NEUTRINO MASS MEASUREMENT AND LEPTON NUMBER NONCONSERVATION EXPERIMENTS

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1. Introduction

It is four years now, that the interest in the problem of neutrino masses is continuously growing. It became a tradition to discuss this problem at many conferences. This conference is not an exception. But can we give the answer to the main question: Has the neutrino a mass ? No, we can not. Not a single experiment has confirmed the ITEP-result. There is no clear indication of the existence of oscillations. The neutrinoless double β-decay is (most likely) not found.

What is the phenomenon when people discuss something "nothing" with ever increasing enthusiasm? - Let me briefly summarize a few points which give motivation to search for massive neutrinos.

1. The ITEP-experiment gave a serious indication for the existence of the neutrino mass and there is no other experiment or analysis to disprove this result so far.
2. The discoveries of the W and Z bosons at the CERN-SPS have triumphantly confirmed the electroweak theory recently. The generalization of the idea of unification and its extension to strong and gravitational interactions (the unification of quarks, leptons and neutrinos in the same family) leads to lepton (and baryon) number violation and, in general, to massive neutrinos.
3. Massive neutrinos are a long expected vital remedy to cure diseases of cosmology such as the hidden-mass problem and could make it possible to understand the present structure of the universe, the uniformity and isotropy of the relic radiation in more detail. Neutrinos with masses at the ITEP-level (- if $M_\nu < 5$eV the neutrinos would not be connected with cosmology-) being the smallest objects of the microcosmos are at some time (along with the photons) the most abundant ones in the universe and determine its mass.

Many people remember the beneficial influence of the hypothesis of parity violation on the development of physics at the end of the 50ies. A lot of remarkable findings in the field once hidden behind the wall of the old physical view-of-world followed. The gist of the present phenomenon is that the idea of the massive neutrino opens up a terra nova between the micro- and macrocosmos. Though not finally proved this idea stimulated many physicists to explore the new field.

Here is a list of questions which arise in this context:

Are neutrinos massive ?
If so, what is the spectrum of mass eigenstates?
Can neutrinos of definite kind interchange their identity?
And finally:
Is the neutrino of Dirac- or Majorana-type?

No one of these questions can be answered definitely at present.

We shall consider the present experimental situation in a very traditional way and I will report the status of

i) the direct measurements of the neutrino mass
ii) the search for neutrino oscillations
iii) the search for the double β-decay and other lepton-number violating processes

here.

2. Direct neutrino mass measurements

2.1. Neutrino mass from the β-spectrum

If the mass of the neutrino $M_\nu \neq 0$ then the β-spectrum $S \sim (E_0-E)\cdot[(E_0-E)^2-M^2)]^{1/2}$ is distorted especially in the end point region. The spectrum is shortened by the value which is equal to the neutrino mass. In principle the neutrino mass can be extracted from any deviation from the expected

β-spectrum. Real life, however, is much more complicated. There are some limitations, namely

i) the resolution. The finite energy resolution function (R) of the apparatus leads to a smearing of the edge of the β-spectrum. R has to be $\sim M_\nu$. To determine M_ν one has to know the shape of the R-function.

ii) the counting rate. The intensity of a β-spectrum falls very rapidly as the energy approaches its maximum, i.e. in the mass-sensitive region. That is why the detection efficiency of the apparatus should be as high as possible.

iii) the background. The closer to the edge of the spectrum one can obtain statistically significant data on the shape of the β-spectrum the higher is the sensitivity to the neutrino mass. It is not possible, however, to come closer to the edge than to a certain distance ΔE_B. This value depends on the background and is determined by the condition that the number of counts from the spectrum has to be equal to that from the background. It does not matter how good the apparatus' resolution is, it can not be used at the edge of the β-spectrum effectively in the interval ΔE_B where the background is larger than the width of R.

iv) the spectrum of the final states. After the β-decay the system is in an excited state ("shake-off" effect, Migdal /1/) and the β-spectrum is a superposition of β-transitions to the levels determined by the final state spectrum (FSS). If one does not pay high attention to the structure at the edge the asymptotic representation of the β-spectrum has the familiar one level form /2/.

$$\begin{aligned} &\int (E_0-E-\Delta)[(E_0-E-\Delta)^2-M_\nu^2]^{1/2}\,W(\Delta)\,d\Delta \\ &\simeq \int [(E_0-E-\Delta)^2-M_\nu^2/2]\,W(\Delta)\,d\Delta \\ &=(E_0^*-E)^2-M_{eff}^2/2 \\ &\simeq (E_0^*-E)\,[(E_0^*-E)^2-M_{eff}^2]^{1/2} \end{aligned} \qquad (2.1)$$

with

$$E_0^* = E_0-\langle\Delta\rangle,\ M_{eff}^2 = M_\nu^2-2\sigma^2,$$
$$\sigma^2 = \langle\Delta^2\rangle-\langle\Delta\rangle^2,\ \langle\Delta^n\rangle = \int d\Delta\, W(\Delta)\,\Delta^n.$$

From this one can determine the experimental parameters E_0^* and M_{eff}^2. However, to extract the physical parameters E_0 and M_ν one has to know the FSS $W(\Delta)$. So, one can see that M_ν^2 and E_0 are model-dependent.

$$M_\nu^2 = M_{eff}^2 + 2\sigma^2 \qquad (2.2a)$$
$$E_0 = E_0^* + \langle\Delta\rangle \qquad (2.2b)$$

One can withdraw the next consequences.

i) M_ν^2 enlarges if σ^2 taken from the data-analysis increases.

ii) $\sigma^2= 0$, i.e. $W(\Delta)= \delta(\Delta)$ implies the model-independent lower limit on M_ν.

iii) On contrary, the upper limit on M_ν is model-dependent.

The more narrow the β-spectrum is the greater is the relative influence of the neutrino mass on its shape. That is why the T β-decay having the decay energy $E_0 \simeq 18.6$ keV became a classical object of investigation.

The most developed method and the best one at present is the method of β-spectrum investigation by a spectrometer. In 1972 K.Bergkvist was the first who demonstrated this in his fundamental work /3/ which became a classical one. Using a spectrometer which had a resolution of 50 eV he achieved a remarkable result: the upper limit of the neutrino mass was set to be at the level of 60 eV.

The further development of this method was made by Lubimov et al. in 1980 /4/. The ITEP-80 spectrometer had a comparable resolution but the background level was reduced by a factor of 16. This alone made it possible to increase the efficiency of the apparatus by an order of magnitude as compared with Bergkvist's spectrometer. The increase in the sensitivity led to the necessity to develop sensitive methods of experimental determination of the resolution function R. The problem of the data analysis became also considerably more complicated facing the possibility of the neutrino mass detection. The ITEP group was then the first who got an indication of a non-zero neutrino mass.

However, the most significant development of the β-spectroscopy method was made with the ITEP-83 spectrometer /5/. The electric field was introduced between the source and the magnetic field and the electrostatic scan was made. The energy of the detected β-particles was varied through the change of the electric field while the magnetic field strength remained constant. The main advantage of this method was the constancy of the energy of the detected particles in all parts of the β-spectrum. Consequently, the detector-efficiency remained the same throughout the whole range of the scanning and did not affect the shape of the β-spectrum. The mode of operation in which the electrons were accellerated in the electric field gave the possibility to fix the focussing magnetic field at the value surpassing the end point energy of the Tβ-spectrum. This led to the 20-fold reduction of the background. The use of the so-called 'pointlike' source and the introduction of a multichannel proportional detector led to the improvement of the resolution down to 20 eV. At the same time the data-taking rate increased. The preliminary results of the measurements of the Tβ-spectrum in valine using the improved apparatus was reported at the Brighton Conference /5/.

It was found that

$$M_\nu \geq 20 \text{ eV} \qquad (2.3)$$

In the work which was presented at this conference by the ITEP-group /6/ the analysis of the total statistics of 86 series of measurements (35 series were used for the Brighton result) with three sources of different thickness of active valine was carried out. Recalibration of the spectrometer was made using a precise measurement of the energies of β-transitions of Tm^{169} (Yb^{169}) /7/. The calibration itself does not affect the fit-value of the neutrino mass-parameter. However, one needs a precise calibration to compare the fit energy characteristics of the β-spectrum with those from other experiments.

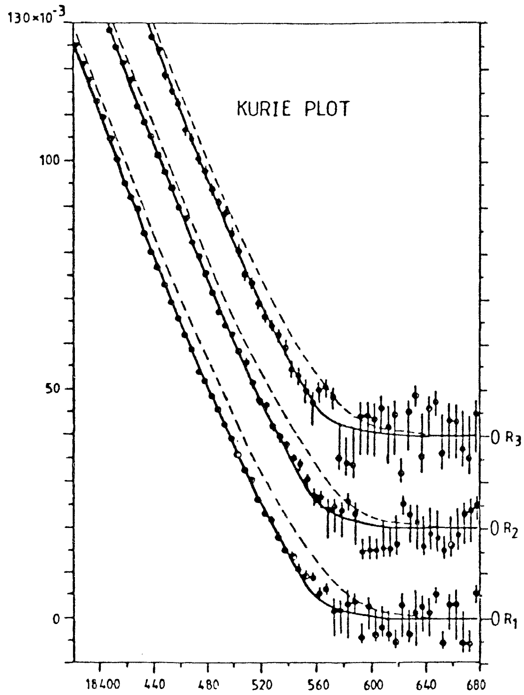

Fig. 1

The influence of the molecular structure of the source on the β-spectrum was taken into account using a high precision calculation /8/ which included correlations of electrons. The FSS used for the fit is based on 51 final states.

The experimental data are shown in fig. 1 as a Kurie-plot in the range close to E_0. The results of the fit with the $M_\nu \neq 0$ using the valine FSS is shown by the solid lines. In the same figure the fit spectra for $M_\nu = 0$ are given (dotted lines).

Table 1

E = 16800 eV

	1	2	3	average
M_ν^2	1696±97/250/	1317±79/180/	1350±140/200/	1401±120
E_0	18588.51±.4/3/	18585.9±.3/2.5/	18586.1±.5/2.7/	18586.6±1.3
χ^2/N_D	322/303	503/509	467/508	

E = 336 eV

	1	2	3	average
M_ν^2	1545±200	1510±175	1371±170	1460±140
E_0	18587.7±1.2	18587.3±.9	18586.6±1.1	18587.1±1.5
χ^2/N_D	183/163	264/318	292/316	

The results of a single mass fit using the FSS of valine for three sources are given in table 1. In square brackets the errors of parameters which take into account statistical fluctuations of all functions entering the fit expression (i.e. variations of the weight and the shape of ionization losses, backward scattering, the optical functions, 'curvature of the spectrum' etc.) are given. For mean values over the three sources the total errors are given. It is worth to point out that the use of the correct shape of the optical function has led to considerable reduction of χ^2 as compared with the analysis /5/.

It is very important that the parameters do not change as the fit energy range ΔE is reduced. In the narrow energy range the influence of the 'curvature' of the spectrum becomes very small. In this case the result does not depend on the uncertainty of the behaviour of the tails of the resolution function in the region out of ΔE.

The average data for valine for the atomic- and δ -function spectra which were used in the analysis are given in table 2. They are the same for all models within statistical accuracy. The second error corresponds to the calibration uncertainty. The fifth line in table 2 gives the mass difference of neutral T and He atoms calculated using the E_0-values. The values of ΔM do not agree with values given in ref. /9/ (ΔM=18573±7). Recently, the results of the measurements of the T-He mass difference from the ICR-spectrometer were published /10/. The resolution obtained in this experiment is 150 times better than in /9/. The lines of the doublet are shown in fig. 2.

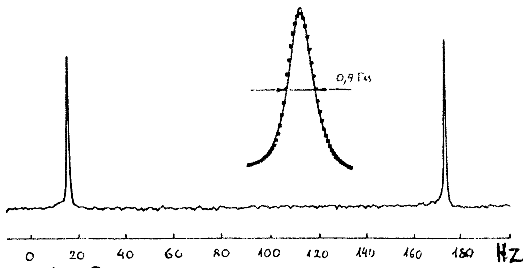

Fig.2

Table 2

FSS	valine	atom	δ-fct. "Nucleus"
M_ν^2	1401±120	1135±95	266±78
M_ν	37.4±1.7	33.6±1.4	16.3±2.5
E_0	18586.6±1.3	18582.8±1.3	18569.6±1
E_0-M_ν	18549.2±2.1±5	18549.2±1.9±5	18553±2.7±5
$M_{T\text{-}He}$	18606±6	18610.4±6	18589. ±6

The authors /10/ obtained the value $M_{T\text{-}He}$ = 18599±3 eV which is in good greement with our value of ΔM for the FSS of valine.

2.2. Measurement of the masses of μ-, τ - and subdominant neutrinos

Similar to the β-decay the masses of μ- and τ-neutrinos can be measured from the spectra of charged particles in processes yielding $\nu_{\mu(\tau)}$. The most precise (direct) measurements of the muon neutrino mass are performed using pions (at rest as well as in flight). Anderhub et al. /11/ have used the pion decay in flight to measure the pion and muon momenta and the decay angle in a spectrometer. The result does not depend on the masses of the pion an muon and is

$$M_{\nu_\mu} < 500 \text{ keV} \quad (90\ \% \text{ c.l.}) \qquad (2.4)$$

The pion decay at rest has been studied by Abela et al. /12/. The combination of the momentum of the pion measured with high precision with the pion mass gives

$$M_{\nu_\mu} < 490 \text{ keV} \quad (90\ \% \text{ c.l.}) \qquad (2.5)$$

New data from MARK II /13/ presented at this conference have been obtained for the τ-decay into a heavy system $\tau \to \rho' \nu_\tau$ ($\rho' \to 3\pi^\pm \pi^0$). The result is

$$M_{\nu_\tau} < 143 \text{ MeV} \quad (95\ \% \text{ c.l.}) \qquad (2.6)$$

One can see that the limits to the masses of ν_μ and ν_τ are much higher (by 4 or 7 orders of magnitude resp.) than the ν_e-limit. On the one hand the reason is that the energy released in the reactions involving ν_μ or ν_τ is much higher than in the case of the β-decay (e.g. of tritium). On the other hand the relative accuracy of the measurement of the charged spectra is much poorer in the cases of ν_μ or ν_τ. That is why direct experiments measuring the masses in the reactions involving ν_μ or ν_τ are hopeless if these masses are small. However, indirect measurements can be much more sensitive in these cases. In fact, if neutrino masses $M_\nu \neq 0$, then the eigen states of the weak interaction should not forcibly coincide with the mass eigen states. In the general case a neutrino of the l-th kind is a superposition of the mass eigen states $|\nu_i\rangle$

$$|\nu_\ell\rangle = \sum_i U_{\ell i}|\nu_i\rangle \qquad (2.7)$$

where U_{li} is a unitary matrix.
As it was shown by Shrock /14/ and many other authors /15/ in a weak process involving all eigen states $|\nu_i\rangle$ can show up with a probability given by $|U_{li}|^2$ in a form of kinks and peaks in the spectrum of the recoil leptons. It is worth to point out that the sterile states which hardly interact in our world can also manifest themselves. A possibility emerges to choose the Q-value of the reaction in the optimal way to match the studied range of neutrino masses. For small masses the T β-decay experiments have the highest sensitivity. The M_{ν_x} -vs.- $|U_{ex}|^2$ plot of the two-mass-fit of the tritium β-spectrum measured in the ITEP-84 experiment is given in fig. 3.

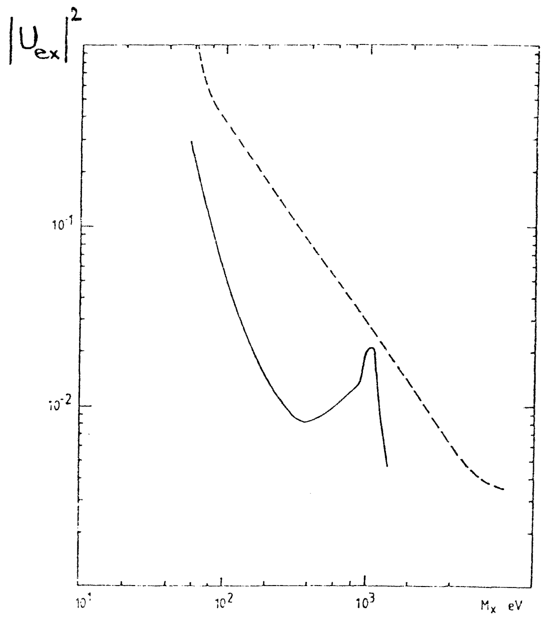

Fig.3

In the interval $20 < M_{\nu_x} < 60$ eV every mixing is possible. For large masses the admixture of the other neutrinos falls very rapidly as the mass increases. At $M_{\nu_x} \sim 1000$ eV the upper limit on the mass increases up to 2 % (90 % c.l.). This reflects the irregularity of the experiment's β-spectrum in the region close to 17550 eV. The fit gives $M_{\nu_x} \simeq$ 1000 eV and $|U_{ex}|^2 = 0.9 \cdot 10^{-2}$. The χ^2-test, however, is also consistent at the 90 % c.l. with the absence of this mass.

In the same figure the limits set by Simpson /16/ for the mass range extending up to 6 keV are shown by a dashed line. The analysis of the β-spectra with large energies gives the possibility to widen the interval of masses of heavy neutrinos up to the MeV range.
For example, from the ^{64}Cu $\beta^{\pm}$-decay $100 < M_x < 200$ keV and the limit on $|U_{ex}|^2$ is $|U_{ex}|^2 = 10^{-2} \div 10^{-3}$ (cf./17/). From some MeV up to 200 MeV the π- or K-two particle decay experiments are most sensitive. The K2e, K2μ-decays were investigated at KEK recently with a much improved spectrometer /18/.
The study of neutrinos with even larger masses M_{ν_H} is connected with the idea of ($\nu_H \to e^+e^- \nu_\ell$)-decay. ν_H can emerge from decays of pseudoscalar mesons (π, K, F, D, etc.) originating from p-target interactions at high energy proton accelerators.

$$M_{PS} \to \nu_H + L + X, \quad \nu_H \to e^+e^-\nu_\ell \qquad (2.8)$$

(X - is the non-leptonic residue).
The probability of this process is $\sim |U_{LH}|^2 \, |U_{eH}|^2$. If $L \equiv e$ then one can determine the matrix element $|U_{eH}|^2$, or if $L \equiv \mu$ $|U_{\mu H}| \cdot |U_{eH}|$. The ν_H-decay idea is very rich, it can also be used for any process with $E_\nu > 1$ MeV for reactor-, solar- and other ν-decays.
In the CHARM-experiment the search for the ($\nu_H \to e^+e^- \nu_\ell$)-events from π/K-decays was made using a wide band ν-beam. The limit on $|U_{eH}|^2$ and $|U_{\mu H}|\,|U_{eH}|$ was set to be $\simeq 10^{-6}$ for a heavy neutrino ν_H in the 200 - 300 MeV range.
The beam dump experiment of the CHARM-collaboration studied ν_H originating from D- and F-meson-decays. The energy interval was widened up to 1750 MeV. For $M_{\nu_H} \leq 1500$ MeV the limit $\simeq 10^{-7}$ was set for $|U_{eH}|^2$ and $|U_{\mu H}|\,|U_{eH}|$. The same experiment permitted, making some assumptions about F-meson cross section and its branching $F \to \nu_\tau X$, to set strict limits on $|U_{e\tau}|^2$, $|U_{e\tau}|^2 < 10^{-6} \div 10^{-10}$ for $M_{\nu_\tau} = 50 \div 250$ MeV. The limits on the elements of mixing matrix set by different experiments obtained for electron- and muon-associated heavy neutrinos are shown in fig. 4 and fig. 5, respectively /18,19/.

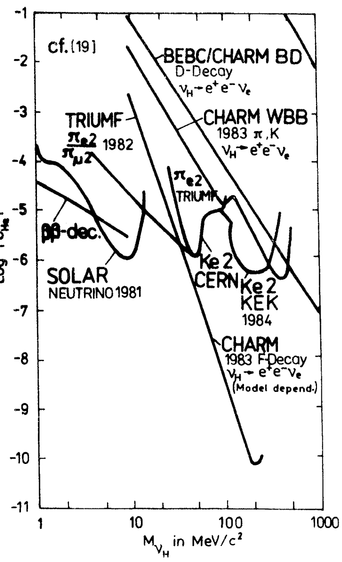

Fig. 4

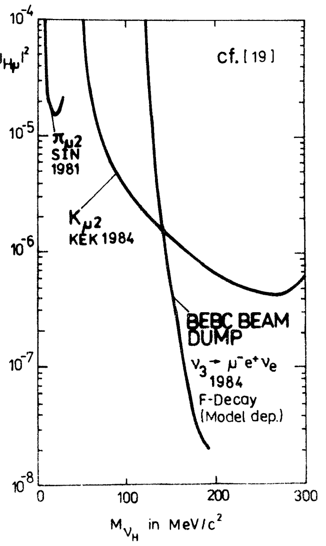

Fig. 5

3. Neutrino oscillations

B. Pontecorvo was the first who put forward the idea of ν-oscillations in 1957 /20/. It was a very brave idea if one takes into account the fact that, firstly, it was formulated before the discovery of neutrinos of different kinds (flavours) and, secondly, in a period when the concept of the neutrino as being a two component zero-mass Weyl-particle was generally accepted. Nowadays, the oscillating neutrino seems to be so natural that despite of mostly negative results of the experiments we are ready to increase the efforts in our **quest for** this beautiful phenomenon.

TEMPORA MUTANTUR!

As we pointed out many times in general neutrinos of one flavour determined by the weak process from which they originate are a linear superposition of mass eigen states.

$$|\nu_L\rangle = \sum_i U_{Li} |\nu_i\rangle \qquad (3.1a)$$

and inversely,

$$|\nu_i\rangle = \sum_L U^{-1}_{Li} |\nu_L\rangle \qquad (3.1b)$$

The different mass states change with time as $\sim \exp[-iE_i t]$, $E_i = (P^2 + M_i^2)^{1/2}$. If there are mass eigen states with different masses the phase of these states is changing. A linear combination corresponding to a flavour eigen state will change, and thus neutrinos of other flavours occure, i.e. there will be an oscillation. It is obvious that neutrino oscillations can take place only if the neutrino possesses a mass $M_\nu \neq 0$. It means that the discovery of neutrino oscillations would give direct evidence that there is at least one neutrino with $M_\nu \neq 0$. However, the existence of non-zero neutrino masses would not necessarily lead to neutrino oscillations to take place:

i) at least two masses from the set of mass eigen states must not be equal to each other,

ii) a mixing between the mass eigen states must exist.

In the simplest case of two mass eigen states the probability of the transition of the neutrino of the i-th kind into a neutrino of j-th kind, i.e. the probability of occurence of a new neutrino in a beam of neutrinos of a certain kind (in a so called occurence or exclusive experiment), is given by the well known expression

$$P(\nu_i \to \nu_j) = \sin^2 2\theta \, \sin^2\left[\frac{1.27\, L\, \Delta M^2}{E_\nu}\right] \qquad (3.2a)$$

and the probabilitiy in a disappearence experiment is given by

$$P(\nu_i \to \nu_i) = 1 - P(\nu_i \to \nu_j) \qquad (3.2b)$$

where L - is the distance between neutrino-origin and the detector.

The mixing matrix is orthogonal

$$\mathcal{U} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \qquad (3.3)$$

θ denotes the mixing angle.

In the occurence experiments the detector registrates neutrinos of a certain kind whereas it is irradiated with neutrinos of another kind. That is why the very fact of detection of 'foreign' neutrinos is the manifestation of oscillations. Therefore the positive result can be achieved qualitatively.

In the disappearence experiment the detector detects neutrinos of the same kind it is exposed to. The change of the neutrino flux at a distance L from the source as compared with the flux expected is the sole indication of disappearence of neutrinos and, hence, of the presence of oscillations. Therefore, to make a disappearence experiment one has to know the absolute flux and the neutrino-spectrum of the ν-source. Thus, these experiments are quantitative experiments. However, the very point of this type of experiments is that the disappearence of the neutrinos of the detected kind in the occurence of neutrino of any other kind ν_x.

$$\left[P(\nu_L \to \nu_x) = 1 - P(\nu_L \to \nu_L)_{Meas.} \right]$$

including sterile neutrinos.
Therefore, the disappearence experiments (also called inclusive) includes a much wider area of physical processes.
The experimental limit on $P(\nu_L \to \nu_X)$ determines a region in the two parameter ($\sin^2 2\theta$ and $M^2_{\nu_L} - M^2_{\nu_x}$)-plane. The two limits on the values of $\sin^2 2\theta$ and ΔM^2 are determined by the expressions

i) along the $\sin^2 2\theta$-axis
$\sin^2 2\theta = 1$

$$\Delta M^2_{min} = \left[P(\nu_L \to \nu_X) \right]^{1/2} E_\nu/(1.27L) \qquad (3.4)$$

ii) along the ΔM^2-axis
with $L/L_o \gg 1$, $L_o = (1.27\Delta M^2/E_\nu)^{-1}$

$$\Delta M^2 \to \infty, \qquad (3.5)$$

$\sin^2(L/L_o)$ oscillates rapidly and is averaged over the detector to give the value of 1/2.

$$\sin^2(2\theta)_{lim} = 2\, P(\nu_L \to \nu_X) \qquad (3.6)$$

The systematic error in the determination of the limit on the mixing angle - $\sin^2(2\theta)_{lim}$ - is mainly determined by the knowledge of the absolute neutrino flux as well as the slope of the spectrum. Systematic errors connected with the flux and the neutrino spectrum can be reduced considerably if detectors positioned at different distances from the source are used in the experiment (two distance experiments). In such experiments it is possible to obtain a so called 'model independent' limit on ΔM^2 (and also on $\sin^2 2\theta$ though in a restricted range of ΔM^2). It is impossible, however, to set a limit to $\sin^2 2\theta$ at $\Delta M^2 \to \infty$.

The oscillation effect is maximal if $\sin^2(1.27\, L\Delta M^2/E_\nu) = 1$, i.e. if $\Delta M^2 \sim E_\nu/L$. Then the value of E_ν/L determines the ΔM^2-range to which the experiment with a given value of E_ν/L is sensitive.
The ranges of ΔM^2 to which the experiments with the different neutrino sources are sensitive to are given in the table 3. (ΔM^2 in eV^2).

Table 3

source	sun	cosmic	reactor	accelerator
	10^{-10}	10^{-4}	1	3 - 50
	10^{-11}	10^{-5}	10^{-2-5}	0.2-1000

Let's start with small values of ΔM^2.

3.1. Solar neutrinos

It is many years now that the solar neutrino paradox exists - the large (almost 3 fold) discrepancy between the neutrino flux measured in the experiment by Davis et al. /21/ and the values predicted by theory. According to /21/

$$R_{exp} = (2.2 \pm 0.4) \text{ SNU} \qquad (3.7)$$

(1SNU = 10^{-36} - captures per sec and atom of ^{37}Cl). The flux predicted by theory is

$$R_{th} = (7.9 \pm 1.5) \text{ SNU} \quad \text{(ref./22/)} \qquad (3.8a)$$

or

$$R_{th} = (5.2 \pm 2.0) \text{ SNU} \quad \text{(ref./23/)} \qquad (3.8b)$$

The difference between theory and experiment could be interpreted as the consequence of neutrino oscillations. In this case one obtains $\Delta M^2 > 10^{-11}$ eV^2 and the mixing is large $\sin^2 2\theta = 1$. However, the uncertainty in the calculation of the flux of solar neutrinos for the experiment ref./21/ does not permit to draw a definite conclusion about the existence of ν-oscillations. The point is that in this experiment the Cl-Ar-method of neutrino detection ($\nu_e + {}^{37}Cl \to e + {}^{37}Ar$) was used. The energy-threshold of detection is 814 keV. ^{37}Cl-experiments are sensitive to solar neutrinos of the so-called boron cycle (E_ν in the range 0 - 14 MeV) and partly to neutrinos from ^7Be, E =861 keV. The overwhelming majority of solar neutrinos originate from the p-p cycle with energies from 0 up to 420 KeV, i.e. values below the threshold of detection of the Cl-Ar-method. Therefore, the solar neutrino paradox is still present. We hope that it will be resolved by further experiments applying ^{71}Ga and ^{115}In which are also sensitive to neutrinos from the p-p cycle.

3.2. Cosmic neutrino-oscillations

At this conference there is a first example in which the large p-decay detectors are used to search for ν - oscillations. The IMB-experiment /24/ measured the up- and downward cosmic neutrino flux (cf. fig.6). Thus, a classical two-distance experiment ($L_1 \sim 1$ km down, $L_2 \sim 10^4$km up) was carried out. It is a flux-independent experiment sensitive to $\Delta M^2 > 5\ 10^{-5} eV^2$.

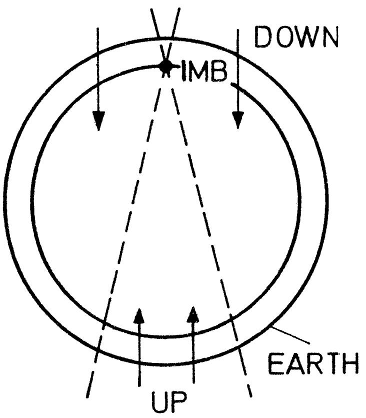

Fig. 6

The up-down ratio for the neutrino-flux obtained is

$$R\ (up/down) = 0.92 \pm 0.28 \qquad (3.9)$$

which is compatible with the absence of ν-oscillations for $\Delta M^2 > 5 \cdot 10^{-5}$ eV^2. There is a 2σ-incompatibility with Davis' experiment

$$R_{exp}/R_{th} = 0.34 \pm 0.14 \qquad (3.10)$$

So, if one interprets the ν -sun-puzzle as a complete oscillation among all flavours one obtains

$$10^{-11} < \Delta M^2 < 6 \times 10^{-5}\ eV^2 \qquad (3.11)$$

This is a very important indication.

3.3. Reactor experiments

3.3.1. The Gösgen experiment /25/

In this experiment the neutrino flux from the β-decay of the fission products of a 2.8 GW power reactor is measured by two detectors situated at the distances of 37.9 and 45.9 meters from the center of the active area of the reactor. The detectors consist of consecutive layers of liquid scintillator and proportional wire chambers filled with ^{3}He. The positrons from the reaction $\bar{\nu}_e p \rightarrow n e^+$ are detected in the liquid scintillator. The energy resolution is $\sigma(E_e) = 0.35\sqrt{E_e}$. Neutrons are detected in the ^{3}He-chambers. The comparison of the results obtained at two distances gives the possibility to set a limit on the inclusive process of $\bar{\nu}_e$-oscillations independently of the knowledge of the absolute neutrino flux, the neutrino spectrum, the detector efficiency and the neutron lifetime. These results are shown in fig. 7. However, as we have pointed out already the two-distance experiment is sensitive to only a limited range of ΔM^2 and, in particular, it does not limit the mixing angle at $\Delta M^2 \rightarrow \infty$. More stringent limits on minimal ΔM^2, and what is even more important, to $\sin^2 2\theta$ at $\Delta M^2 \rightarrow \infty$ were obtained by comparison of the measured spectrum with the theoretical calculated spectrum.

As one can see from fig. 7 the Gösgen-experiment excludes $\bar{\nu}_e \rightarrow \bar{\nu}_x$ oscillations for the regions

$$\sin^2 2\theta > 0.15 \text{ at } \Delta M^2 \rightarrow \infty \qquad (3.12a)$$

and

$$\Delta M^2 > 0.014 \text{ at } \sin^2 2\theta = 1 \qquad (3.12b)$$

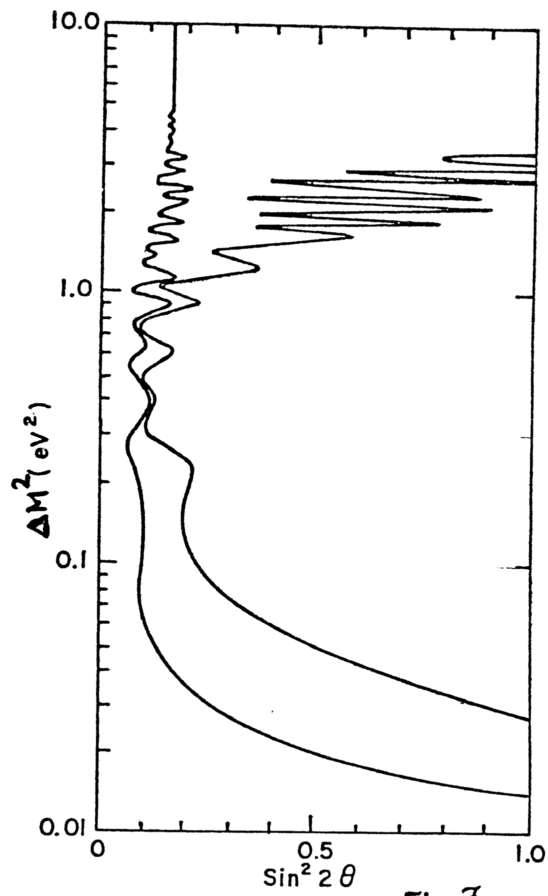

Fig. 7

(cf. ref. /25/)

3.3.2. The Le Bugey experiment /26/

The experiment was carried out at a 2.75 GW power reactor. The characteristic feature of this experiment is that the detectors are situated very close to the active area at the distances 13.6 and 18.3 m. It gives the possibility to considerably improve the statistical accuracy of the experimental data and consequently increase the sensitivity of the experiment. (The neutrino flux incident to the detector in the Le Bugey experiment is almost an order of magnitude higher than that of the Gösgen experiment.) The statistical accuracy of the measured spectra is 2 % / 500 keV and 4 % / 500 keV at positions 1 and 2, respectively. The spectrum of the ratio (position I) / (position II) is shown in fig. 8. The

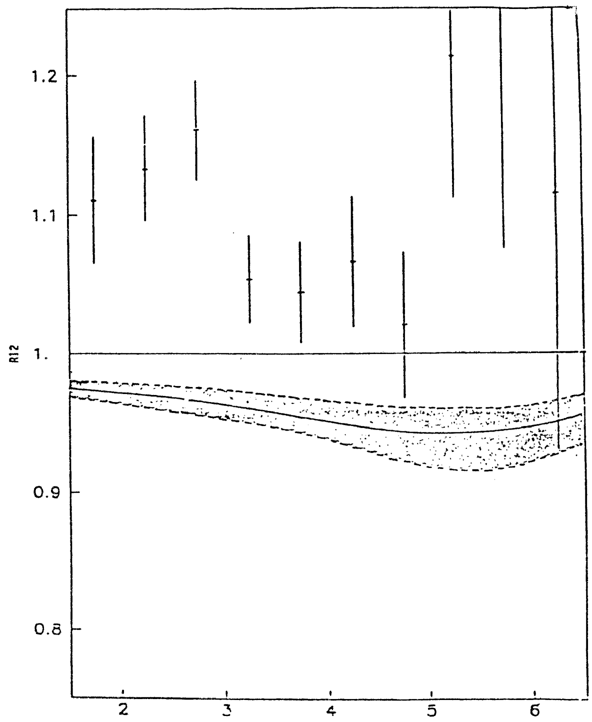

Fig. 8

measured values are much higher than the values predicted by the theory. The systematic errors (which are the smallest in the case of a two distance experiment) are included in the theoretical calculations. The mean ratio integrated over the 1.5 - 6.5 MeV interval is

$$R = 1.102 \pm 0.014(\text{statist.}) \pm 0.028(\text{syst.}) \quad (3.13)$$

So, there is a 3σ-indication of the existence of ν-oscillations. The best fit obtained is

$$\Delta M^2 = 0.2 \ \text{eV}^2 \quad (3.14a)$$
$$\sin^2 2\theta = 0.25 \quad (3.14b)$$

In this experiment oscillations manifest themselves only in the change of the measured neutrino flux in the transition from position 1 to position 2 and not in the deviation of the shape of the spectrum from that expected in the case of the absence of oscillations.
It means that the reliability of the result as reflecting the presence of oscillations is determined to a great extent by the accuracy of determination of the acceptance of the detectors at positions 1 and 2. The latter does not seem to be a simple problem in a view of the peculiar geometry of the experiment. The detector at positions 1 and 2 view the active area of the reactor at different angles.
Fig. 9 shows the Gösgen- and the Le Bugey-results. The shaded area is allowed for both experiments and marks the range of possible ν-oscillation. More experiments are needed to check these results.

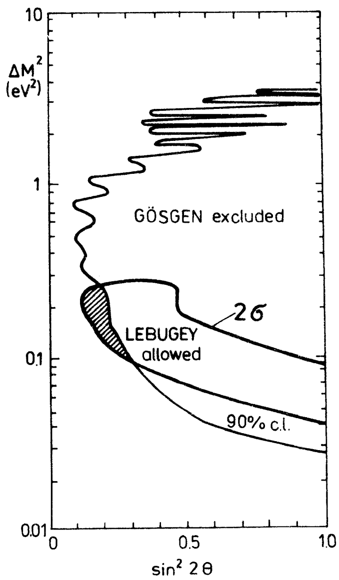

Fig. 9

3.4. ν-oscillations at accelerators

There are appearence and disappearence experiments from CERN and CCFR with recent results (cf. /27/).

Table 4

	E_ν [GeV]	D_1[m]	D_2[m]	process
CDHS	3	130	900	$\nu_\mu \to \nu_x$
BEBC	2.5	133	950	$\nu_\mu \to \nu_e$
CHARM	1.5	130	930	$\nu_\mu \to \nu_e$; $\nu_\mu \to \nu_x$
CCFR	40...230	700	1100	$\bar\nu_\mu \to \bar\nu_x$
IHEP Serpukhov	2...30		150	$\nu_\mu \to \nu_x$

Table 4 summarizes the neutrino-energy, the detector distances D_1, D_2 and the processes investigated in the respective experiments. Figures 10 and 11 show the limits on ΔM^2 and $\sin^2 2\theta$ obtained in these experiments.

DISAPPEARENCE EXPERIMENTS

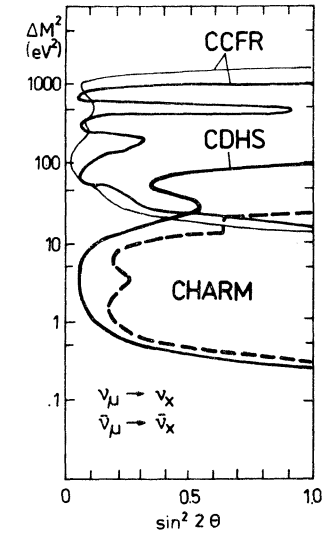

Fig. 10

APPEARENCE EXPERIMENTS

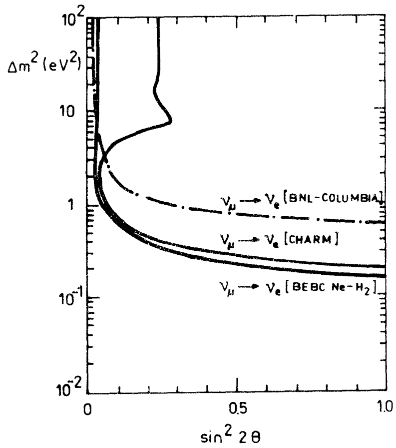

Fig. 11

3.5. Beam dump experiments and ν-oscillation

For some years the measurement of prompt electron- and muon neutrinos from CERN beam dumps indicated a ratio $R(\# \nu_e / \# \nu_\mu)$ less than unity. It could be interpreted as evidence for ν-oscillations. But more recent results from CERN and the data at Fermilab gave a large range of measured values which have prevented a definite conclusion so far.

Table 5 (cf. ref. /28/)

Experiments	Distance [m]	$R(\# \nu_e / \# \nu_\mu)$
CERN (77-79)	900	0.57 ± 0.09
CERN (82)	450	0.74 ± 0.10
FNAL (81-82)	60	$1.09 \pm 0.09 \pm 0.10$

The statistical analysis of all data shows that the $\nu_e \rightarrow \nu_x$ oscillation hypothesis (at constant ν_μ- flux) has the probability 0.35 whereas no oscillation gives 2.10^{-4}. The best fit yields:

$$\Delta M^2 = 350 \pm 40 \qquad (3.15a)$$

$$\sin^2 2\theta = 0.32^{+0.18}_{-0.08} \qquad (3.15b)$$

The $\sin^2 2\theta$ value is different from that obtained in the Gösgen experiment by 2σ.

4. The double β-decay and other lepton-number violating processes

4.1. The double β-decay

A well known classical weak process is the β-decay in which, as a result of the four fermion interaction $(n\bar{p})(e\bar{\nu})$, the nuclear transition with the emission of an electron and an antineutrino takes place

$$A(Z) \longrightarrow A(Z+1) + e^- + \bar{\nu} \qquad (4.1)$$

According to the same law, provided that the transition energy of the appropiate pair of nuclei is high enough and there is no single β-transition, the process with the emission of two electrons and two antineutrinos - the $(2\beta, 2\bar{\nu})$ decay - has to take place. This is a second order process in the standard theory.

$$B(Z) \longrightarrow B(Z+2) + 2e^- + 2\bar{\nu} \qquad (4.2)$$

The $(2\beta, 2\bar{\nu})$-decay as a weak process itself does not give new information as compared with the ordinary β-decay. However, another type of double β-decay is of interest. Because the neutrino is a neutral particle, neutrino and antineutrino may be identical. The particles of this kind are called Majorana particles. If the neutrino is a Majorana particle then the process (4.2) can take place without emission of neutrinos (ν and $\bar{\nu}$ annihilate virtually because $\nu \equiv \bar{\nu}$).

$$B(Z) \longrightarrow B(Z+2) + 2e^- \qquad (4.3)$$

This process which violates lepton number $(\Delta L = 2)$ is directly connected with the problem of massive neutrinos we are discussing in this talk. Let us line out this in more detail. In the framework of the standard V-A theory of weak interaction all fermions ($(n\bar{p})(e\bar{\nu})$ in our case) are two-component particles and the weak current is **left**-handed. It means that all particles are polarized in the direction opposite to the direction of their motion. The polarization is equal to their velocity (v/c). If the neutrino mass is equal to zero (e.g. the two component neutrino of Weyl-type) then it is fully polarized (v/c = 1) and both neutrino and antineutrino have the same helicity and annihilation is impossible (ν (left-handed) = $\bar{\nu}$ (right-handed)). The neutrinoless double β-decay (4.3) is thus forbidden. In the case when the neutrino mass is not zero and, therefore, the neutrino velocity is not equal to the velocity of light, then one of the neutrinos may have the inverse polarization (with the probability $\sim m_\nu/E$). The annihilation becomes possible and the neutrinoless double β-decay (4.3) has to take place. Its probability will depend on the neutrino mass. Hence, the experimental detection of the neutrinoless double β-decay would give a direct evidence for the existence of a massive Majorana neutrino. The last statement is valid if the interaction is described by the standard V-A theory. However, the (2β, 0ν)-decay may also be due to a V+A interaction with right-handed current. In principle a good experiment giving information about kinematical parameters of the produced particles in the case of a positive result offers the possibility to determine the mechanism of the (2β, 0ν)-decay. Firstly, the angular distribution is different in both cases and, secondly, the $0^+ - 2^+$ transition is possible only through right-handed currents whereas the $0^+ - 0^+$ transition is possible in both mechanisms.

Two classes of experiments exist:

The passive (cumulative) experiments are geochemical experiments in which daughter nuclei are accumulated in a sample during a long geological period. A geochemical experiment is very sensitive but it does not distinguish between (2β, 2ν)- and (2β, 0ν)-decays. The main phase of the experiment is made by nature itself.

Active (laboratory) experiments are counter- or even Track-finding experiments in which every 2β-decay event is detected and some kinematical characteristics are measured. In these experiments it is possible to distinguish between (2β, 2ν)- and (2β, 0ν)-decays and also between $0^+ - 0^+$ and $0^+ - 2^+$ transitions.

During the last 30 years a lot of geochemical studies of the half-width of the transitions $Se^{82} \rightarrow Kr^{82}$, $Te^{130} \rightarrow Xe^{130}$ were made. The positive results obtained in them agree within a factor of 5 with each other and give the mean value (Kirsten /29/)

$$T_{1/2}(Te^{130} \rightarrow Xe^{130}) = (2.55 \pm .2)\ 10^{21} \text{ years} \quad (1950 - 1982) \qquad (4.4a)$$

$$T_{1/2}(Se^{82} \rightarrow Kr^{82}) = (1.45 \pm 15)\ 10^{20} \text{ years} \quad (1969 - 1971) \qquad (4.4b)$$

It is most likely that the 2β-decay does exist. The detection of 2β-transition in geochemical experiments indicates only the existence of the (2β, 2ν)-decay at the energies of 2β transitions $\sim 5m_e$, because in Te^{130} and Se^{82} the probalility of the (2β, 2ν)-process is much higher than that of the (2β, 0ν)-decay. The question about the existence of the neutrinoless 2β-decay is still not answered.

However, some indirect indications of the neutrinoless 2β-decay can be in principle obtained from geochemical studies. Following the well known suggestion by B. Pontecorvo /30/ one can measure the ratio of lifetimes $R = T_{1/2}(Te^{128}) / T_{1/2}(Te^{130})$. The measurement of the ratio of lifetimes of close isotopes has many advantages. Firstly, it is quasifree fo systematic errors which is characteristical for the geochemical method (determination of the sample age, estimation of daughter nuclei conservation etc.), and, secondly, it is more or less independent of theoretical uncertainties in the calculation of matrix elements. Thus, the ratio R is only dependent on a well determined kinematical factor. Since the energy of the 2β-transition in Te^{130} is 3 times higher than in Te^{128} and the phase spaces of (2β, 2ν)- and (2β, 0ν)-decays differ radically (as Q^6) the ratio R is sensitive to the decay mode as

$$R = 2 \cdot 10^{-4} \text{ for } (2\beta,\ 2\nu) \qquad (4.5a)$$

and

$$R = 4 \cdot 10^{-2} \text{ for } (2\beta,\ 0\nu) \qquad (4.5b)$$

Unfortunately, the experimental situation in the case of the measurements made by this method is ambiguous.

According to the measurements by Hennecke et al. /31/ (1975-78)

$$R = (6.37 \pm .4)\ 10^{-4} \qquad (4.6)$$

which suggests the existence of the (2β, 0ν)-decay as a consequence of a Majorana mass M_ν = 40 eV /32/ or due to right-handed

currents $\eta = 5\cdot10^{-5}$.
However, in the experiment by Kirsten et al. (1982)

$$R = (1.03\pm1.13)\ 10^4 \quad (4.7)$$

was obtained which is consitent with the absence of the neutrinoless 2β-decay. From this the limits are /34/

$$M \leq 5.6 \text{ eV} \quad \text{or} \quad \eta \leq 2.4\cdot10^{-5} \quad (4.8)$$

To resolve the problems of the 2β-decay new (especially 'active'- counter- or track-) experiments have to be carried out.
A great number of counter experiments devoted to the $(2\beta, 0\nu)$-decay to search in different elements (Cu^{48}, Ge^{76}, Se^{82}, Mo^{100}, Te^{130} /35/, Nd^{150} /36/) were made.
None of these experiments has detected the $(2\beta, 0\nu)$-decay. The most stringent limit on the neutrinoless 2β-decay is set by the Milano group /37/ for Ge^{76}. Two crystals of Ge(Li) (7.76 % Ge^{76}) served as a Ge^{76}-source and detector. The active volume of the detectors was 120 and 150 cm^3 resp. The detectors were surrounded by the passive shielding made of high purity materials (3 times distilled mercury, oxygen-free copper, lead of low radioactivity). The set up was situated under the Mont-Blanc massive (5000 mWE).
The only measured parameter was the energy of the 2β-decay. The energy resolution was $\simeq$ 2.0 keV. The limit on the half lifetime set after 11000 hours of exposition is

$$T_{1/2} \gtrsim 10^{23} \text{ years} \quad (4.9a)$$

Consequently the limit on the neutrino mass is

$$M_\nu < 4 \text{ eV} \quad (4.9b)$$

if the transition-matrix element given in /35/ is used.
The limit on right-handed currents is

$$\eta < 10^{-5} \quad (4.9c)$$

One has to point out, however, that the determination of the limit on the neutrino mass derived from the measured upper limit of the $(2\beta, 0\nu)$-decay probability is connected with the uncertainty of the calculation of the nuclear matrix elements. In different models these calculations give results which differ from one to the other by a factor of 10 or even more.
The theoretical problem of calculation of the matrix elements can be resolved experimentally through the measurement in laboratory experiments on the standard $(2\beta, 2\nu)$-decay using different elements. Presently there is only one experiment by Moe and Lowenthal /38/. They claim the detection of the $(2\beta, 2\nu)$-decay of Se^{82}. The half lifetime $T_{1/2} = (1\pm.4)\ 10^{19}$ years turned out, however, to be an order of magnitude smaller than that measured by the geochemical method ($T_{1/2} = 1.45\pm.15)\cdot10^{20}$ years) though it is in good agreement with the theoretical calcualtions by Haxton /34/.
The Pomansky-group /36/ measured $T_{1/2}$ of Nd^{150} for different channels.

i) $T_{1/2}(2\nu) > 1.3\ 10^{19}$ yr (95 % c.l.) (4.10a)

ii) $T_{1/2}(0\nu, M_\nu \neq 0) > 1.2\ 10^{21}$ yr (95 % c.l.) (4.10b)

iii) $T_{1/2}(0\nu, \lambda_{RHC} \neq 0) > 0.8\ 10^{21}$ yr (95 % c.l.) (4.10c)

The extracted upper limit for the nuclear matrix element $1/2\,|M_{GT}|_{exp}$ is

$$1/2\ |M_{GT}|_{exp} < 0.25 \quad (4.11a)$$

which is much smaller than that by Haxton /34/

$$1/2\ |M_{GT}|^{HAXTON} \simeq 1.4 \quad (4.11b)$$

It is in agreement with the geochemical experiment. In ref. /36/ the limits

$$\langle M \rangle_{2\beta} \leq 29 \text{ eV} \quad (4.12)$$

and

$$\lambda_{RHC} < 2.2\ 10^{-4} \quad (4.13)$$

were obtained independently from the calculation of $|M_{GT}|$ from the ratios of the lifetimes (4.10a,b) and (4.10a,c).
Neclecting the present theoretical and experimental uncertainties the present limit on $(2\beta, 0\nu)$ limits $\langle M \rangle_{2\beta}$

$$\langle M \rangle_{2\beta} \leq 5 \ldots 10 \text{ eV} \quad (4.14)$$

Is the result in conflict with the ITEP-result $\langle M \rangle_\beta > 20$ eV?
The $(\langle M \rangle_{2\beta} - \langle M \rangle_\beta)$-discrepancy is currently discussed by many authors /35,39/. What does this 'conflict' mean, if the tendency mentioned reflects the reality? As we have pointed out many times, in the general case the massive electron neutrino is a linear superposition of different neutrino-mass eigen states. This leads to different mixings of masses and results in different effective masses for tritium- and $(2\beta, 0\nu)$-decay experiments. The respective masses are

$$\langle M \rangle_\beta = \Big(\sum_i |U_{Li}|^2 M_i^2\Big)^{1/2} = \big(\overline{M^2}\big)^{1/2} \text{ for tritium /2,4/} \quad (4.15)$$

$$\langle M \rangle_{\beta\beta} = \sum_i |U_{Li}|^2 M_i = \overline{M} \text{ for the } 2\beta\text{-decay} \quad (4.16)$$

From this it follows that in the most general case of mixing $\langle M \rangle_\beta$ is not equal, but is larger or equal to $\langle M \rangle_{\beta\beta}$.

In equation (4.15) all terms are positive ($\sim M^2$) whereas in equ. (4.16) they can have different signs due to the different CP - parity of the mass eigen states. Wolfenstein /40/ was the first who suggested the possibility of compensation in 2β-decay. In the simplest two-mass case the expressions (4.15) and (4.16) are reduced to

$$\langle M \rangle_{\beta} = (\cos^2\theta\ M_1^2 + \sin^2\theta\ M_2^2)^{1/2} \qquad (4.17)$$

$$\langle M \rangle_{\beta\beta} = \cos^2\theta\ M_1 \pm \sin^2\theta\ M_2^2 \qquad (4.18)$$

In the case when the sign of the second term is negative the compensation of the effective mass takes place for the 2β-decay. Let us consider the two extreme cases consistent with neutrino oscillation experiments.

i) $\Delta M^2 \leq 0.016$ eV (Gösgen), $\sin^2 2\theta \simeq 1$, $\theta \simeq \pi/4$ then $\langle M \rangle_{\beta} \simeq M_1 (M_1 \simeq M_2 = 30$ eV from the tritium β-decay, ITEP); $\langle M \rangle_{2\beta} \simeq M_1(\cos^2\theta - \sin^2\theta) \simeq 0$, i.e. full compensation.

ii) ΔM^2 - is large, $\sin^2 2\theta \sim 0.16$, $\theta \leq 0.04$, the full compensation of $\langle M \rangle_{2\beta}$ will also occur under the condition that $tg^2\theta \simeq M_1/M_2$.

Thus, the existence of the subdominant mass $M_2 \simeq M_1/tg^2\theta$, i.e. $M_2 \gtrsim 500$ eV (assuming $M_\nu = 30$ eV and $\theta \leq 0.04$) can give the full compensation of the effective mass which determines the probability of the 2β-decay. Presumably the sign of mass eigen states should be different.

As for the tritium experiment it is sensitive to both masses if the difference of the dominant and subdominant masses is large.

Concerning the limits on $M_2 > 10$ MeV Leung and Petcov /41/ showed that destructive interference in $\langle M \rangle_{2\beta}$ can occur only if the heavy neutrino mass is situated in the ranges 20 MeV $\leq M_\nu \leq$ 30 MeV, 60 MeV $\leq M_\nu \leq$ 140 MeV, and 170 MeV $\leq M_\nu \leq$ 200 MeV.

The discussed mechanism corresponds to the case of Majorana neutrinos. One should not conclude from the fact that the 2β-decay was not detected that the neutrino is a Dirac particle as some authors do /42/. This argument is valid only in the case of total absence of mixing.

However, the experimental situation with both 2β-decay (unresolved experimental and theoretical difficulties) and the tritium β-decay (the only positive result of the ITEP-group) is not clear enough to make the far reaching physical conclusions including the above arguments about compensation. The purpose of these arguments was to show that the $\langle M \rangle_{\beta}$ - $\langle M \rangle_{2\beta}$ - 'conflict', if it exists, should not be considered as a contradiction.

4.2. Other lepton number violating processes

In the beginning of the sixties the experiments on the ($\mu \to e\gamma$), ($\mu \to 3e$)-decay gave negative results at the level of 10^{-6}. These results have promoted the idea of existence of different kinds of neutrinos, ν_μ and ν_e, which was discussed extensively those days.

In many models currently discussed the flavour is a bad quantum number, and once again we come back to the flavour violation search, but at a modern level.

For example, the SINDRUM group at SIN /43/ presented remarkable data on the ($\mu \to 3e$)-decay search. The experiment was made at the magnetic spectrometer SINDRUM. About 10^{13} μ^+-particles were stopped in a target. 7742 events of the allowed ($\mu \to 3e2\nu$)-decay were detected. No $\mu \to 3e$ event has been seen. From this the ratio

$$R(\mu \to 3e) = \frac{\Gamma(\mu \to 3e)}{\Gamma(\mu \to e\nu\nu)} < 2.4\ 10^{-12} \quad (90\ \%\ \text{c.l.}) \qquad (4.19)$$

is derived.

Mischke et al. /44/ (Crystal Ball) determined the limits on $\mu \to 3e$, $\mu \to e\gamma$ and $\mu \to e2\gamma$ at the level of 10^{-10}.

The search for flavour violation was carried out at TRIUMF /45/ by investigating of the reaction

$$\mu\ Ti \to e\ Ti \qquad (4.20)$$

The process was not found at the level of $< 3 \cdot 10^{-11}$ (90 % c.l.) as compared to the normal μ-capture.

5. Conclusions, present status and perspectives

The new measurement at ITEP using the considerably improved apparatus confirmed the indication of the existence of a non-zero mass.

The main problem is still the uncertainty connected with the final state spectrum of He^{3+} in the molecular environment. This problem can be resolved in the $T\beta$-decay experiments which are made and planned to be made in the nearest future /46-49/.In these experiments a resolution of 2 - 10 eV can be obtained. The authors ref. /46/ proposed the use of atomic tritium. Boyd et al. /49/ use a cryogenic T-source.

It makes one to believe that the question about the neutrino mass at the level claimed by ITEP will be answered in the coming 1 - 2 years.

If the neutrino has a mass, the neutrinoless double β-decay can help to decide the question whether the neutrino is of Majorana- or Dirac-type. At present the neutrinoless double β-decay has not yet been seen. $\langle M \rangle_{\beta\beta}$ is limited by

$$\langle M \rangle_{\beta\beta} < 4 - 10 \text{ eV}$$

The planned experiments of the new generation are a step forward both quantitatively /50,51/ and qualitatively and have an order of magnitude higher sensitivity. The TPC-based 'total information' experiments have also to be counted to the qualitatively new experiments. Among them the most promising experiment is the 'live target' /52/, where the 2β-radioactive material is at the same time the working substance and a track detector.

The advantage of a track experiment is also the possibility to investigate both types of 2β-decays. This gives the possibility to resolve the problem of the nuclear matrix elements experimentally.

What can be said about the mass eigen states of the neutrinos? From the limits on the neutrino-oscillation parameters two scenarios emerge.

Case A. $\sin^2 2\theta \cong 1$, $\Delta M^2 \leq 0.02$ eV, and $M_1 \sim M_2 \sim M_3$ ... Let $\langle M \rangle_\beta \simeq M_1$. Then $\langle M \rangle_{2\beta}$ can be very small, $\langle M \rangle_{2\beta} \lesssim \Delta M^2/2M_1$ $\sim 3\ 10^{-4}$, if $M_1 \sim 30$ eV.

Case B. $\sin^2 2\theta < 0.2$, ΔM^2 large, $M_{\nu_e} \simeq M_1$, $M_{\nu_\mu} \simeq M_2$, $M_{\nu_\tau} \simeq M_3$, ...

i) if there is a direct hierarchy $M_1 < M_2 < M_3$ ..., compensation in the $(2\beta, 0\nu)$-decay is possible. If $M_1/M_2 = tg\theta$, $M_1 \simeq 30$ eV then M_2 should be larger than 500 eV. In this case the ν_H-search experiments are favourable.

ii) if there is a reverse hierarchy /53/ ΔM^2 has a limit $\Delta M^2_{lim} \cong M_1^2 (M_2 \sim M_3 \sim ... \approx 0)$. The oscillation experiments for $\Delta M^2 \sim 1000$ eV^2 are favourable and $\langle M \rangle_\beta \sim M_1$, $\langle M \rangle_{2\beta} \sim M_1$; a compensation is impossible.

The experimentum crucis to choose between case A and case B is an experiment on solar neutrinos which uses Ga or In for the neutrino detection. Cosmic neutrino experiments using the earth-diameter as oscillation length which are sensitive to $\Delta M^2 \gtrsim 10^{-4}$ eV^2 are important.

I want to end these conclusions mentioning an interesting idea which concerns the puzzle of solar neutrinos.

Bilenkii and Pontecorvo /54/ pointed out that one positive result of an oscillation experiment which gives small mixing (i.e. the confirmation of the Le Bugey result) does not definitely mean that the solar neutrino paradox does no longer exists. If from N-kinds of neutrinos (N-m) are mass degenerate (large mixing angles) and m have different masses (small mixing angles), then the solar neutrino experiment (of Davis or a furture experiment) will show the reduction of the flux $\sim 1/(N-m)$. That is why in the case of m = 1 and N = 3 the solar experiment will show a considerable reduction of the flux (1/2 instead of 1/3, the difference one would not detect even in the future experiments). If then (generalizing /54/)one assumes N = 6, (transitions to sterile neutrinos) the oscillation of solar neutrinos will be the total one even at m = 3.

The investigations concerning the neutrino mass problem provided us with various limits on the range of possible neutrino masses and mixing angles. However, the question whether or not neutrinos are massive is still unanswered.

It is clear, how to proceed.

i) the ITEP-result has to be checked

ii) further solar neutrino searches have to be carried out,

iii) the 2β-decay must be further searched for,

iv) further oscillation experiments are necessary and the Le Bugey result has to be checked,

v) the search for heavy neutrinos must be continued at low (in the β-decay) and at large masses (W- and Z-decays, Tevatron experiments).

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DISCUSSION

G.MARX

Would it be technically possible to use a different chemical compound in the ITEP-experiment?

V.LUBIMOV

We plan to measure with another kind of a chemical compound in future.

H.TERAZAWA

Just before I left Tokyo my colleague, Dr. Oshima, told me that he had reached the point where he can now measure the ν_e-mass with the accuracy of 10 eV by improving both the tritium-source and the β-spectrometer at our Institute of Nuclear Study, University of Tokyo.

G.WACHSMUTH

Concerning indications of ν-oscillations in beam-dump experiments ($\nu_e/\nu_\mu \sim 1/2$): Two CERN beam-dump experiments (BEBC,CDHS) have reported to this conference showing that prompt ν_e- and ν_μ- fluxes are compatible with being equal. Especially, a value of $\nu_e/\nu_\mu = 1/2$ is excluded by the BEBC-result by 4 standard deviations. Thus, there seems to be no reason to invoke ν -oscillations to explain results of beam-dump experiments.

V. LUBIMOV

I feel personally that we need further experiments to clarify the situation.