2\theta = 0.4 - 0.6$$

(17)

for $\nu_\mu - \nu_\tau$ oscillations and

$$\Delta m^2 = (0.3 - 2) \cdot 10^{-2} \text{ eV}^2, \quad \sin^2 2\theta = 0.35 - 0.8$$

(18)

for $\nu_\mu - \nu_e$ (fig.5). In the indicated regions the data from different experiments are described
at about $2\sigma$ level and, consequently, the total probability that all the data are fitted by the parameters (17,18) is rather small.

Note that maximal mixing is excluded as a solution of the atmospheric neutrino problem by Frejus result on the double ratio and by IMB result on stopping/through going muons, and the uncertainties of both results are rather small. This fact is very important for theoretical implications.

7. Another explanation\textsuperscript{64} is related to possible proton decay: $p \rightarrow e^+\nu\nu$. The smallness of the double ratio is due to excess of the e-like events from the decay. The observed value $R(\mu/e)$ can be reproduced for the lifetime $T = \left(4.0^{+1.9}_{-1.0}\right) \cdot 10^{31}$ years. Obviously, the excess is at energies $E^{\text{vis}} < 1$ GeV, and there is no deficit of the upwardgoing muons. The energy distribution of events was in agreement with distribution observed by Kamiokande. However the IMB and the latest Kamiokande results for $E^{\text{vis}} > 1.33$ GeV seem to show the effect (smallness of double ratio) at high energies too. Also the deficit of the contained events with muon decay testifies against proton decay solution. Moreover, SOUDAN-II can measure a proton recoils due to the neutrino scattering. In the analyzed sample 5 showers with a proton recoil have been observed which is in agreement with predicted value 3.9. In case of proton decay there is no proton in final state.

Larger statistics in the SOUDAN experiment and the calibration of the water Čerenkov detectors at KEK may change a status of the problem.

SOLAR NEUTRINOS

Recently, all four collaborations measuring the solar neutrino fluxes have published new results.

1. \textit{Homestake experiment} ($\nu_e + ^{37}Cl \rightarrow e + ^{37}Ar$, $E_{\text{th}} = 0.816$ MeV). There are final results from five runs (115 - 119) and preliminary results from three new runs (120 - 122) of the measurement of the Ar-production rate\textsuperscript{65,66}. The end of the latest run 122 is dated by 1992.177 y; new points are concentrated around $N_{Ar} \approx 0.7 - 0.8$ at/day. The average counting rate over all the time of observation (after background subtraction) is

$$Q_{Ar} = 2.28 \pm 0.16(\text{stat}) \pm 0.21(\text{syst}) \text{ SNU}.$$  

(19)
The Ar-production rate in a series of the experiment in 1986 - 1992 (after stop of the experiment in 1985 - 86), $Q_{Ar} = 2.85 \pm 0.16 \text{ SNU}$, is appreciably higher than the average. Time combined ($\approx 5$ years) Ar-production rate is shown in fig.6. Clearly the rate in the last bin is higher than in the previous ones. The latest data do not confirm the anticorrelation with solar activity: large number of the sunspots in 1991 - 1992 was accompanied by high counting rate. On the other hand the data confirm 2 - 3 years period variations of signal.

2. Kamiokande III ($\nu_{e,x} + e \rightarrow \nu_{e,x} + e$, $E_{th} \sim 7.5 \text{ MeV}$). The observations during 627 days (Dec '90 - July '93) give the ratio of the measured flux of the boron neutrinos to the predicted one

$$R_{\nu e}^{III} \equiv \frac{F_{\nu e}^{exp}}{F_{SSM}^{SSM}} = 0.54^{+0.06}_{-0.05} \pm 0.06,$$

where $F_{SSM}^{SSM} \equiv 5.8 \cdot 10^5 \text{ cm}^{-1} \text{ s}^{-1}$ is the central value of the flux predicted by the Standard Solar Model (SSM) of Bahcall and Pinsonneault. The combined result from Kamiokande-II and III is

$$R_{\nu e}^{II+III} = 0.50 \pm 0.04\text{(stat.)} \pm 0.06\text{(syst.)}, \quad (1\sigma).$$

Time dependence of signals is shown in fig.7. The data agree with constant neutrino flux. No anticorrelations with solar activity was found. Possible time variations should not exceed 30%. The energy distribution of the events can be fitted with practically the same probabilities by constant and MSW-nonadiabatic suppression factors.

3. GALLEX ($\nu_e + ^{71}Ga \rightarrow e + ^{71}Ge, E_{th} = 0.233 \text{ MeV}$). Final results from 15 runs of GALLEX-I experiment have been published. Exposure period is from 14 May 1991 to 29 April 1992; counting has been finished on November 1992. The average Ge-production rate is just 2 SNU below the preliminary result, see (22) (although the changes of the results of the individual runs are larger).

There is a number of changes in the GALLEX-II experiment: it runs in another tank, the exposure time is larger: about 1 month, etc. Preliminary results from 6 runs of the GALLEX-II (19 August 1992 - 3 February 1993) give the average Ge-production rate, $Q_{Ge}^{II}$, about $1\sigma$ higher than in first series. The points have rather small spread around 100 SNU, and only in one run a low signal has been detected. Combined result of GALLEX-I and
GALLEX-II is 87 SNU.

| GALLEX | $Q_{Ge}$, SNU (1σ) |
|--------|------------------|
| $Q_{Ge}^I$ | 81 ± 17(stat) ± 9(syst) |
| $Q_{Ge}^{II}$ | 97 ± 23(stat) ± 7(syst) (prelim.) |
| $Q_{Ge}^{I+II}$ | 87 ± 14(stat) ± 7(syst) (prelim.) |

The following aspects of new result are important for implications. 1). The error bars become smaller: a combined error is ∼ 16 SNU as compared with 24 SNU in the first series. 2). The lower limit goes up:

$$Q_{Ge} > \begin{cases} 71 \text{ SNU} & 1\sigma \\ 56 \text{ SNU} & 2\sigma \end{cases}$$

(23)

3). The deviation from the SSM predictions (122 - 132 SNU) is on the same level as before: the data are ∼ (2.2 – 2.6)σ below the expected value.

Let us note that the production rate obtained from L-peak (1.2 kev) is larger than that from K-peak (10.4 kev) in both series:

| GALLEX | K-peak | L-peak |
|--------|--------|--------|
| I      | 64 SNU | 105 SNU |
| II     | 89 SNU | 110 SNU |

(Obviously, the signals from both peaks should be the same). The above result may be just a statistical fluctuation (at present of the order of 2σ) or indication on some systematical error. (The background at low energies is larger).

At present GALLEX-II experiment is performed with a frequency 1 run a month. The calibration with $^{51}$Cr source is planning to be in summer 1994.

4. SAGE. The preliminary result$^{70}$ from runs of 1990 and 1991 was $Q_{Ge} = 58 ± 14(stat) ± 7(syst) \text{ SNU} \ (1\sigma)$. The results of 4 new runs have been published$^{71}$ at TAUP-93. In two runs best fit corresponds to zero signal. In combined statistical analyses the run 1990-5 is again removed and combined Ge-production rate in 15 runs is

$$Q_{Ge} = 70 ± 19(stat) ± 10(syst) \text{ SNU} \ (prelim. \ 1\sigma).$$

(25)

Let us remark the following. In 5 runs (from 15) best fit gives zero flux. The goodness of the fit is apparently lower in the runs with low signal. Time distribution of events in the
counters (summed over all the runs) agrees with 16.5 day meanlife, but it does not yet give a compelling proof that signal corresponds to the $^{71}\text{Ge}$-decay. It seems that the distribution can be fitted by a decay curve with shorter period. Although the systematic error due to radon is estimated to be rather small (5 SNU).

5. There are two aspect of the solar neutrino problem.

1). All the experiments have detected signals which are lower than the predictions of the consistent solar models (fig. 8); the ratios $R \equiv (\text{observations})/(\text{central predicted values})$ for two SSM are

|   | $B - P^{73}$ | $TC - L^{74}$ |
|---|-------------|---------------|
| $R_{Ar}$ | $0.285 \pm 0.030$ | $0.365 \pm 0.030$ |
| $R_{\nu e}$ | $0.50 \pm 0.07$ | $0.63 \pm 0.07$ |
| $R_{Ge}$ | $0.66 \pm 0.12$ | $0.71 \pm 0.13$ |

(The errors are only from the experiment).

2). Signal in the Cl - Ar experiment is suppressed more strongly than the signal in the Kamiokande. It follows from (26) that

$$\frac{R_{Ar}}{R_{\nu e}} = \begin{cases} 0.58 \pm 0.12, & B - P \\ 0.57 \pm 0.12, & TC - L \end{cases}$$

(27)

This statement can be relaxed if one takes into account the Cl- Ar data only for a period of the operation of Kamiokande: $\frac{R_{Ar}}{R_{\nu e}} = 0.78 \pm 0.22$. But this evidently, implies the time variations of Homestake data.

One can perform a direct test of consistency of Cl - Ar and Kamiokande results suggesting that there is no distortion of the energy spectrum and that Kamiokande signal is due to the electron neutrino scattering only. Taking the boron neutrino flux as measured by Kamiokande one finds the contribution of boron neutrinos to Ar production rate: $Q_{Ar}^B = 3.0 \pm 0.4$ SNU which is even larger than total measured rate even if one neglects the contribution from Be-neutrinos. With Cl-data during 1986 - 1992 one removes a direct contradiction, but it is difficult to reproduce such a situation by modification of the solar model.

Tacking into account a difference in the thresholds of different experiments one can conclude on the following energy dependence of the suppression factors: there is weak (or
zero) suppression at low energies (pp-neutrinos), strong suppression at moderate energies (Be- neutrinos); moderate suppression at high energies (B-neutrinos).

There are several directions in which the source of the discrepancy is looked for.

6. After GALLEX publications it becomes fashionable to discuss the “detection” solution of the problem, keeping in mind that some of the experimental results may have incorrect interpretation.

GALLEX results are rather stable and convincing. It is difficult to expect appreciable changes of numbers. Probably, fixing of the K - L difference diminishes the counting rate. On the other hand the calibration experiment may result in the renormalization of the effect and in increase of the measured neutrino flux. SAGE experiment confirms GALLEX results.

Kamiokande results are stable, convincing, and the experiment had been calibrated.

Homestake experiment shows the strongest suppression of signal. There is no calibration. The following features of the data which have small statistical probability are remarked: the probability that the data correspond to the constant flux is smaller than 5\%\textsuperscript{65}. The suggested effect of the anticorrelation with solar activity is now \(\sim 2\sigma\). There is very low signal during 1978 (five runs with near to zero counting rate). There is a general tendency in increase of the signal. The signal during 1986 - 1992 is appreciably larger than the average one. There is a concentration of the points around \(N_{Ar} \sim 0.7 - 0.8\) at/day. The signal at the level \(Q_{Ar} \sim 4\) SNU could be accommodated by astrophysics, thus changing the status of the problem.

7. Astrophysical solution. Neutrino fluxes decrease with diminishing of temperatures in the center of the Sun. A number of modifications of solar models (such as low concentration of heavy elements, low opacity, WIMPS, fast central rotation etc.) were suggested which result in \(T_c\) decrease. However, diminishing \(T_c\) suppresses the boron neutrino flux more strongly than the berillium neutrino flux, (using 1000SSM the empirical relations \(F_B \propto T_c^{18}\) and \(F_{Be} \propto T_c^8\) have been found\textsuperscript{72} for small region \(T_c\) near \(T_c^{SSM}\)) and consequently, the double ratio in (27) should be larger than 1 in contradiction with experimental result. (Although, the production regions of boron and berillium neutrinos differs and modifying the temperature profile one may change, to some extend, the above relation\textsuperscript{76,77}. Essentially
for this reason a combined fit of all the data for arbitrary astrophysical parameters is rather bad (fig. 9) (any astrophysical solutions are excluded at 98% C.L.\textsuperscript{78}). Moreover, this bad “best fit” can be reached at unacceptably strong stretching of the model (e.g., by diminishing central temperatures by 6 - 8%)\textsuperscript{78}.

This statement is relaxed if one uses the Homestake data only for a period of the operation of Kamiokande. But this implies the time variations of the Cl - Ar signal.

8. Particle physics solution. The data obtained so far can be perfectly described by the resonant flavor conversion (MSW-effect)\textsuperscript{79} $\nu_e \to \nu_\mu(\nu_\tau)$. Energy dependence of the suppression factor allows to reproduce at definite values of parameters even the central values of the observed signals. For two neutrino mixing (which is a good approximation when the mass spectrum has a strong hierarchy and the admixture of the third neutrino is small) the data pick up two regions of parameters (see fig. 10). The one corresponds to small (vacuum) mixing solutions\textsuperscript{80,81}:

\begin{equation}
\Delta m^2 = (0.5 - 1.2) \cdot 10^{-5} \text{ eV}^2, \quad \sin^2 2\theta = (0.3 - 1.0) \cdot 10^{-2}, \tag{28}
\end{equation}

another one to large mixing solution:

\begin{equation}
\Delta m^2 = (1 - 3) \cdot 10^{-5} \text{ eV}^2, \quad \sin^2 2\theta = (0.65 - 0.85). \tag{29}
\end{equation}

Lower bounds on Ge-production rate from GALLEX (24) disfavor the third region with large mixing and small $\Delta m^2$. In presence of third neutrino the allowed domains become larger, in particular, the region of small mixing solutions can be extended\textsuperscript{82} up to $\sin^2 2\theta = 8 \cdot 10^{-4}$ and $\Delta m^2 = 8 \cdot 10^{-5} \text{ eV}^2$.

9. The region of small mixing is quite plausible from theoretical point of view. The angles in (28) are a little bit smaller than $\theta_l \equiv \sqrt{\frac{m_e}{m_\mu}}$, where $m_e$ and $m_\mu$ are the masses of the electron and muon ($\sin^2 2\theta_l \sim 0.02$). One can correct this expression by adding the contribution from the neutrino mass ratio ($\theta_\nu$):

\begin{equation}
\theta_{e\mu} = \left| \sqrt{\frac{m_e}{m_\mu}} - e^{i\phi} \theta_\nu \right|, \tag{30}
\end{equation}

where $\phi$ is a phase. Such a relation between the angles and the masses is similar to the relation in quark sector\textsuperscript{83,84} and follows naturally from Fritzsch ansatz for mass matrices.

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There are the models which realize such a possibility in terms of the see-saw mechanism of mass generation\textsuperscript{85}.

Also large lepton mixing corresponding to solutions (29) can be reproduced by the see-saw mechanism. The enhancement of mixing (as compared with quark sector) may take place due to certain structure of mass matrix of the right handed neutrinos which, in turn, can be explained by certain family symmetry\textsuperscript{86}.

10. Alternatively the data can be described by \textit{long length vacuum oscillations} (“just-so”)\textsuperscript{87} with parameters\textsuperscript{88,89}:

\[ \Delta m^2 = (0.5 - 1.0) \cdot 10^{-10} \text{ eV}^2, \quad \sin^2 2\theta = 0.70 - 1.0, \quad (31) \]

(see fig. 11). The parameters (31) can be rather naturally reproduced by Planck scale interactions with flavor universal effective couplings\textsuperscript{90,91}. However, the mixing with parameters (31) is disfavoured by the data from SN1987A\textsuperscript{92}. For large mixing the transitions $\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e$ ($\bar{\nu}_\tau$) result in the modification of the $\nu_e$-energy spectrum. In particular, the appearance of the high energy tail is expected, since the original $\bar{\nu}_\mu$ ($\bar{\nu}_\tau$) energy spectrum has a larger average energy than the spectrum of $\bar{\nu}_e$. The events with $E > 40 - 50$ MeV are predicted in contrast with observations. The excluded region (fig. 11) covers the region of “just-so” solution\textsuperscript{92}.

Although a solution of the solar neutrino problem will be possible with data from new solar neutrino experiments, already present data allow to make some firm conclusions (independent on the model of the Sun etc.). Kamiokande gives the model independent restrictions on the neutrino parameters from measurements of energy spectra of the events and from search for day/night effect\textsuperscript{67}. Lower bound on $Q_{Ge}$ obtained by GALLEX allows to exclude (practically in model independent way) a large region of the neutrino parameters (fig. 10).

12. \textit{Reconciliation}. Is it possible to reconcile the particle physics solution of the solar neutrino problem (28,29,31) with other positive indications of nonzero neutrino masses and mixing, namely, with explanation of muon neutrino deficit in the atmospheric flux in terms of oscillations or/and with existence of neutrino with mass in the cosmologically interesting
region
\[ m \sim 2 - 7 \text{ eV}. \]  

(32)

Such a neutrino could be a component of the hot dark matter which is needed to explain a formation of large scale structure of the Universe\(^\text{93}\).

Let us make remarks.

1). The neutrino parameters (28) for \( \nu_e \to \nu_\mu \) can be easily reproduced in the see-saw mechanism with Majorana mass of the RH neutrinos \( 10^{10} - 10^{12} \text{ GeV} \). For third neutrino, being main component of \( \nu_\tau \), one gets \( m_3 \sim 1 - 30 \text{ eV} \) just in the region (32). New experiments at CERN (CHORUS and NOMAD) will be able to study a large region of mixing angles of such a neutrino. However, in this case there is no room for a solution of the atmospheric neutrino problem.

2). The parameters for the solar and atmospheric neutrino problems can be reconciled in terms of the see-saw mechanism if \( m_2 \sim m_\odot \) and \( m_3 \sim 0.1 \text{ eV} \). Moreover, large mixing of \( \nu_e \) and \( \nu_\mu \) may be related to a relatively weak hierarchy of masses: \( m_3/m_2 = 10 - 30 \). However, in this scenario neutrinos can not play the role of the hot dark matter (32).

3). The reconciliation of the solutions of all three problems requires more sophisticated models. One possibility is the highly degenerate spectrum with \( m_1 \approx m_2 \approx m_3 \approx 1 - 2 \text{ eV} \)\(^\text{94}\). Small mass splitting: \( (m_2 - m_1)/m_2 \sim 10^{-5} \) and \( (m_3 - m_2)/m_2 \sim 10^{-3} \) can solve the solar and the atmospheric problems correspondently. Another possibility is related to the introduction of the light sterile neutrino(s) which could play the role of the hot dark matter or participate in the conversion of solar neutrinos\(^\text{95}\).

**CONCLUSIONS**

The laboratory experiments (direct measurements of the neutrino masses, searches for the double beta decay, kinks on the Kurie plots, oscillations, neutrino decays, etc.) give negative results: no effects of the neutrino masses, mixing as well as new interactions have been found. This gives the upper bounds on the masses and mixing at the level of predictions of the “electroweak see-saw”.

Positive indications of the existence of the neutrino masses and mixing are related to the
atmospheric and solar neutrino problems. Recent data do not change essentially their status. New Kamiokande data further confirm the smallness of the double ratio. First “provisional” results from SOUDAN-II are not yet decisive, although they indicate the smallness of the double ratio too. The neutrino oscillations are considered as the most plausible solution of the problem.

New solar neutrino data also confirm previous results. If the interpretation of all the experimental data is correct any astrophysical solutions of the problem are disfavoured. The results can be well described in terms of the resonant conversion or long length vacuum oscillations (although the latter is disfavoured by SN1987A data).

Reconciliation of these results allows to trace possible patterns of the neutrino masses and lepton mixing, and the latter seems not to coincide with mixing in quark sector.

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FIGURE CAPTIONS

Fig. 1. The bounds on the electron (anti) neutrino mass from tritium β-decay experiments: Los Alamos$^2$, Mainz$^3$, Livermore$^4$, Zürich$^5$, Tokyo$^7$, (95% CL). Also the upper bound on the effective Majorana mass of the electron neutrino from double beta decay searches is shown.

Fig. 2. The restrictions on the tau neutrino Majorana mass as functions of the lifetime (invisible decay $\nu_\tau \rightarrow \nu'_\chi$ is suggested). Hatched line shows the laboratory bounds from ARGUS and CLEO. Solid lines correspond to restrictions from the Primordial nucleosynthesis: 1 - from ref.$^{13}$, 2 - from ref.$^{14}$, 3 - from ref.$^{16}$. Dashed line shows the bound from total energy density in the Universe.

Fig. 3. Results from direct searches for the neutrino mixing. Hatched lines show present limits from the oscillation experiments ($\nu_e \leftrightarrow \nu_x$, $\nu_e \leftrightarrow \nu_\tau$). Dashed line shows the provisional result from the BUGEY-III experiment; dotted lines correspond to the level of sensitivity of future experiments ($\nu_e \leftrightarrow \nu_\tau$); Dashed dotted lines show the upper bound from double beta decay searches ($m_{ee} = 1.4$ eV) as well as the level of the sensitivity of future searches ($m_{ee} = 0.1$ eV). Also shown are the bounds on mixing from searches for kinks in Kurie plots in the kev - region: 1 - INS, 2 - Zürich, 3 - Argonne, 4 - Oklahoma.

Fig. 4. Results on double ratio for atmospheric neutrinos (1σ).

Fig. 5. Allowed regions of oscillation parameters for atmospheric neutrinos (shadowed) The restrictions follow from oscillations experiments at reactors and accelerators (hatched lines), contained events (solid lines), upward going muons (dashed lines), stopping upward going muons (dashed-dotted line). (See$^{49,63}$ for details).

Fig. 6. Time averaged signal in the Cl - Ar experiment on the solar neutrinos$^{66}$. The expected counting rate according to SSM is about 1.6 at/day.
Fig. 7. Results from Kamiokande II and III on solar neutrinos (from\textsuperscript{51}).

Fig. 8. Comparison of the observed signals (hatched regions) with predictions of different standard solar models (1\sigma): 1, 2 - Bahcall-Pinsonneault\textsuperscript{73} (with and without diffusion), 3 - Turck-Chieze-Lopez\textsuperscript{74}, 4 - Bertomieu et al.\textsuperscript{75}, 5 - Castellani et al.\textsuperscript{76}.

Fig. 9. The allowed regions of the boron and berillium neutrino fluxes from the combined fit of the Kamiokande, Homestake and Gallium results at 90, 95 and 99\% C.L. (negative values of $\phi(Be)$ are allowed). For $\phi(Be) > 0$, $\chi^2 > 5.6$, i.e. any astrophysical solution are excluded at > 98\% C.L. Also shown are the predictions from various nonstandard solar models (from paper\textsuperscript{78}).

Fig. 10. The MSW solutions of the solar neutrino problem. The allowed regions of neutrino parameters in two neutrino case (from\textsuperscript{81}). Also the region excluded by lower limit from GALLEX experiment is shown.

Fig. 11. Vacuum oscillation (“just-so”) solution of the solar neutrino problem. The regions of the parameters for two neutrino mixing $\nu_e \leftrightarrow \nu_\mu$ (from\textsuperscript{88,89}). Also shown are the upper bound on the mixing from SN1987A (dashed line)\textsuperscript{92} and the predictions from flavor universal Planck scale interaction\textsuperscript{91}.
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