THE NEUTRINO MASS FROM THE TRITIUM BETA-SPECTRUM IN A VALINE
(ITEP - 1984)

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The results of a new set of measurements of the β-spectrum of tritium in a valine molecule are given. The measurements were carried out at the ITEP magneto-electrostatic spectrometer. The principle of its operation and the conditions of measurement were described in /1/. For the calibration 29 conversion lines of ^{169}Yb were used applying the data on γ-transition energies given in ref. /2/. We estimate the accuracy of the absolute calibration to be 5eV.

The total response function (TRF) depends on

1) the optical line (OL) of the spectrometer which represents the probability for the electron to pass through the substance of the working-source without interactions,
2) the spectrum of ionization (SI) of the electron interacting in the source,
3) the backward-scattering effect (BSE).

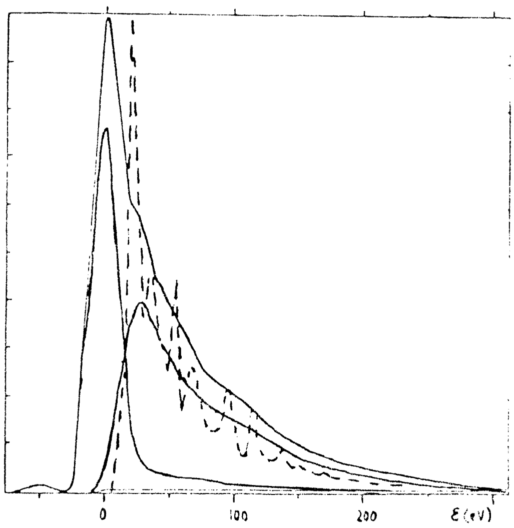

Fig.1: The total resolution function(TRF). The contributions of the optical resolution function (ORF),the ionization loss spectrum (ILS)(and ILS convoluted with ORF) and the backward scattering spectrum.

In the previous analysis presented at the Brighton-Conference /1/ only the symmetrical part of the OL was used.This proposition was safe because it could be used to reduce the mass parameter. However, χ^2 was rather bad (χ^2=521/296).

We investigated the OL searching for conversion lines (^{169}Tm) with different energies. The conversion line is not a monoline. There are some contributions of the excitation-spectrum due to the "shake-off"-effect after the emission of the conversion electron. This effect was investigated using the lines with small energies (decc. mode) where the width of the OL is relatively small. In fig. 2 the conversion-electron lines (E_{M1}=18.4 keV (accel. mode), E_f=22keV;E_L=10.6keV, E_f=14keV) deconvoluted with the Lorentzian of the intrinsic width Γ_{M1}= 14.7eV, Γ_{L1}=5eV are shown.The difference in the range of the"tails" is seen.

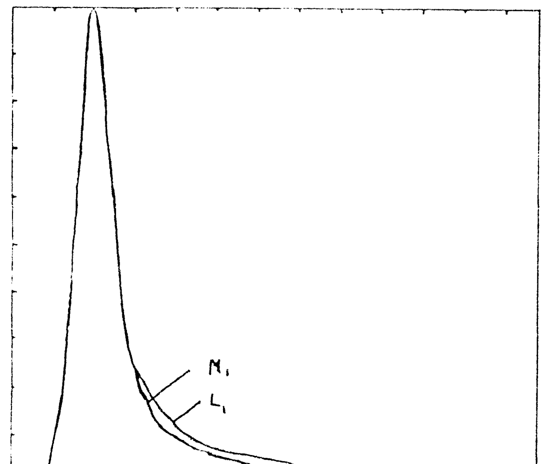

Fig.2

After subtraction of the "shake-off" - spectrum the OL (fig.3) has the uniform shape for any line in the energy interval: 4.5-56 keV. This shape of the OL was used in the analysis.

The procedure of the fitting of the experimental data was in principle the same as in

/1/.

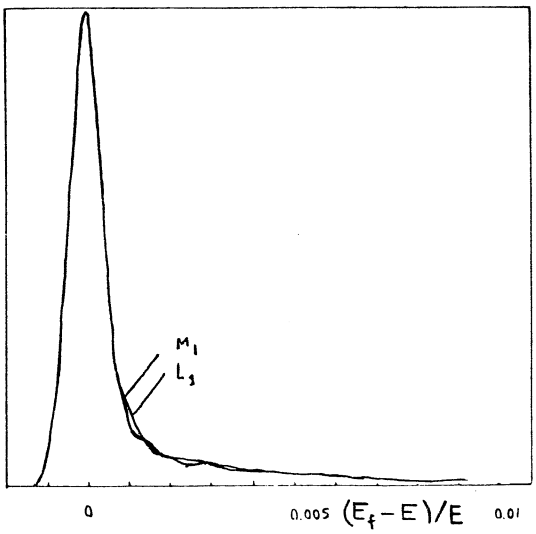

Fig.3.

The fit-parameters are M_ν^2, E_0, and α. In this work we use the result of the most precise calculations /3/ of the final state spectrum(FSS) of T-valine in which the overlap of Hartree-Fock-configurations (electron correlations) is taken into account. The calculated spectrum of the FSS used in the fit-procedure has 51 levels. Apart from that the analysis was made for the model of atomic FSS and for a single-level ("nucleus") model. The experimental data in the range close to E_0 are shown in fig.4 as Kurie-plots. The result of the total fit with the M_ν=0 - hypothesis is also shown. In fig.5 the energy dependence of $(S^{exp,fit}(E)-S^{fit}(E,M_\nu=0))/\sigma^{exp}(E)$ is shown in the whole range of the measurements. As in fig.4 the statistics at every energy point is a sum over all detector channels and over all runs. In table 1 the results of a single mass fit for three sources using valine FSS are given. The errors given in square brackets take into account the statistical variations of all functions which enter the fit-expression, namely the weights of the OL,SI,BSE,the variation of the "curvature" of the β-spectrum etc. For the mean values the total errors are given. It is worth to mention that the introduction of the correct TRF considerably reduces χ^2 as compared with/1/. The important point is that the values of the parameters are stable if the energy range ΔE of data included in the fit-procedure is reduced. In a short range the effect of the"curvature" and an uncertainty of the long tail of the TRF is very small. In table 2 the average results for different FSS's are given. The value of the physical limit of the β-spectrum (E_0-M_ν) is model-independent within the statistical accuracy. The second error is due to the uncertainty of the calibration. The mass difference of neutral He and T-atoms was calculated using the value E_0.

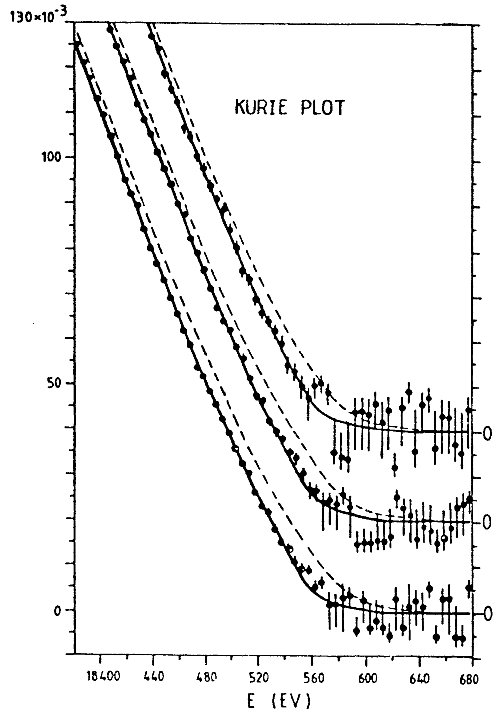

Fig.4:Kurie-plots of the exp.data close to E_0 with 3 sources.The lines are the total best fits with the valine FSS.The dashed lines are fits with M_ν= 0.

The value of M_{T-He^3} disagrees with the value 18573±7eV from /4/. The recent result from the ICR-spectrometer/5/ which has a resolution 150-times better than that achieved in /4/ is M_{T-He^3} =18599±3eV in good agreement with our value for the valine FSS. The results given in tables 1 and 2 show that according to the χ^2-test the experimental data are in agreement with the single-mass representation of the β-spectrum. To determine the upper limit of the mass for subdominantly coupled neutrinos the fit which uses the model of the β-spectrum $S(M_x, |U_{ex}|^2, M_1, E_0, \alpha)$ was carried out. M_x was fixed in the range of values 0-1.5keV. In fig.6 the values $|U_{ex}|^2$ vs. M_x for the 90% c.l. are shown. M_1 and E_0 do not differ much from values which are obtained with the single-mass fit.

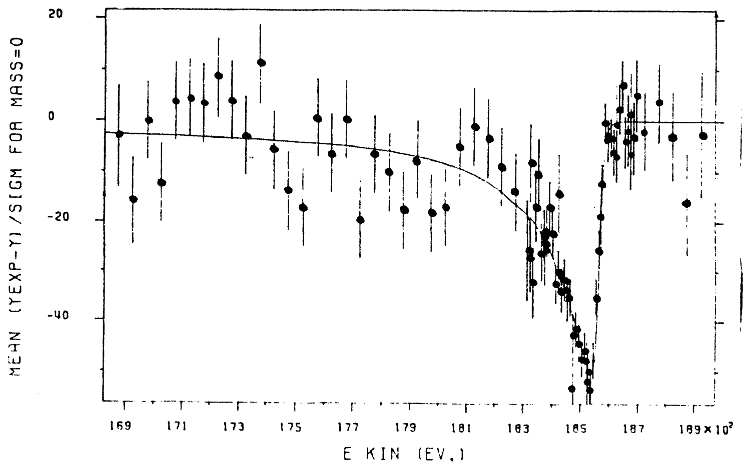

Fig.5 : The difference between the experimental (or best fit) data and the theoretical curve $M_\nu=0$ normalized to the experimental error.

As one can see from table 2 the lower limit for M_ν (δ-function treated as FSS in the fit-procedure) is incompatible with $M_\nu = 0$. So, we have a model-independent limit

$$M_\nu > 9 \text{ eV} \quad (90\ \%\ \text{c.l.})$$

But the SF as FSS is rather formal. A more realistic result is

$$20 < M_\nu < 45 \text{ eV} .$$

Table 1

Source	R 1	R 2	R 3	Avarage value
		ΔE=1680 eV		
M_ν^2 eV²	1364.0±63 [260]	1174. ±81 [180]	1146. ±140 [200]	1215± 130
E_0 eV	18585.2±.3 [3]	18584.1±.3 [2.5]	18583.5±.5 [2.7]	18584.2±1.6
χ^2/N	317/303	523/509	471/508	
		ΔE= 330 eV		
M_ν^2 eV²	1384. ±175 [170]	1416. ±156 [120]	1261. ±283 [130]	1375± 140
E_0 eV	18585.2±1.2 [2.4]	18585.5±.9 [2.]	18584.4±1.5 [2.2]	18585.1±1.4
χ^2/N	184/165	266/318	294/316	

Table 2

FSS	Valine	Atom	δ-Fct. ("Nucleus")
M_ν^2 eV²	1215. ±130	954. ±95	190. ± 80
M_ν eV	34.8 ±1.9	30.9 $^{+1.5}_{-1.6}$	13.8 $^{+2.5}_{-3.5}$
E_0 eV	18584.2±1.6	18580.5 ±1.3	18567.4 ±1.
E_0-M_ν eV	18549.4±2.1±5	18549.6±1.9±5	18553.4±2.7±5
M_{T-He} eV	18603.6±6	18608.1±6	18586.8±6

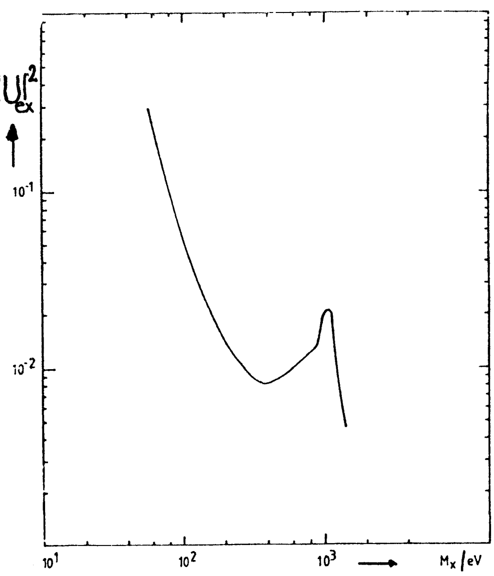

Fig.6 : $|U_{ex}|^2$ vs. M_x (90 % c. l.)

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SEARCH FOR HEAVY NEUTRINOS IN KAON DECAY

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The lepton momentum spectrum in a two-body decay of a pseudoscalar meson is expected to show satellite lines of weakly coupled neutrinos at different momenta, as proposed by Shrock /1/. This method covers quite a wide range of neutrino masses with a very high sensitivity to small mixing ratios. The neutrino ν_i here can be either the τ neutrino or any other unknown particle.

In 1981 we made a dedicated experiment (E89) at KEK to search for heavy neutrinos in the decay of K^+ /2/ and in 1983 we carried out an improved experiment. We achieved higher momentum resolution, more effective background suppression and better particle identification. Here we present new results from this experiment (E104).

We obtained a new constraint of $|U_{\mu i}|^2$ versus $m(\nu_i)$, as shown in Fig.1. Because of the better resolution the lower end of the neutrino mass was reduced to 40 MeV. In Fig.1 are also shown other upper limits. One is from $\pi^+ \to \mu^+\nu_i$ done /3/ at SIN. Another comes from the $^3He(\mu^-,\nu_i)$ reaction /4/.

For the first time we obtained e^+ spectrum with rejection of the three body decay mode. Hitherto only the $e^+\nu_e$ peak region of 247 MeV/c was known /5/. From the analysis of the spectrum we obtained a new constraint on $|U_{ei}|^2$ in a wide mass range between 140 and 350 MeV, as shown in Fig.2. The $\pi^+ \to e^+\nu_i$ experiment /6/ at TRIUMF covers a complementary mass region. A recent experiment to search for neutrino decays at CERN /7/ gave a new constraint on $|U_{ei}|^2$, but the present experiment has yielded a one-order of magnitude better constraint. It should be noted that the deduction of $|U_{ei}|^2$ from the CERN experiment requires a model for heavy neutrino decay, while in the present experiment it is given purely kinematically.

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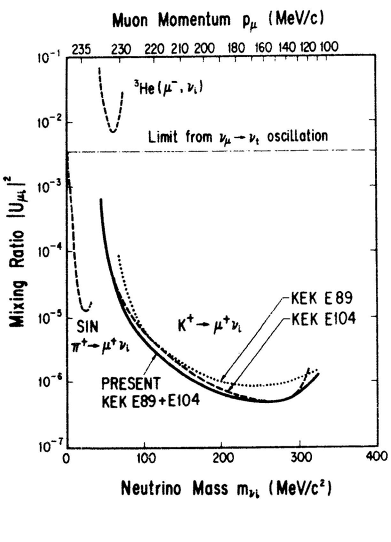

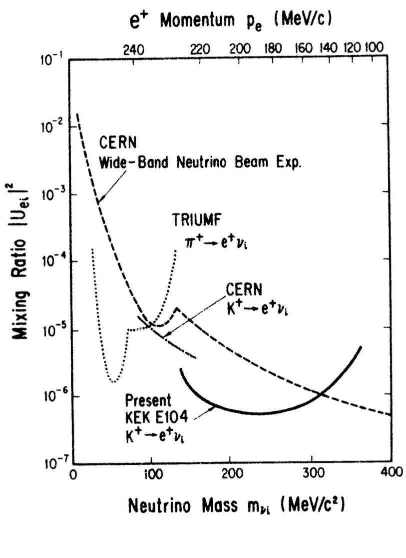

LIMITS ON LEPTON MIXING FROM SEARCHES FOR NEUTRINO DECAYS

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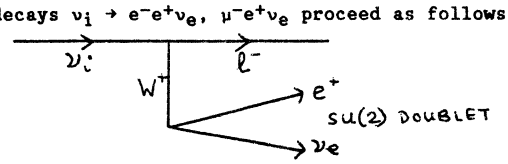
The latest limits on $|U_{ei}|^2$ and $|U_{\mu i}|^2$ derived from searches for the neutrino decays $\nu_i \to e^-e^+\nu_e$, $\mu^-e^+\nu_e$, are illustrated as full lines in figs 1 and 2, respectively. Limits derived from π, K decay, β and double β decay are also shown for comparison. I will briefly describe the ν decay limits, a full version of this talk may be found in ref. [1].

The decays $\nu_i \to e^-e^+\nu_e$, $\mu^-e^+\nu_e$ proceed as follows



with a lifetime scaled from muon decay as

$$\frac{1}{\tau_p} = \Gamma = \Gamma_{\mu \to e\nu\bar{\nu}} \cdot \left(\frac{m_\nu}{m_\mu}\right)^5 \cdot |U_{\ell i}|^2 .$$

Any conventional source of light ν's may contain heavy ν's produced through lepton mixing. Thus, in general, there is mixing in production of a heavy ν and mixing in its decay. Hence the limits are applicable to any neutral heavy lepton coupled to the flavour eigenstates.

(1) CHARM set limits on $|U_{ei}|^2$ for the mass range $10<m_\nu<490$ MeV by searching for the $\nu_i \to e^-e^+\nu_e$ decay of ν_i produced in π, K $\to e\nu_i$ decay in the Wide Band Beam (WBB) [2].

(2) CHARM have also set limits on $|U_{e3}|^2$ for the mass range $10 < m_\nu < 250$ MeV, by searching for the $\nu_3 \to e^-e^+\nu_e$ decay of ν_3 produced in $F \to \tau\nu_\tau$, $\tau \to \nu_\tau$ decay in the beam dump beam [2]. Since $|U_{\tau 3}|^2 \sim 1$, there is very little mixing in ν_3 production and stringent limits are obtained, despite combined uncertainties of a factor of 2-5 in the F production rate and the F branching ratio $F \to \tau\nu_\tau$. The published limit should be degraded by about a factor 2 to allow for the change in the measured mass of the F since last year, and the limit should be restricted to $m_\nu < 190$ MeV.

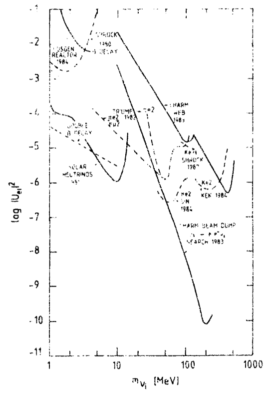
(3) BEBC have set a limit on $|U_{\mu 3}|^2$ for the mass range $110<m_\nu<190$ MeV, by searching for the $\nu_3 \to \mu^-e^+\nu_e$ decay of ν_3 produced in F decay in the beam dump beam [3]. This will be the dominant decay mode of ν_3 if $|U_{\mu 3}|^2 >> |U_{e3}|^2$. Hence such a measurement is necessary to limit the total lifetime of ν_3. This limit exploits the bubble chamber technique. Oppositely charged particle pairs originating from a clean vertex are clearly seen. Electron and muon identification is unnecessary since the requirement $m(\mu^-e^+) < 250$ MeV is sufficient to eliminate all candidates. The limit has been derived using the new F mass, 1.97 GeV, and an F production rate consistent with the limit on ν_τ production deduced from the NC/CC interaction rate in the same experiment [4].

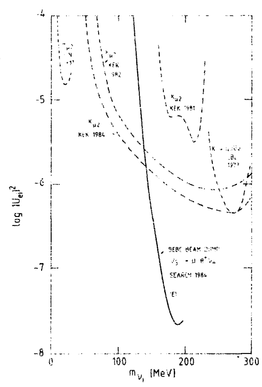
(4) Heavy neutrinos from the sun may decay into $e^-e^+\nu_e$ near the earth. The solar ν limit illustrated was derived on the assumption that all e^+ observed near earth are due to this source. Since cosmic ray spallation in interstellar space can explain the entire e^+ flux at earth, this limit is very conservative, even though the theoretical, rather than the measured, solar ν flux was used [5].

(5) If the Gosgen reacter is considered as a heavy ν source a limit on $|U_{ei}|^2$ may be deduced by comparing the e^-e^+ momentum spectrum expected from $\nu_i \to e^-e^+\nu_e$ decay with that observed [6].

In the future we may expect improvements in these limits: (a) the CHARM decay detector in the wide band beam should improve on the limits illustrated by a factor of 10, (b) CERN-PS-191 [7], a dedicated ν decay experiment, should further improve the limits by a factor of 5 $\to$ 10, (c) CHARM/BEBC should publish limits on $|U_{ei}|^2$, $|U_{\mu i}|^2$, in the mass range 10 MeV $< m_\nu <$ 1.8 GeV by searching for ν_i produced in D decay in the beam dump experiments [8].

Such limits may be combined with cosmological limits to constrain neutrino properties as predicted by popular unification schemes [9].





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UPPER LIMIT ON THE ν_τ MASS*

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This is an update of a result published[1] by the Mark II collaboration. Since the only change is a 50% increase in the data sample I will be brief.

We have collected data with a luminosity of 220 pb^{-1} with the Mark II detector at the e^+e^- storage ring PEP at a center of mass energy of 29 GeV. We looked for $\tau^+\tau^-$ events in which one of the τ's decayed to $3\pi^\pm\pi^0\nu_\tau$. The shape of the high mass end of the 4π mass spectrum from this decay is sensitive to the ν_τ mass.

The figure shows this mass spectrum. The portion above 1.5 GeV/c^2 was compared to the expected behavior for various ν_τ masses and a limit on m_{ν_τ} inferred. There are 22 events in the fit region. We assumed the spectrum is dominated by the ρ' resonance (this gives a less stringent limit than phase space).

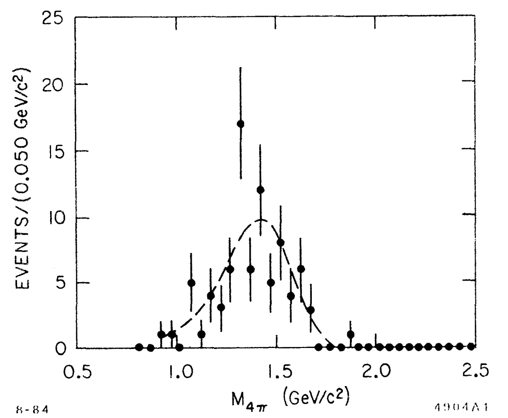

Fig. 1. The $3^\pm\pi^0$ invariant mass distribution for selected decays. The curve is for $m_{\nu_\tau} = 0$ and the assumption that the four pion state is dominated by the ρ' resonance.

After including uncertainties in background, resolution, and knowledge of the ρ' mass and width we obtain on upper limit on the ν_τ mass of 143 MeV/c^2 at the 95% CL.

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NEUTRINO OSCILLATIONS AT ACCELERATORS AND REACTORS

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- Abstract -

Recent experimental results on the determination of neutrino oscillation parameters are presented. While all accelerator experiments give only limits, the result of a recent reactor experiment can be possibly interpreted in terms of ν oscillations.

- Introduction -

Neutrino oscillations can take place if the weak interaction eigenstates are a mixture of mass eigenstates. Although mixing may occur between neutrinos of all types, all experiments have been interpreted in terms of a dominant two channel mixing.

The probability that starting with a source of ν_a neutrinos of energy E, at a distance L neutrinos ν_b will be present, is given by

$$P(\nu_a \rightarrow \nu_b) = \sin^2 2\vartheta \sin^2 (1.27\, \Delta m^2 L/E) \qquad (1)$$

Where:

$\Delta m^2 = |m1^2 - m2^2|$, m1, m2 being the masses of the two mass-eigenstates in eV.
L = source-detector distance (km or m)
E = neutrino energy (GeV or MeV)

Experiments which search for ν_b neutrinos at a distance L from a source of ν_a neutrinos are called APPEARENCE or EXCLUSIVE experiments. While the term $\sin^2 2\vartheta$ in (1) is the intrinsic amplitude of the oscillation, the value of Q = L/E gives the range of Δm^2 values accessible to a given experiment.

In fact the minimum detectable value of Δm^2 will be given (for $\sin^2 2\vartheta = 1$) by

$$\Delta m^2 = \frac{P(\nu_a - \nu_b)^{1/2}}{1.27\, Q}$$

while for large Δm^2 ($\Delta m^2 \gg 1/Q$) the oscillating term will average out at 0.5 integrating over the finite dimensions of the source, of the detector and over the energy spectrum of the neutrino beam. In these conditions, in the high mass limit, the value of $\sin^2 2\vartheta$ will be

$$\sin^2 2\vartheta = 2\, P(\nu_a \rightarrow \nu_b)$$

Exclusive experiments check mixing between two types of neutrinos. There are on the contrary experiments which look for the disappearence of a particular neutrino flavour.

These experiments, INCLUSIVE or DISAPPEARENCE experiments, are sensitive to the mixing of this type of neutrino to any other type (including unknown and sterile neutrinos).

In the disappearence experiments the knowledge of the absolute flux is needed for one detector experiments. To minimize systematic errors, two detectors can be used at distances D_1 and D_2 from the source.

The ratio

$$R = \frac{F(D_1)}{F(D_2)}$$

where $F(D_{1,2})$ is the measured flux at distances $D_{1,2}$ is then compared with the expected ratio Re. For a point source and two identical detectors Re = D_2^2/D_1^2 under the no oscillation hypothesis.

In experiments with two detectors there will be also a maximum detectable Δm^2. In fact for large Δm^2 the oscillation term will average to 0.5 in both detectors.

In the following we shall review the results obtained at accelerators both in disappearence and appearence experiments using ν_μ beams and disappearence experiments at reactors where $\bar{\nu}_e$ are available.

For these experiments in fact new results have been presented at this Conference. Recent reviews of the experimental situation can be found in /1/ and /2/.

- $\overset{(-)}{\nu}_\mu$ disappearence experiments -

In the last two years the experimental situation in this field has greatly improved and results of several experiments have been presented.

Two experiments have been performed at the low energy CERN PS neutrino beam (E ≅ 1.5 GeV) by the CDHS /3/ and CHARM /4/ collaborations.

Two detectors have been used and the ratio of fluxes is in agreement with the no oscillation hypothesis. Also in agreement with this hypothesis are the results obtained by the CCFR collaboration both for neutrinos /5/ and antineutrinos /6/ using the Fermilab NB beam. The average momentum of this experiment is much higher than the CERN one, so that the accessible Δm^2 range is extended to higher values. At this conference results have been presented also by an IHEP group at Serpukhov /7/. This is a single detector experiment in which the cross sections for quasi elastic ν_μ and $\bar{\nu}_\mu$ processes are compared with the predictions of the standard V-A theory. No deviations are found.

The results of the experiments mentioned above expressed in terms of limits on the oscillation parameters are shown in fig. 1 and given in table 1.

Combining all these results, the experimental situation can be summarized in the following way: for values of $\sin^2 2\vartheta$ larger than 0.1-0.2, Δm^2 values larger than 0.5 eV^2 are excluded. Two detector experiments forbid the region 0.5-1000 eV^2.

- $\nu_\mu \rightarrow \nu_e$ appearence experiments -

Two results on $\nu_\mu \rightarrow \nu_e$ have been presented at this Conference. The CHARM collaboration with the same set up used for the disappearence experiment has also performed a two detector appearence experiment.

The Athens-Padova-Pisa-Wisconsin /8/ collaboration has presented limits for the same process obtained from a BEBC exposure. BEBC filled with a N_e-H_2 mixture, has been exposed to the low energy CERN PS horn focused neutrino beam.

These limits are preliminary and correspond to one quarter of the final statystics.

Both the experiments give negative results and the obtained limits are given in table 2.

These limits and previous results of the BNL-Col. /9/ collaboration are shown in fig. 2.

- $\bar{\nu}_e$ reactor disappearence experiments -

Results of two experiments have been presented at this Conference. The Caltech-SIN-TUM /10/ group has presented results obtained at the Goesgen reactor and the Grenoble-LAPP /11/ group results obtained at Le Bugey. Both experiments measure, with similar apparatus, the rate of the reaction

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

at two distances.

The ratio of fluxes at the two distances is

Goesgen R = 1.01 ± 0.03 stat ± 0.02 syst
Le Bugey R = 1.102 ±0.014 stat ± 0.028 syst

While the Goesgen result is well in agreement with the expected value of 1, (no oscillation hypothesis) the Le Bugey result can be interpreted as evidence of oscillations. The contour of the allowed region in the plane $\sin^2 2\vartheta$, Δm^2 is given by curve a in fig.3. In the same figure the region to the right of curve b is excluded by the Goesgen results. As can be seen there is a part of the allowed region of the Le Bugey result that is not excluded by Goesgen. This region (dashed in fig. 3) is centered at $\Delta m^2 = .2$ eV^2 and $\sin^2 2\vartheta = .15$.

Curve c in fig. 3 gives the Goesgen result obtained comparing the e^+ spectra with the predicted ones. The limits are much more stringent but depend on the assumptions needed for the computation of the predicted positron spectrum.

- Conclusions -

In the last year new negative results have been obtained at accelerators for ν_μ neutrinos both in appearence and disappearence experiments. Limits on oscillation parameters have been significatively improved. For what concern $\bar{\nu}_e$ disappearence experiments, while the Goesgen results do not show any oscillation effect, the Le Bugey results give a possible effect which is not inconsistent with the Goesgen results, when using only flux ratios.

At present accelerator experiments are not sensitive enough to explore the Δm^2 region indicated by Le Bugey, but planned or already running experiments on $\nu_\mu \rightarrow \nu_e$ will cover this Δm^2 region.

These experiments and new and improved results from reactor experiments will clarify the situation in the future.

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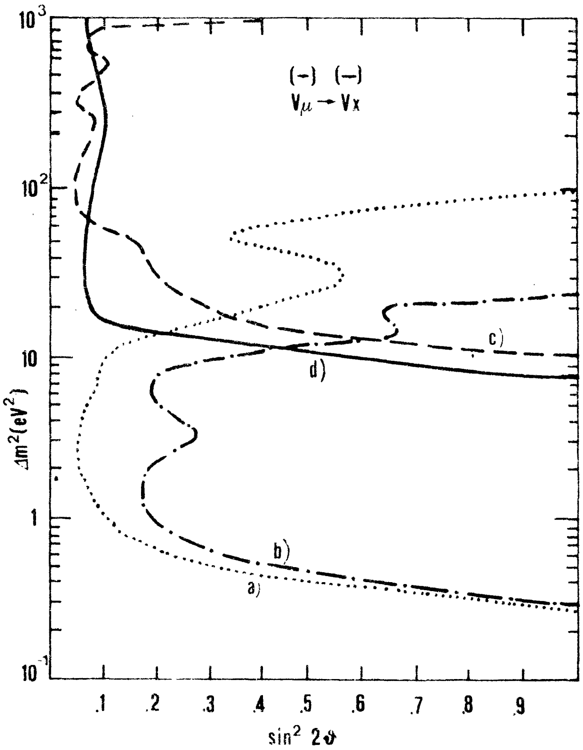

Fig. 1 - 90% c.l. limits in the Δm^2, $\sin^2 2\vartheta$ plane for $\overset{(-)}{\nu}_\mu - \overset{(-)}{\nu}_x$ Curve a) ν_μ CDHS /3/; b) ν_μ CHARM /4/; c) combined ν_μ and $\bar{\nu}_\mu$, CCFR /6/; d) $\nu_\mu + \bar{\nu}_\mu$ Serpukhof /7/.

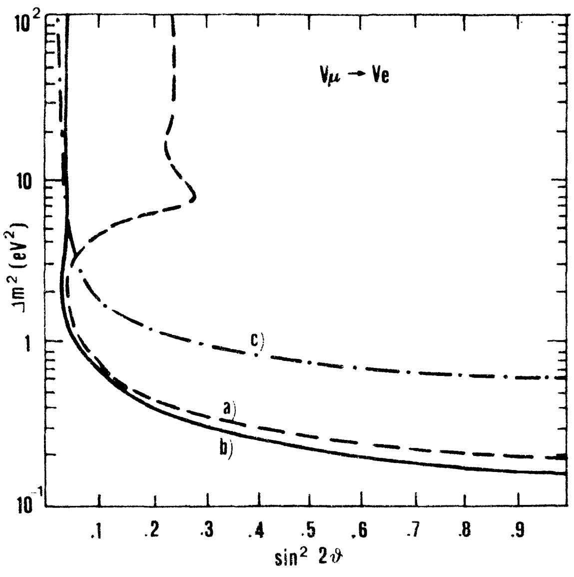

Fig. 2 - $\nu_\mu \rightarrow \nu_e$ 90% c.l. in the Δm^2, $\sin^2 2\vartheta$ plane curve a) CHARM /4/; curve b) Athens-Padova-Pisa-Wisconsin Coll. /8/; c) BNL-Columbia /9/.

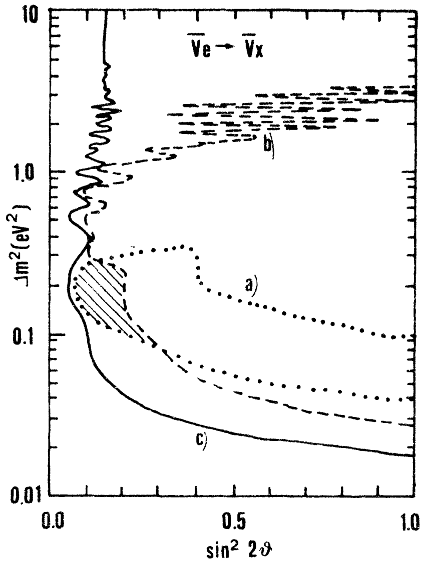

Fig. 3 - $\bar{\nu}_e \rightarrow \nu_x$. Curve a) contour of the allowed region in the $\sin^2 2\vartheta$, Δm^2 plane /11/; b) 90% c.l. from ref. /10/. Both results use flux-ratios. Curve c) 90% c.l. using predicted positron spectra ref. /10/.

TABLE 1

Limits on oscillation parameters in $\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_x$

EXP	Δm^2 min (eV^2) $\sin^2 2\vartheta = 1$	Δm^2 max (eV^2) $\sin^2 2\vartheta = 1$	$\sin^2 2\vartheta$ min
CDHS ν /3/ E≅3 GeV	.26	90.	.06 (Δm^2 ~3 eV^2)
CHARM ν /4/ E≅1.5 GeV	.29	22	.20 (Δm^2 ~2 eV^2)
CCFR ν /5/ E ≅40-230 GeV	15.0	1600	.02 (Δm^2 ~100 eV^2)
CCFR $\bar{\nu}$ /6/ E ≅50-150 GeV	15.0	1000	.05 (Δm^2 ~80 eV^2)
SERPUKHOF $\nu + \bar{\nu}$ /7/ E ≅3-30 GeV	6.5	-	.07 (Δm^2 ~30 eV^2)

TABLE 2

Limits on oscillation parameters in $\nu_\mu \rightarrow \nu_e$

EXP	CHARM /3/	BEBC /8/
Δm^2 min (eV^2) $\sin^2 2\vartheta = 1$	.20	.16
minimum $\sin^2 2\vartheta$	.04	.03
at Δm^2 (eV^2)	2.	2.5
$\sin^2 2\vartheta$ large Δm^2	.22	.03

SEARCH FOR NEUTRINOOSCILLATIONS AT THE NUCLEAR POWER REACTOR IN GOSGEN

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Violation of leptonnumber and non vanishing neutrino masses can give rise to the phenomenon of neutrino oscillations, where the weakly interacting neutrino types evolve in space-time as a coherent superposition of neutrino fields with distinct masses. In the simple case, where only two mass states m_1 and m_2 are interfering, the flux of a propagating neutrino beam, emitted in the weak ν_α-state is modulated as a function of distance L (in m) and energy E (in MeV):
$P_{\alpha\alpha}(E,L,\Delta m^2,\Theta)=1-0.5*\sin^2 2\Theta*(1-\cos(2.53\Delta m^2 L/E))$
where $\Delta m^2 = |m_1^2 - m_2^2|$ (in eV^2) and $\sin^2 2\Theta$ descibes the admixture of the two mass eigenstates ν_i /1/.

ß-decaying fission products make nuclear reactors a strong source of electron antineutrinos with energies up to 8 MeV. Our neutrino detector is installed at the site of the 2806 MWth PWR in Gösgen (Switzerland) and makes use of the inverse ß-decay of the neutron: $\bar{\nu} + p \rightarrow n + e^+$
which constitutes the most favourable antineutrino detection reaction. A correlation in time and position between positron and neutron serves as signature of a good neutrino event and the energy spectrum of the incident antineutrino flux. /2/.
The detector consists of five planes of six liquid scintillator cells alternating with four ^{3}He multiwire proportional chambers. Following an antineutrino interaction with one of the protonsin the liquid scintillator, the e is slowed down, producing a prompt light pulse in the scintillator. The neutron is thermalized rapidly in the scintillator and diffuses within 200μsec into one of the adjacent ^{3}He-chambers. As a special feature both detector systems allow for position sensitive particle detection. An additional requirement of position correlation cuts down the accidental background by a factor of 7, with a 92% acceptance for $\bar{\nu}$-events. Fast cosmic ray neutrons, which can fake a true event by leading to a recoil proton in a scintillator cell followed by a neutron capture in ^{3}He are suppressed by pulseshape discrimination. The detector is completely surrounded by a liquid scintillator veto system, followed successively by a passive shielding consisting of 5mm boron carbid, 20cm water, 15cm steel and 2m of concrete, with another 2m concrete overhead. The entire assembly is positioned outside the reactor containment building, providing an extra 8m of concrete shielding towards the core.
In the first stage of our experiment at a distance of 37.9m from the reactor core, limits on the oscillation parameters Δm^2 and $\sin^2 2\Theta$ were derived from the shape of the recorded positron spectrum and the known integral neutrino flux. Since the interpretation of results from one-position measurement relies on the exact knowledge of the reference neutrino spectrum, limits obtained independent of external parameters are desirable. This can be accomplished by comparing the spectra recorded at different positions, with an identical detector set up. For this purpose the neutrino spectrum was remeasured in a second position, 45.9m from the reactor core to allow a relative comparison with the 37.9m data.
Neutrino spectra from fission products of essentially four fissile isotopes (^{235}U, ^{239}Pu, ^{238}U, ^{241}Pu) contribute to the sum neutrino spectrum at the detector site. Their mean contribution to the reactor power was 61.9%, 27.2% 6.8% and 4.2% in the 37.9m position and 58%, 29% 6.8% and 5% in the 45.9m position, respectively. This resuls in a difference of less than 1.3% in the two predicted neutrino spectra. The time dependence of the $\bar{\nu}$-spectra over one measuring cycle was explicitly taken into account. For the dominant fissile isotopes ^{235}U and ^{239}Pu neutrino yields derived from measured beta spectra of the fission products were used /3/. For the less important isotopes calculated spectra of ref./4/ were taken.
In a nine months reactor-on period a total of 10590±190 neutrino induced events were observed at the 45.9m position, at the 37.9m position 10930±220 neutrino events were recorded. The correlated background was measured during the normal annual reactor shutdowns. Fig.1a shows the total positron yield recorded in the reactor-on and-off runs in the second position, together with the accidental background component (dashed line). Fig.1b illustrates the results obtained by subtracting the correlated background from the reactor on data in the 37.9m position (dashed, right scale) and the 45.9m position (solid, left scale).
The analysis of the Gösgen experiment uses a maximum likelihood method, which checks the relevance of an oscillation solution, found as the best possible fit, when testing the compatibility of various oscillation hypotheses ($\Delta m^2,\Theta$) with the data. There are three steps in which the analysis proceeds. First we restrict ourselves to a comparison of the two Gösgen measurements. For this purpose we leave the input parameters of the reference reactor spectrum free and we determine the best fit by varying a common source spectrum and the oscillation parameters Δm^2 and Θ in a χ^2-function. Testing the significance of the thereby determined χ^2_{min} against all other oscillation parameters, yields the solid curve (Gösgen relative) in fig.2, where all parameters to the right of the curve are excluded. Parameters to the left of the curve especially the no-oscillation hypothesis are

supported by our data. We furthermore can include into the analysis the data of a measurement at 8.7m from the pure ^{235}U core of the ILL reactor /5/. The combination of the ILL and the Gösgen results (relative normalisation 7% (1σ)) is based on the sound knowledge of the detector (both the same) and the relative difference of the main contributing fissile isotopes ($\Delta(N_\nu(235U)/N_\nu(PWR)) \leq 3\%$). Because of the large difference in distance, 8.7m compared to 37.9m and 45.9m, the ILL data help to extend the sensitivity towards smaller mass-parameters. The area to the right of the dashed-dotted line (Gösgen+ILL) in fig.2 indicates the excluded parameter region in this second step of the analysis. Finally we can include the reference L=0m spectrum, which renders the ILL data statistically insignificant. By varying now, with fixed input parameters for the reactor spectrum, the oscillation parameters Δm^2 and Θ in a χ^2-function the best fit is obtained and the result of the maximum likelihood test is shown by the dashed line (Gösgen absolute) in fig.2.

Our results can be compared to those of a similar experiment, performed by the ISN-LAPP collaboration at 13.6m and 18.3m from the core of the 2.8 GWth reactor in Bugey (France) /6/. In this experiment a deficit in the neutrino flux was observed in the far position, which can be explained by oscillations with parameters lying inside the dotted line of fig.2. Although there is a small region around $\Delta m^2 = 0.2$ eV^2, which cannot be ruled out by the Gösgen two position analysis (solid curve in fig.2), these oscillation solutions are,however, in contradiction if more relevant information is included in the Gösgen analysis (dashed-dotted, dashed curves).

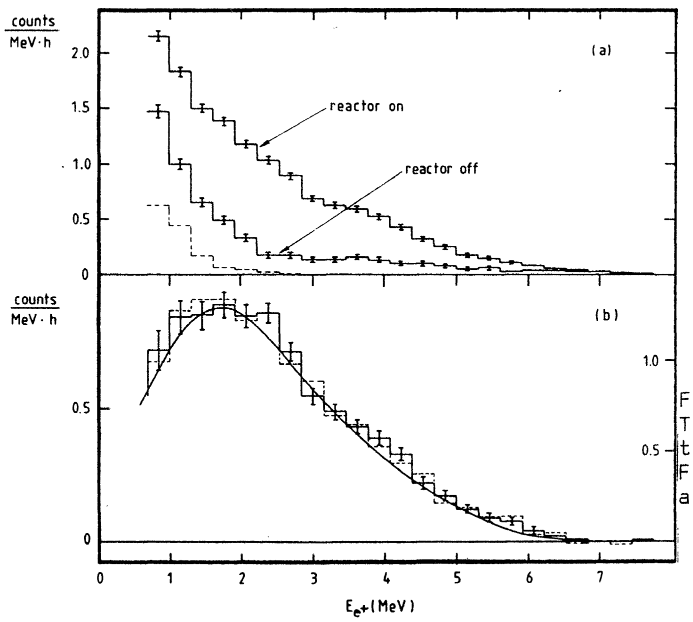

Fig.1: (a) Reactor on and reactor off spectra at 45.9m. Errors shown are statistical. Accidentals are indicated by the dashed curve. (b) Experimental positron spectra (reactor on - off) at 37.9m (dashed, right scale) and at 45.9m (solid, left scale). The predicted spectrum is the solid curve.

In summarizing, the Gösgen analysis shows no evidence for neutrino oscillations. Assuming a neutron lifetime of 912 sec, limits on the oscillation parameters of $\Delta m^2 \leq 0.016$ eV^2 (90% c.l.) for full mixing and $\sin^2 2\Theta \leq 0.16$ (90% c.l.) for large Δm^2 can be stated. Presently the Gösgen experiment is continued in a distance of 65m. These new data will increase our sensitivity in the controversial range of $\Delta m^2 \cong 0.2$ eV^2.

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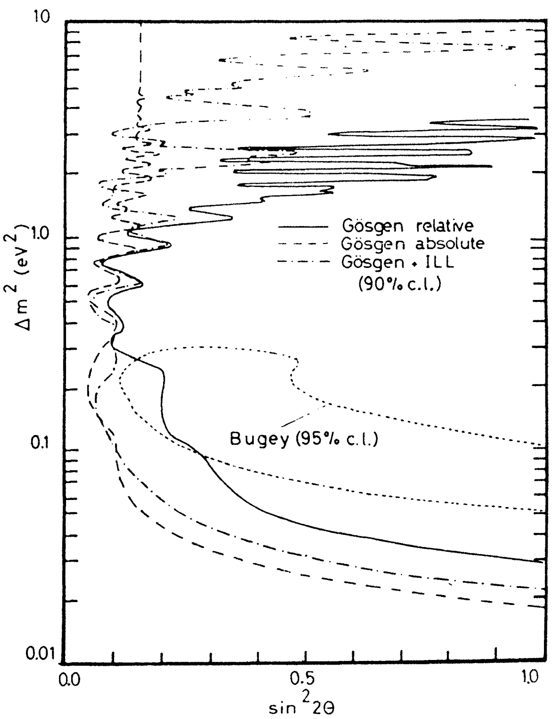

Fig.2: Limits on the oscillation parameters. The Gösgen analysis excludes the region to the right of the contourlines with 90% c.l. For Bugey the area inside the curve is allowed.

REVIEW OF DOUBLE BETA DECAY

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The observation of neutrinoless double beta decay requires lepton number nonconservation and that (1) the electron neutrino have mass and/or (2) the weak interaction have right-handed currents. It is possible for double beta decay to occur because the pairing energy in nuclei with even numbers of neutrons and protons provides tighter binding than in adjacent odd-odd nuclei. The even-even nucleus, energetically forbidden to decay to the neighboring odd-odd nucleus, may be able energetically to decay to the next even-even nucleus via the second-order weak interaction,

$[A,Z]\rightarrow[A,Z+2] + 2e^- + 2\bar{\nu}_e$ (called here $(\beta\beta)_{2\nu}$).

There is new information at this conference on this process which furnishes an important check on calculations of the more interesting decay

$[A,Z]\rightarrow[A,Z+2] + 2e^-$ (called here $(\beta\beta)_{0\nu}$),

and there is also new information on this widely-sought decay. Clearly $(\beta\beta)_{0\nu}$ violates lepton number conservation, requiring that the virtual $\bar{\nu}$ from the first e^- emission be reabsorbed as a ν to permit a second e^- to be emitted. This means $\nu\equiv\bar{\nu}$, or the neutrino is of the Majorana type for $(\beta\beta)_{0\nu}$, whereas $(\beta\beta)_{2\nu}$ can occur for Dirac or Majorana neutrinos. The zero neutrino decay would be favored over that with two neutrinos by a phase space factor $\sim10^6$, but in addition to possible inhibitions due to lepton number nonconservation, parity violation in β decay makes $(\beta\beta)_{0\nu}$ absolutely forbidden even for Majorana neutrinos, unless the neutrino can have a small amount of the "wrong" helicity state because the neutrino has a mass and/or right-handed currents exist. Experiment can distinguish between these two possibilities by observing the $0^+\rightarrow2^+$ transition to the first excited state, which can occur only for right-handed currents (RHC), but only the more favored $0^+\rightarrow0^+$ transition to the ground state will be discussed here, because of lack of space for dealing with both lifetime limits.

With this introduction to double beta decay completed, we can turn now to the issues which are currently important in this field. These are (1) lifetime limits for $(\beta\beta)_{0\nu}$ and (2) relating these limits to corresponding limits on m_ν (neutrino mass) and RHC, which involves theoretical uncertainties and checks from $(\beta\beta)_{2\nu}$ decays. The first of these also involves two categories: (A) geochemical results, and (B) laboratory experiments.

There is nothing new in the past year from geochemical experiments, in which noble gas products from double beta decay are sought in $\sim10^9$-year-old rocks. The main results,[1] after some controversy, appear to be that lifetimes are observed one to two orders of magnitude longer than are calculated for $(\beta\beta)_{2\nu}$ decay, and that there is no evidence from the ratio of $^{128}Te/^{130}Te$ decays for the existence of $(\beta\beta)_{0\nu}$ decay. The interpretation of these results enters into issue (2), which will be discussed shortly.

On the other hand, there has been a great deal of activity in the past year on category (B), particularly searching for ^{76}Ge decay. Although promising work is in progress on other nuclei (particularly ^{100}Mo and ^{136}Xe), the present best limits come from Ge experiments, and there is room for reporting only these. Ge, which has 7.76% of the isotope ^{76}Ge which can undergo double beta decay, is a very precise electron detector. The $0^+\rightarrow0^+$ transition would give a peak, summing the energies of the two electrons, at 2040.71±0.52 keV[2] with a full width of only about 3 keV. Thus the experimenter is required to use as much Ge as possible in an environment which has as low a background at 2 MeV as possible. Backgrounds come from both cosmic rays (especially secondary neutrons) and from radioactivity. In discussing these experiments, we shall note the fiducial volume of Ge, where the experiment is located (which is relevant particularly to the cosmic ray background), what the background is at 2 MeV normalized to a 100 cm^3 detector, and the lifetime limit. The limit can be obtained in different ways, the two most common being a calculation of the fluctuation in the measured background near 2 MeV, and a maximum likelihood method, which gives a greater limit if there is a downward fluctuation in the background right at 2.04 MeV. We will give both here, if the information is available, with the latter in parentheses.

The Milan group, operating in the Mt. Blanc tunnel was the first[3] to do this experiment, and they still have the best lifetime limit. Their 116 cm^3 detector with 1.4×10^{-3} counts/keV·hr per 100 cm^3 has operated for 15,000 hours, giving a limit of 5.8 (or 7.3)x10^{22} y. Their 143 cm^3 detector has a much improved background of 0.24x10^{-3} and gives a limit in 4,000 hours of 6.9 (or 4.0)x10^{22} y. The UCSB/LBL group[4] has operated only two of its eight 160 cm^3 detectors (enclosed by 15 cm of anticoincidenced NaI) with a background of 0.76x10^{-3} above ground, giving in 1,400 hours a lifetime limit of 3.6x10^{22} y. More detectors will be added shortly, and the experiment, which has the best above-ground background so far, is moving underground to a site at the Oroville dam. The Guelph/Aptec/Kingston group, operating in a salt mine with a background of 2.1x10^{-3}, has the best published[5] limit of 2.2 (or 3.2)x10^{22} y. using a 194 cm^3 detector for 2363 hours, but they now have about 600 cm^3 of working detectors. The Osaka group[6] has 160 cm^3 of Ge shielded by 7.5 cm of NaI, giving a background of 1.6x10^{-3} above ground, resulting in a limit in 2,000 hours of 1.9 (or 2.2)x10^{22} y. They are now operating in the Kamioka mine. The CalTech group, using a 90 cm^3 detector with a plastic scintillator shield, achieved a background of 1.8x10^{-3} above ground and a limit in 3820 hours of 1.9(or 2.0)x10^{22} years.[7] Their apparatus has now been installed in the Gotthard tunnel, and they are also designing a composite detector of 1000 cm^3. The Batelle/South Carolina collaboration[8] at sea level with a 125 cm^3 detector inside NaI had a background of 6.1x10^{-3} and a limit of 1.3x10^{22} y. in 4054 hours. Now installed in the Homestake mine, they have a background of 0.2x10^{-3} and have achieved about the same limit in less than 1000 hours. With better detectors and backgrounds, these experiments should rapidly produce much improved results.

Given these limits, what can be said about m_ν and RHC? First, regarding RHC, Doi, Kotani, and Takasugi[9] have made the important observation that for the case which is usually assumed[10] to give neutrinos mass (in which right-handed Majorana neutrinos are heavier than all left-handed leptons), the limits on the amplitude of RHC from $(\beta\beta)_{0\nu}$ are about 10^3 times more stringent than those from μ^+ decay. Another positive result is that Takasugi[11] has emphasized that using a proper P-wave relativistic wave function for the electron for RHC instead of the usual plane wave approximation makes $(\beta\beta)_{0\nu}$ limits on RHC much ($\sim$5x) more sensitive than assumed heretofore.

Secondly, regarding m_ν, confusion has increased during the past year. Limits on m_ν are usually obtained from lifetime limits using the calculations of Haxton and Stephenson.[12] These Los Alamos calculations agreed with the Irvine result[13] on the ^{82}Se lifetime, but disagreed by $\sim$20 with geochemical results. Now two pieces of experimental information and one theoretical one may indicate that the geochemical result is more nearly correct. First, Moe and Hahn,[14] with a TPC substituted for a cloud chamber, are not seeing $(\beta\beta)_{2\nu}$ at the previously observed rate. Second, in a contribution to this Conference, the Moscow group[15] using a coincidence between two of the four planes of plastic scintillators with two sheets of 92%-enriched ^{150}Nd between, reported a limit of 1.3x10^{19} y for $(\beta\beta)_{2\nu}$, which they say is longer than expected from the Los Alamos calculations[12] (though ^{150}Nd has not been calculated explicitly) and in agreement with geochemical results on nearby nuclei. Third, Takasugi[11] has also pointed out that the problem with the Los Alamos calculations may be the use of the closure approximation in determining the average energy of the intermediate states. He notes that Tsuboi, Muto, and Horie[16] have shown that in the case of ^{48}Ca the nuclear matrix elements of low-lying and high-lying states have opposite signs, resulting in a much smaller average excitation energy. Neglect of pairing states in the nuclei of interest (^{76}Ge, ^{82}Se, ^{128}Te, ^{130}Te) may lead to important errors in this way. Note that the m_ν limits now are uncertain not only for ^{76}Ge, but also from the geochemically determined ^{128}Te/^{130}Te ratio, because the assumption that the nuclear matrix elements of the two Te isotopes cancel in the ratio may not be justified, since the average energies of the excited states could differ significantly.

The usual review of this sort concludes with a plot of m_ν limits vs. RHC limits for lines of constant lifetime. At this time such a plot would not be very meaningful, since there are doubts about relating both m_ν and RHC limits to lifetimes. Suffice it to say that the lower limit Lubimov gave at this Conference for m_ν from tritium β decay of 9 eV can not be considered in disagreement with $(\beta\beta)_{0\nu}$ results, quite apart from the arguments that the neutrino may be a Dirac particle, or that the mixture of neutrinos may provide a cancellation which makes the effective mass less in double beta decay.[17] The much improved experiments may see a positive effect soon!

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A NEW UPPER LIMIT FOR THE DECAY $\mu^+ \to e^+e^+e^-$ AND FOR ANOMALOUS MUON CONVERSION $\mu^-Ti \to e^-Ti$

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A report is given on the status of presently running experiments looking for muon number violating μ-decays.

In the simplest version of the standard model of Glashow, Salam and Weinberg the neutrinos are massless and cannot mix. Hence the generation number in the leptonic sector is conserved. Extensions of this minimal model include the introduction of massive neutral leptons, right-handed currents, doubly charged leptons or more than one Higgs doublet. Other sources of generation mixing have been proposed like horizontal symmetries, technicolor theories, composite models and supersymmetric models. No numerical predictions of branching ratios of muon number violating decays can be made, since masses and mixing angles of the particles introduced are arbitrary. Ratios of the branching ratios can be predicted within each model and it is therefore necessary to look for all possible decays such as $\mu \to e\gamma$, $\mu \to e\gamma\gamma$, $\mu \to 3e$, $\mu N \to eN$, $\pi^0 \to \mu e$, $K^0 \to \mu e$, $K \to \pi\mu e$.

At SIN we have continued the search for the decay $\mu^+ \to e^+e^+e^-$ with the magnetic spectrometer SINDRUM. The detector has been described in ref.1. In the present experiment all five MWPC-chambers were installed and used. A surface μ^+ beam of 28 MeV/c momentum was stopped in a thin low density target with a rate of $5 \cdot 10^6$ s^{-1}. During the experiment a total of $7.5 \cdot 10^{12}$ μ^+ were stopped. 8838 events were found offline with two positrons and one electron prompt within 1 ns (timing resolution 700 ps FWHM) and with a common origin in space on the target surface (vertex resolution 3 mm FWHM). Figure 1a shows their distribution of the total energy E versus the missing momentum $|\Sigma \vec{p}c|$. Indicated is the cut $E + |\Sigma \vec{p}c| = 112$ MeV below which events of the allowed decay $\mu \to 3e2\nu$ should be confined. The events from figure 1a are projected onto a $E + |\Sigma \vec{p}c|$ axis and their distribution is plotted in figure 2 (solid histogram). A number of (7833 ± 90) events $\mu \to 3e2\nu$ is found after subtraction of a 4.7% accidental background (dotted histrogram). For the decay $\mu \to 3e$ we have the relation $|\Sigma \vec{p}c| = 0$. Since the uncertainty of $\Sigma \vec{p}$ is dominated by the errors in $|\vec{p}|$ ($\Delta p/p = 10\%$ FWHM at 35 MeV/c) a separate coplanarity cut was applied. Events were rejected for which the sum of the three emission angles relative to any plane exceeds 5^0. The resulting 899 events are plotted in figure 1b together with contours in which 90% and 68% of the $\mu \to 3e$ events should occur. No event was found within these boundaries. The acceptance of the detector and the efficiencies of all cuts were determined by Monte Carlo simulation using the EGS-code (2). Standard electroweak interactions were assumed for $\mu \to 3e2\nu$ and a constant matrix element for $\mu \to 3e$. Table I summarizes the efficiencies.

Table I

Results for the $\mu \to 3e$ search with SINDUM.

	$\mu \to 3e$	$\mu \to 3e2\nu$
Acceptance	24%	$2.6 \cdot 10^{-4}$
Trigger efficiency	85%	26%
Chamber efficiency	92%	92%
Offline cuts	73%	53%
Total efficiency	$(13.7 \pm 1.5)\%$	$(3.3 \pm 0.5) \cdot 10^{-5}$
Events observed	0	7833 ± 90
Number of stops	$7.5 \cdot 10^{12}$	$7.5 \cdot 10^{12}$
Branching ratio	$<2.4 \cdot 10^{-12}$	$(3.2 \pm 0.5) \cdot 10^{-5}$
Theory		$3.5 \cdot 10^{-5}$

Having not observed any $\mu \to 3e$ candidate we obtain an upper limit for the branching ratio.

$$\Gamma(\mu \to 3e)/\Gamma(\mu \to e\bar{\nu}\nu) < 2.4 \cdot 10^{-12} \quad (90\%\ C.L.)$$

With the overall acceptance·efficiency of $(3.3 \pm 0.5) \cdot 10^{-5}$ for the decay $\mu \to 3e2\nu$ we obtain a branching ratio of

$$\Gamma(\mu \to 3e2\nu)/\Gamma(\mu \to e\bar{\nu}\nu) = (3.2 \pm 0.5) \cdot 10^{-5}$$

in good agreement with the expected number of $3.5 \cdot 10^{-5}$ (3).

The anomalous $\mu^- \to e^-$ conversion in muonic Ti is being searched for at TRIUMF (4) with the help of a time projection chamber TPC (5). Cloud muons with 73 MeV/c momentum are stopped at a rate of $5 \cdot 10^5$ s^{-1}. During an initial running period, $3 \cdot 10^{12}$ muons were captured in the Ti target. After all cuts were applied the electron momentum spectrum shown in figure 3a was obtained ($\Delta p/p = 4\%$ FWHM at 100 MeV/c). This spectrum is consistent with being due to bound μ^- decay. Figure 3b shows a calculated spectrum for the coherent reaction $\mu^-Ti \to e^-Ti$ with an assumed branching ratio of 10^{-10}. The effective acceptance·efficiency for the data was 3.5% on average. A preliminary upper limit for the branching ratio is

$$\Gamma(\mu^-Ti \to e^-Ti)/\Gamma(\mu^-Ti \to \nu_\mu + \ldots) < 2 \cdot 10^{-11} \quad (90\%\ C.L.)$$

The experiment is continuing.

A search for the three decays $\mu \to e\gamma$, $\mu \to e\gamma\gamma$ and $\mu \to 3e$ is under way at LAMPF (6). The apparatus used is the crystal box. It consists of 396 NaI crystal surrounding a 8 plane stereo drift chamber. A sensitivity of a few times 10^{-11} for all decays is expected within a year from now. In an initial running period an upper limit for the branching $\mu \to 3e$ of $1.3 \cdot 10^{-10}$ (90% C.L.) has been obtained.

References

1) SINDRUM collaboration, W. Bertl et al., Phys. Lett. 140B, 299 (1984).
2) R.L. Ford and W.R. Nelson, SLAC-210 (1978).
3) D.Y. Bardin et al., Sov. J. Nucl. Phys. 15, 161 (1972).
4) C.K. Hargrove et al., contributed paper this conference.
5) C.K. Hargrove et al., Nucl. Instr. Meth. 219, 461 (1984).
6) R. Mischke et al., contributed paper this conference.

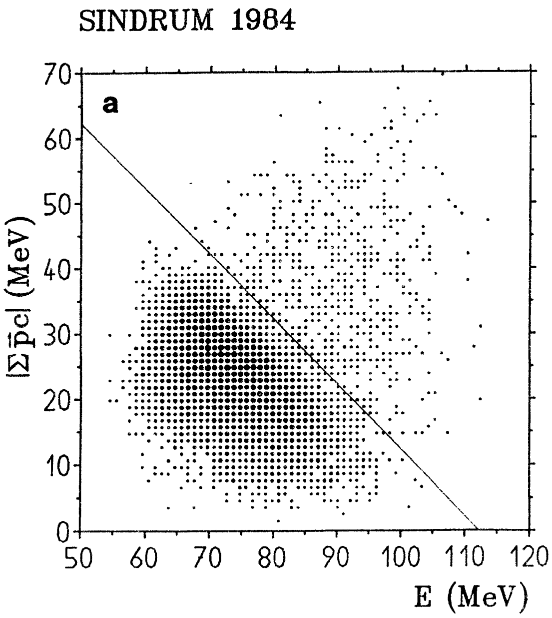

Fig.1a: Distribution of missing momentum $|\Sigma\vec{p}c|$ versus total energy E of 8838 $e^+e^+e^-$ events, remaining after a correlated vertex-time cut. Indicated is the line $E+|\Sigma\vec{p}c|=112$ MeV, below which $\mu\to 3e2\nu$ events should be confined.

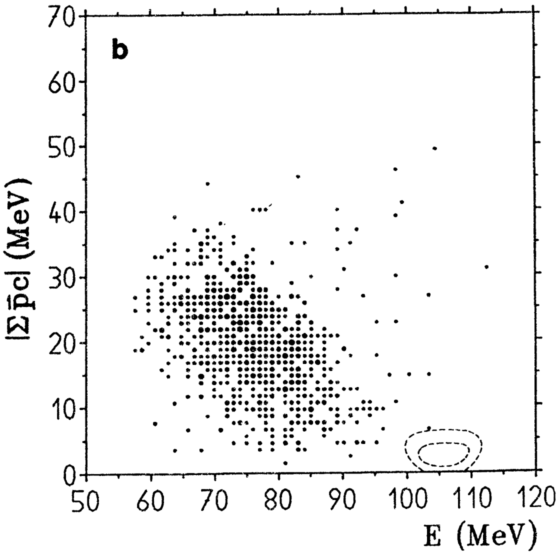

Fig.1b: 899 events remaining from fig.1a after an additional coplanarity cut (see text). The contours contain 90% and 68% of $\mu\to 3e$ events.

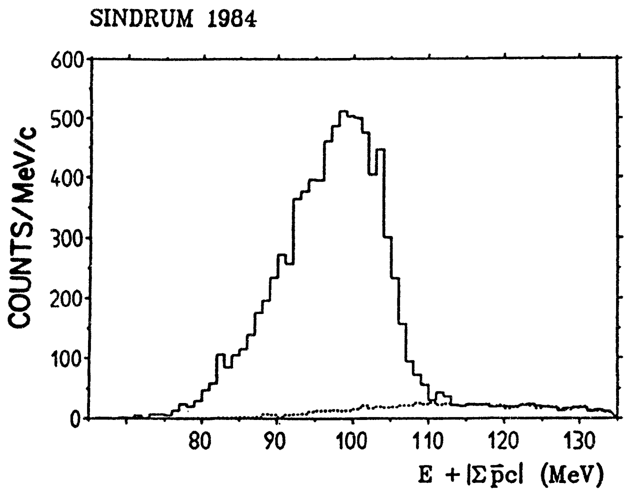

Fig.2: Distribution of $E+|\Sigma\vec{p}c|$ for prompt events (solid histogram) and accidental events (dotted histogram).

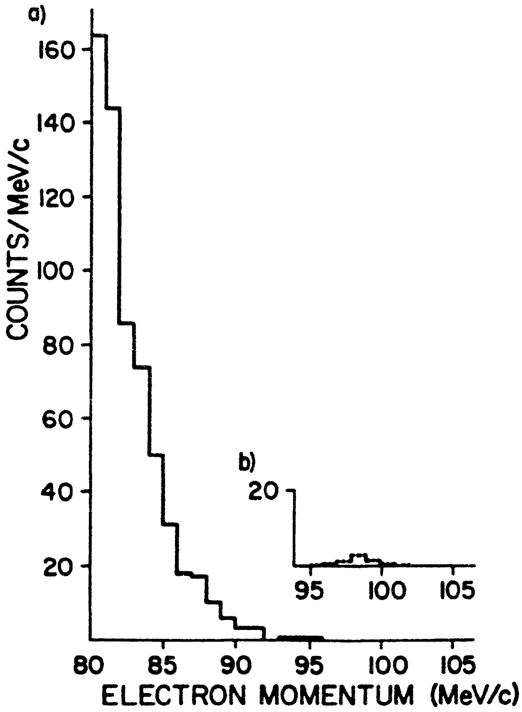

Fig.3a: The observed electron spectrum.
Fig.3b: The dashed lines represent a Monte Carlo generated spectrum for $\mu^- Ti \to e^- Ti$ with a branching ratio of $R=10^{-10}$.