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MEASUREMENTS OF NEUTRINO MASS

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In this review we shall consider "direct" experimental information on neutrino mass as derived from the study of nuclear and elementary-particle weak decays. Neutrino oscillations, double β decay and searches for heavy neutrinos admixed with lighter ones will not be discussed as they are given extensive treatment by others.¹ Similarly, only cursory consideration will be given to cosmological limits on neutrino mass.

I. Tritium Beta Decay

a. The ITEP Experiments

As is well known, a group at the Institute for Theoretical and Experimental Physics (ITEP) in Moscow has reported^{2,3,4} evidence for a massive electron antineutrino ($\bar{\nu}_e$) from a long experimental campaign. The basic method is a careful study of the beta spectrum from tritium decay

$$\frac{dN}{dE} = G_F^2 \frac{m^5 c^4}{2\pi^3 \hbar^7} \cos^2 \theta_c |M_{if}|^2 F(Z_f, E) p E (W_0 - E) [(W_0 - E)^2 - m_\mu^2]^{1/2} \quad [1]$$

where M_{if} is the nuclear matrix element (for ^3H decay $|M_{if}|^2 \sim 5.55$) and $F(Z_f, E)$ is the Fermi Coulomb distortion factor.⁵

$$F(Z_f, E) \sim x(1 - e^{-x})^{-1} (1.002037 - 0.001427v/c) ,$$

where

$$x = 2\pi Z_f \alpha / (v/c)$$

The function $F(Z_f, E)$ differs from unity by about 20% for ^3H near the endpoint. To simplify notation, we refer to neutrino masses as m_ν , m_μ and m_e , and further make no distinction between neutrino and antineutrino mass. The total energy is W_0 . Since

actual experiments are usually done in the center-of-momentum frame, the observed maximum energy of betas is less by about 3 eV, the energy of nuclear recoil.

This expression applies to the decay of a bare nucleus and when atomic electrons are also present it is necessary to express the total decay probability as a sum of individual branches to all possible final states. Ching and Ho⁶ have given the general expression, which is indistinguishable (at the level of about 10^{-3}) from simply replacing W_0 by

$$W_n = W_0 + V_n$$

in [1] where $V_n = E_i - E_{fn}$, the difference between atomic electron binding energies in the initial and final states.

For the free tritium atom, one can calculate both the branching and the excitation energies to great accuracy (see Williams and Koonin⁷) (Fig 1). Such a calculation can probably also be done for T_2 , although even in this elementary molecule the situation is vastly more complex because excited states in the ^3He daughter are now in the continuum and have a finite width. For example, Martin and Cohen⁸ find that 58% of the decays lead to the $^3\text{HeT}^+$ ground state, 26% lead to excited $^3\text{HeT}^+$ states (which can dissociate or decay radiatively) and the remaining 16% goes to the continuum. For a molecule as complicated as valine, used by the ITEP group, a detailed calculation is very difficult, especially for the continuum. Kaplan, Smutnyl and Smelov⁹ have reported large-basis calculations for valine.

Much has been made of this "final-state" problem, and it does indeed appear to be a serious limitation on how accurately a neutrino mass can be determined. Nevertheless, a model-independent statement about a lower limit to the mass can be made by attempting to fit the data with expression [1], the "nuclear" case. Both the endpoint energy W_0 and the neutrino mass m_β are treated as free parameters. Actual spectra are a superposition of many spectra with different endpoints W_n ranging up to a maximum W_0 . Thus, lumping all constants into a single parameter A ,

$$dN/dE = \sum_n A \lambda_n pE (W_n - E)^2 [1 - m_\beta^2 / (W_n - E)^2]^{1/2}$$

where λ_n is the weight of the n th state. Consider now the case $m_\beta = 0$, expand W_n , and carry out the summations,

$$dN/dE = ApE (W_0 - E + \bar{V}_n)^2 [1 + (\bar{V}_n^2 - \bar{V}_n^2) / (W_0 - E + \bar{V}_n)^2]$$

This spectrum looks like a simple Fermi spectrum with extrapolated endpoint $W_0 + \bar{V}_n$ and a "neutrino mass" squared of $-2(\bar{V}_n^2 - \bar{V}_n^2)$, provided one does not inspect the endpoint region with good resolution. However $\bar{V}_n^2 - \bar{V}_n^2$ is always ≥ 0 , and causes an excess of counts in the endpoint region, rather than a deficiency as would result from an actual neutrino mass. The most conservative assumption that can be made is $\bar{V}_n^2 - \bar{V}_n^2 = 0$ (i.e. only one final state). If, under that assumption, the "nuclear" case, one still sees a deficiency of counts in the endpoint region, then it can only be due to neutrino mass.

This is a very powerful result that permits the use of complex sources to determine whether the neutrino has mass. Although there are innumerable other kinds of experimental error that could subvert the conclusion, final-state effects cannot affect this model-independent lower limit.

Similar arguments can be made about the effect of instrumental resolution. Let the resolution function be $R(E, E')$, the normalized probability of observing an energy E when the actual energy is E' . We assume that $R(E, E')$ is sharply peaked around $E \sim E'$, and therefore neglect the effect on the terms pE in the spectral distribution.

$$dN/dE \sim ApE \int ((W_0 - E' + \bar{V}_n)^2 - m_\beta^2/2 + \sigma_V^2) R(E, E') dE'$$

$$\text{where } \sigma_V^2 = \bar{V}_n^2 - \bar{V}_n^2$$

Then

$$dN/dE = ApE ((W_0 - \bar{E}_R + \bar{V}_n)^2 - m_\beta^2/2 + \sigma_V^2 + \sigma_R^2)$$

where

$$\bar{E}_R = \int E' R(E, E') dE'$$

$$\sigma_R^2 = \int (E')^2 R(E, E') dE' - \bar{E}_R^2$$

Again, this expression will be valid close to, but not at, the endpoint. One can see that resolution plays the same role as final states, and that, in the absence of knowledge of $R(E,E')$ one could make the conservative assumption that $\sigma_R^2 + \sigma_V^2 = 0$. If there were still a deficiency of counts at the endpoint, that could only be due to neutrino mass. Unfortunately no experiment has sufficiently good resolution (yet) to obtain useful results under this assumption.

To briefly review the history of the ITEP measurements: the first report¹⁰ of data from the tritium experiment in the Tret'yakov toroidal spectrometer¹¹ gave, curiously, an upper limit of 35 eV (90% C.L.). By 1981, a great deal more data had been accumulated and the result

$$14 < m_\beta < 46 \text{ eV} \quad (99\% \text{C.L.})$$

was published². (The earlier data were included in this.) The lower limit was established in the model-independent assumption of one final state. However, Simpson¹² pointed out that, in measuring the resolution function, the natural linewidth of the ^{169}Yb conversion lines had been overlooked, and the resolution was therefore better than assumed. As described above, this has the effect of reducing the derived neutrino mass, and the best-fit value fell from 34.3 to 28.0 eV, based on measurements by the ITEP group and by Bennett *et al.*¹³ of the ^{169}Yb linewidths. After this correction, the model-independent (one-final-state) lower limit went to zero. The original analysis for the best fit value made use of the atomic approximation, and the ITEP group claims⁴ that re-analysis with valine distributions brings m_β back up to 36.4 eV because $\sigma_{\text{valine}} > \sigma_{\text{atom}}$. There seems to be no basis for this claim in published calculations,⁹ which would indicate $\sigma_{\text{valine}} < \sigma_{\text{atom}}$ and therefore an even lower value for m_β , 21 eV.

After 1981, the resolution was improved from about 45 to about 20 eV by setting up a potential gradient along the source to compensate for finite source size. The background was reduced 20-fold by accelerating the betas by 4 kV into the clear region above the tritium endpoint (based on, we believe, a suggestion¹⁴ of the Los Alamos

group!) New results were reported in 1983 at Cornell³ (and at Brighton). The best-fit value (valine distribution) was 33.0 eV and a "model-independent" lower limit of 20 eV was claimed. However, (Fig. 2) the spectrum could not be well fit by any theoretical description. Two massive neutrinos were proposed, but did not really alleviate the problem.

There were two major errors in the 1983 analysis. The "model-independent" lower limit was derived by examining the last 40-50 eV of the spectrum and claiming that, because this region was free of final states (other than the ground state), the total energy release and therefore the neutrino mass could be derived unambiguously. That was incorrect, because not only are there many states in this region⁹, but the derived endpoint lay *outside* the region chosen. This erroneous claim should not be confused with the type of model-independent limit discussed earlier. The second error was in relating the measured line shapes of ¹⁶⁹Yb conversion lines to the instrumental resolution. It was incorrectly assumed that the conversion lines have symmetric, Lorentzian shapes and that the observed low energy tails were entirely instrumental. In fact conversion lines are always accompanied by lower energy shakeoff satellites and by degraded electrons that have scattered in the source backing (see, for example, Freedman¹⁵). This assumption led to the bizarre spectrum distortions observed. Thus the results reported³ at the Cornell and Brighton meetings can be disregarded.

Finally, at the 1984 meeting in Leipzig, the ITEP group reported⁴ new data with what appears to be a substantially correct analysis and a genuine model-independent lower limit. Three runs are shown in Fig 3. Chi-squared per degree of freedom is essentially 1. The best-fit value (valine distribution) is 34.8 ± 1.9 eV, and the model-independent lower limit ("nucleus" distribution) is 9 eV (90% CL). Until a detailed account of the new work is published, we can only speculate on what kinds of problem may still remain.

In our opinion, the most serious concern is that Kurie plots are never straight (for an exception, see Simpson⁵). The reasons are as follows:

1. The efficiency of the spectrometer may vary with energy. By accelerating the betas to a fixed energy, the variation of detector efficiency can be eliminated, but it is replaced by a variation in spectrometer acceptance.
2. The energy calibration may be non-linear. This may be due to instrumental problems or binning errors (Bennett *et al.*¹).
3. Scattering in the source leads to an excess of low-energy counts.
4. Nuclear recoil loss changes from a maximum of 3 eV at the endpoint to smaller average losses further down in the spectrum.¹⁶

One is extremely sensitive to errors in the extrapolated endpoint energy -- depending on details of the spectrum, an endpoint error of 10 eV (due to spectral distortions rather than absolute error) can account entirely for a 35 eV neutrino mass. As has been pointed out by Bennett *et al.*¹³, a proper treatment of energy calibration and spectrum curvature is thus important. We have some limited reassurance on this point in that the ITEP group gets essentially the same results from the last 330 eV of the spectrum as from the last 1690 eV in the 1984 data set.⁴

b) The $^3\text{He-T}$ Mass Difference

Although not required for deriving the neutrino mass, the $^3\text{He-T}$ mass difference clearly provides an important constraint. The final state spectrum used fixes $\overline{V}_n$ and therefore must give the correct endpoint energy. Also, experimental problems might be revealed through an endpoint discrepancy. Finally, using a fixed value for the endpoint energy can in principle improve the accuracy with which m_β can be derived. Fig. 4 shows that the situation is not very satisfactory. The data of Bergkvist¹⁷ and of Trct'yakov *et al.*² have been corrected for changes in calibration energies, and the datum of Simpson⁵ is not included because of probable systematic errors (Dixon *et al.*²⁰). There is good agreement between the ITEP data^{2,4} and the Ion Cyclotron Resonance (ICR) result

of Lipmaa⁴, which lends some support to the ITEP claims. However, other ICR data (not shown) are not in agreement, but likely suffer from systematic errors. Further independent mass measurements are obviously desirable.

c) Other Tritium Experiments

At this writing, we are aware of 17 groups involved in (or intending to be involved in) tritium beta-decay measurements of m_{β} . For reasons of brevity, we will simply tabulate our information, with the disclaimer that some of it may now be inaccurate and/or out-of-date.

TABLE I
Tritium Experiments

<i>Investigator</i>	<i>Location</i>	<i>Spectrometer</i>	<i>Source</i>	<i>Resolution (eV)</i>
Lyubimov	ITEP	Toroidal Magnetic	Valine-T	20
Bergkvist	Stockholm	Iron-core Magnetic	Al-T	25
Kundig	Zurich	Toroidal Magnetic	C-T	12
Jelley	Oxford	Cylind. Mirror	Na-palmitate-T	15
Fackler	Livermore	Retarding E-S	T ₂ Solid	1.3
Stoeffl	Livermore	Toroidal Magnetic	T,T ₂ Gas	6
Boyd	Ohio State	Retarding E-S	T ₂ Solid	12
Graham	Chalk River	2 Magnetic	Ti-T	18
Bowles, HR	Los Alamos	Toroidal Magnetic	T,T ₂ Gas	30
Ohshima	Tokyo	2 Magnetic	?	30
Clark	IBM	Retarding E-S	?	?
Hughes	Yale	?	T ₂ Gas	?
Kalbfleisch	Oklahoma	?	?	?
Moore	McGill	Retarding E-S	?	?
Lobashov	Moscow	Retarding E-S	T,T ₂ Gas	8
Simpson	Guelph	Solid-State Si	Si-T	250*
Hansen	Berkeley	Solid-State Ge	Ge-T	250

* Experiment completed (Ref. 5). $m \leq 65$ eV (95% C.L.)

An experiment²² is under development at Los Alamos National Laboratory to study the spectra of free atomic and molecular tritium. With these sources, one can eliminate uncertainties associated with the final-state distribution. For reasons of greater familiarity, we will describe this experiment in more detail.

The apparatus, shown in Fig. 5, consists of three principal sections: a source region, a pumping restriction and extraction region, and a toroidal magnetic spectrometer. The basic concept of the experiment is to measure the beta-decay spectrum of an intense gaseous atomic tritium source. An extended source is required to reach a sufficient source intensity. Placing this source in a strong axial magnetic field with a pinch at one end allows one to extract most of the betas from the tritium decays into the extraction region. The pumping restriction and extraction region serves two purposes: to stop tritium molecules from reaching the spectrometer and to focus the betas emerging from the source region into the spectrometer. The toroidal spectrometer analyzes the momentum of the betas, allowing a precise measurement of the tritium energy spectrum near the endpoint.

The source region consists of a 4 m long 3.8 cm diameter highly polished aluminum tube which is pumped by Hg diffusion pumps located at both ends. An RF dissociator produces the atomic tritium gas which enters the tube at the midpoint between the two pumps. The tube is cooled to a temperature of about 120 Kelvin to minimize recombination of the atomic gas. The expected integrated source intensity will be 10^{15} - 10^{16} atoms/cm² of 85-90% pure atomic tritium.

Sapphire standoffs allow the aluminum tube to be thermally regulated but electrically isolated, so that the potential of the tube can be varied up to 20 kV. Hence, the betas from the source region can be differentiated from background tritium decays that occur elsewhere in the system. Another advantage of varying the source potential is that it is possible to step the source voltage instead of the spectrometer magnetic field.

The source tube is enclosed in superconducting solenoid which produces a field on the order of 1.5 kG with a small axial gradient. The electrons are constrained to spiral about the field lines, allowing 93% of the betas from tritium decays in the source region to enter the extraction region.

The pumping restriction and extraction region is a differential pumping system that guides electrons to the focus while limiting tritium contamination of the spectrometer to 2.5 mCi/day. The accelerated beta particles from the source are focused to a collimator located at the object of the spectrometer. The collimator limits the acceptance of the spectrometer so that no betas that emerge from or strike the source walls enter the spectrometer. The extraction efficiency has been measured to be 25% with a ^{169}Yb source and is in good agreement with ray-tracing calculations.

The design of the toroidal spectrometer, an improved version of an earlier design by Tret'yakov¹¹, has been described previously²³. The resolution of the spectrometer is determined mainly by source diameter and is calculated to be about 30 eV FWHM for 25 keV electrons and a 1 cm diameter source. A two-axis cosine coil active magnetic shielding system surrounds the spectrometer and cancels the ambient magnetic field to the necessary 20 milligauss level. The detector is a single-wire proportional counter.

Understanding the system's characteristics and behavior is critical to obtaining unambiguous results. There is a variety of diagnostics to ensure that we understand our system. Offline diagnostics include an electron gun to study orbits, wall effects, and resolution. Several solid sources and a gaseous $^{83\text{m}}\text{Kr}$ line source will also be used to study system resolution and extraction. Online diagnostics include a detector to monitor total source activity, a UV laser to determine the molecular fraction of the source gas, and a residual gas analyzer to monitor gas composition.

The construction of the experimental apparatus is nearly complete. Data taking should commence during the next year. We expect a count rate of 1 Hz in the last

100 eV below the endpoint and an ultimate sensitivity to neutrino mass better than 10 eV.

II. ^{163}Ho and ^{158}Tb

In 1981, Bennett²⁴ and de Rujula²⁵ urged that a study of internal bremsstrahlung (IB) emission in electron capture (EC) be undertaken to look for spectral distortions near the endpoint caused by neutrino mass. Usually, IB is a relatively weak process, but under the right conditions⁶, a resonant enhancement process makes it practical for use in neutrino-mass searches. Just as in tritium beta decay, one searches for the loss of phase space near the endpoint caused by neutrino mass.

The technique has been applied successfully to the EC decay of ^{193}Pt , from which a limit on m_β of 500 eV was obtained²⁶. This is certainly the best limit obtained specifically for the electron neutrino, although CPT invariance requires that the limits obtained for $\bar{\nu}_\beta$ must also apply to ν_β . The decay Q-value for ^{193}Pt is 56.8 keV, and it appeared the ^{163}Ho might be a more favorable case because of a much lower Q-value, 2.3 ± 1.0 keV. After a great deal of experimental effort in determining the Q-value and half-life of this isotope, it appears that it will not be possible to achieve a result competitive with the ITEP measurements. In part, this is due to experimental difficulties, but there are more fundamental problems of interpretation. Although it was claimed by de Rujula²⁵ that atomic and molecular problems were insignificant, that argument considered only the low probability for shake-up and shake-off. A more serious difficulty discovered by Bennett²⁷ is that the tails of distant resonances, which lie close to the valence level and even in the continuum, have substantial effects on the IB spectrum shape. The effects probably cannot be calculated to sufficient accuracy. Another problem is the difficulty in measuring the instrumental response to sufficient accuracy -- as Bennett observed²⁷, the energies of X-rays following electron capture and photoionization are slightly different because of differences in screening potentials in the two cases.

A second promising candidate was found by Raghavan,²⁸ who reported that the decay of ^{158}Tb proceeded to the 1187-keV level of ^{158}Gd by orbital K-capture and emission of a neutrino with energy only 136 ± 17 eV. A massive neutrino would alter the line shape of subsequent X-rays and would even alter the total K-capture rate to this level by a few percent. Unfortunately, Raghavan's value for the energy release is in substantial conflict with mass measurements made by Burke²⁹ (by nuclear reactions) and by Barber³⁰ (by direct mass spectroscopy). Recently Thomas *et al.*³¹ have repeated the coincidence experiments of Raghavan, and find no evidence for the reported K-capture decay. It thus appears that ^{158}Tb does not have the reported low-energy K-capture branch.

III. Limits on Massive Neutrinos From Cosmology

There is abundant evidence from the dynamics of galaxies that the universe is filled with non-luminous matter.³² While the precision with which the total mass can be determined is limited, the successful inflationary models and general philosophical considerations suggest that the universe is flat (closed but not bound). The abundances of ^2H , ^3He , ^4He and ^7Li all indicate that the baryon density is no more than 10% of that needed for closure, and that the remaining 90% must therefore be non-baryonic. The initial ITEP reports of a mass for ν between 14 and 46 eV were greeted with enthusiasm because a neutrino mass in this range could close the universe exactly. However, this appealing picture quickly ran into difficulties with the damping-out of the primordial density fluctuations needed to trigger the formation of galaxies. Relativistic neutrinos free-stream away from density knots, and it is only at a late epoch that a 30 eV neutrino would have become non-relativistic. By that time the scale of fluctuations is very large, and not only would one find galaxies to be much younger than they actually are, but the clustering of galaxies would be quite different from that observed. Briefly, a neutrino massive enough to produce the appropriate clustering would over-close the universe.

Hur and White³³ have reviewed the question of whether one can, using only particles known to exist, reach a cosmology consistent with observation. They conclude that if one neutrino is massive enough to close the universe and stable then another must be substantially more massive (in order to catalyze clustering early enough) as well as unstable (to avoid over-closing the universe). Furthermore, the only possible instability is of the form:

$$\nu_H \rightarrow \nu_L + l$$

where l is a neutrino or charged lepton. Fig. 6 shows more quantitatively how restrictive the limits on the properties of the heavy neutrino are. Boundary 1 is set by the plausible assumption that the coupling for neutrino decay will not be stronger than G_F . Boundary 2 is the condition that the heavy neutrinos should have decayed at least by the time quasars formed, Boundary 3 is the lower limit of lifetime that permits clustering on the right scale, and Boundary 4 roughly (and conservatively) indicates limits established by Krauss³⁴ and Lindley³⁵ that rescue deuterium from destruction by inverse-Compton photons from the charged lepton decay products. The line 5 is the recently established³⁶ upper limit on m_τ (164 MeV). The experimental limit^{37,38} on m_μ (.5 MeV) almost eliminates it as a candidate, and there is relatively little room even for m_e . One has

$$0.1 < m_\tau < 10 \text{ MeV}$$

$$\text{and } 10^3 < \tau_\tau < 10^9 \text{ s}$$

Central to this conclusion is the belief that the mechanism of galaxy formation and clustering is adequately understood.

IV. Conclusions

The present knowledge of the masses of the three known types of neutrino may be summarized as follows:

- a. ν_β From recent measurements of the tritium beta spectrum⁴

$$20 < m_\beta < 45 \text{ eV} \quad (\text{model dependent})$$

$$9 < m_\beta \quad (\text{model independent})$$

b. ν_μ From measurements^{37,38} of the energy release in $\pi^+ \rightarrow \mu^+ + \nu_\mu$

$$m_\mu < 500 \text{ keV (90\% C.L.)}$$

c. ν_τ From observation³⁶ of the decay $\tau \rightarrow 3\pi^\pm \pi^0 \nu_\tau$

$$m_\tau < 164 \text{ MeV (95\% C.L.)}$$

Figure Captions

Fig. 1 Branching in the decay of free atomic tritium to various final states in ^3He .

Fig. 2 ITEP data of 1983, expressed as deviations from a curve with $m_\beta = 0$. The solid line is the best fit for a single neutrino with $m_\beta = 33$ eV. (Units on the ordinate are not given)

Fig. 3 ITEP data of 1984. The solid curves are for the best-fit value of 35 eV, and the dashed curves for $m_\beta = 0$. Runs with 3 separate sources are shown.

Fig. 4 Difference between atomic masses of ^3H and ^3He . Data are from Bergkvist¹⁷, Smith¹⁸, Smith¹⁹, Dixon *et al.*²⁰, the ITEP group^{2,4} and Lipmaa *et al.*⁴.

Fig. 5 Cross-section of the Los Alamos atomic tritium experiment. The overall length of the apparatus is 16m.

Fig. 6 Constraints on the mass and lifetime of a "heavy" weakly decaying neutrino. See text for an explanation of the lines.

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Final State Spectrum Following Atomic Tritium Beta Decay