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# NEUTRINO MASS, DOUBLE BETA DECAY AND NEUTRINO OSCILLATIONS

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In this session were three topics, the direct measurement of the neutrino mass, double beta decay and various searches for oscillations. There is interest in these topics from a broad range of individuals that have not worked closely in the field. Accordingly, this introduction will be aimed primarily at the non-expert and we will forego the luxury of a complete review.

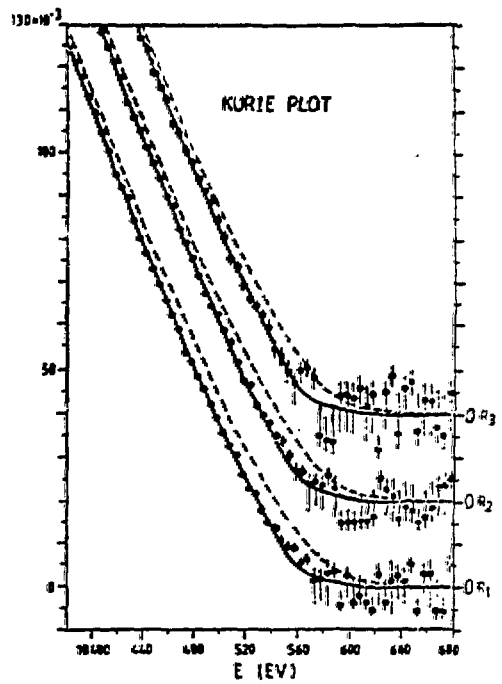
The direct measurement of the neutrino mass has used the reaction $^3H \rightarrow {}^3He + e^- + \nu$ almost exclusively. The low Q value (18.4 Kev) enhances the sensitivity of the spectrum shape to neutrino mass effects. The spectrum is only modified for about $2 \times m_\nu$ from the end point and this translates into an effect on about $2\ 10^{-8}$ of the decays for a neutrino mass of 20 eV. Intense sources and large aperture spectrometers are necessary therefore. Although this kind of measurement has been made for some time, a great deal of interest has been stimulated by the results of the ITEP group (Lyubimov, et al.) who have performed two experiments which have given indications of a finite neutrino mass.

The first measurements(1) used valine as a source ($C_5H_9T_2NO_2$) with a spectrometer of 45 eV resolution. The end point of the spectrum varies as $E_\nu p_\nu$ and this translates into an electron spectrum shape

$$(E - E_0^*)\ ((E - E_0^*)^2 - m_{eff}^2)^{1/2}$$

where $E_0^* = E_0 - \langle\Delta\rangle$ and $m_{eff}^2 = m_\nu^2 - 2\sigma^2$. The Tritium is bound and the helium is left in a spectrum of final states so that the energy available to the $e\nu$ pair depends on these effects in a complex way. $m_{eff}$ would be exactly equal to $m_\nu$ if the nucleus were infinitely massive and nuclear recoil would be irrelevant. However, the recoil of the helium has the effect of reducing the neutrino mass effect that may be observed. The first ITEP experiment attempted to estimate these effects arriving at a finite value for the neutrino mass. They also used a "model-independent" analysis in which they set $\langle\Delta\rangle$ at the binding energy and of the tritium and $\sigma = 0$, then their derived value of $m_\nu$ was 0. Many questions were asked, with the main effect that a number of other experiments were planned.

The first of these to come to fruition was a second measurement by the ITEP group reported by Lyubimov at the Leipzig meeting. The spectrometer was rebuilt achieving a resolution of 20 eV and the new measurements were made with three different source thicknesses. Extensive calculations were made of the target effects, and the data is shown in Fig. 1. The result is that $20 < m_\nu < 45$ eV with the allowed band reflecting the spread of the corrections for different




assumptions. The "model independent" approach gives $m_\nu > 9$ eV which the authors believe to be an absolute lower limit of course. Apart from the caution which greets such a complex and important measurement it is still true that the value of $E^0$

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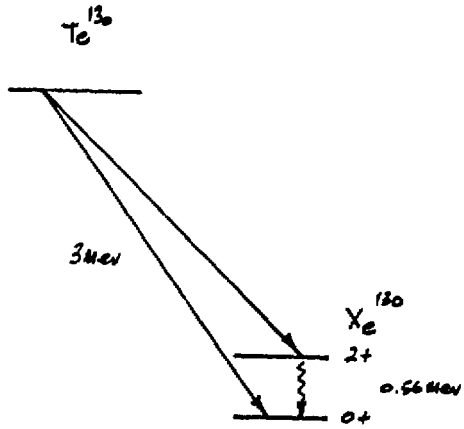
from this measurement and the direct measurements[2] varies rather more than is to be expected from the quoted errors. This measurement certainly cannot be ignored, but a firm conclusion that the electron has a mass of a few tens of eV will probably have to wait confirmation by one or more of the experiments described below.

DOUBLE BETA DECAY




When the ground state of the nucleus (A, Z + 1) is more massive than (A,Z) then beta decay cannot occur. However, if the nucleus (A, Z + 2) is lighter than (A,Z) then not only is double beta decay allowed but it will not be masked by the normal weak process. We show in Fig. 1 the example of $^{130}$Te in which the combination occurs. In the Tellurium case, this combination occurs also in $^{128}$Te but with much less energy difference between $^{128}$Te and $^{128}$Xe. Double beta decay is a conventional process within the framework of the

second order weak theory. The theory is sufficiently well established that it is expected that the nuclear matrix element should be calculable and certainly the four body phase space should be also. The matrix element has been calculated most recently by Haxton[2] et al. with a prediction that the lifetime should be $10^{20}$ years.

Double beta decay has been searched for in Tellurium ores that have been dated as being more than $10^9$ years old with the result shown in Fig. 2.

These results are from Kirsten et al.[3] and come from a mass spectrometer scan of Xe extracted from the ore. Ores must be selected that will not have much natural Xe occluded and since $X^{122}$ is not accessible by double beta decay it offers a measure of the natural Xe in the sample. It is obvious that there is a strong $^{130}$Xe signal, and this represents clear evidence for double beta decay.

The lifetime measured from this experiment for $^{130}$Xe is $2.55 \pm 0.30 \times 10^{21}$ years in clear conflict with the calculation. A way out of this problem is to look at the ratio of the lifetimes of $^{128}$Xe and $^{130}$Xe in the expectation that the matrix elements will be the same and the ratio is given by the phase space factor. The amount of $^{128}$Xe in the sample from natural Xe is estimated from $^{132}$Xe with known atmospheric abundances. There is then no evidence for any $^{128}$Xe from double beta decay in accord with the expectation from the 4 body phase space factors.

Neutrinoless double beta decay

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

will violate lepton number through a mechanism involving finite mass neutrinos or right handed currents. Because the phase space factor is for two fermions, the ratio is much less pronounced than for four fermions and if the $^{130}$Xe were neutrinoless then the $^{128}$Xe signal should be much stronger than it is. Kirsten et al. have used this limit on $^{128}$Xe from double beta decay to set limits on the neutrino mass ($m_\nu < 5$ eV) or the amount of right handed currents ($\eta < 2 \times 10^{-5}$). Although this ratio argument for the matrix elements may be right, the large discrepancy in the absolute value is a worry.

Our next two papers are searches for neutrinoless double beta decay directly by observing the total energy of the electrons. Unfortunately, background processes limit them to neutrinoless decay and the discrepancy in the nuclear matrix element calculation for the Tellurium measurements makes a similar estimate for neutrinoless beta decay correspondingly uncertain.

## OSCILLATIONS

The three neutrino flavors $\nu_e$, $\nu_\mu$, $\nu_\tau$ appear to have a separate lepton number to good approximation. If there is a violation of this number with mixing between flavors and if the masses of the neutrinos are not degenerate, then neutrino oscillations can occur. The probability that neutrinos of type 2 at a distance $\ell$ is

$$P_{1\to 2} = \sin^2 2\theta \sin^2\left(1.27 \sin^2 \Delta m^2 \frac{\ell}{E_\nu}\right)$$

where $\sin^2 2\theta$ is the mixing parameter, $\Delta m^2 = m_1^2 - m_2^2$ in $eV^2$, $\ell$ is the distance from the source in meters and $E_\nu$ the neutrino energy in MeV. This simple treatment may be readily extended to the case of three or more families. In order to test the oscillation hypothesis, a nearly pure beam of one type is used either with low energy neutrinos ($= \nu_e$) or high energy neutrinos above the pion production threshold ($= \nu_\mu$). Low energy neutrinos are used from reactors, including the Sun, and high energy neutrinos are used from accelerators or cosmic rays. Within these limitations there are two classes of experiments, disappearance experiments are also where the beam attenuation with distance may be other than that explained by solid angle effects, and appearance experiments where neutrinos of different flavor are detected in anomalous quantities at a distance from the source. At present there is one experiment which has seen evidence for oscillations at the Bugey reactor.[4] The detector was placed alternately at 13.6 and 18.3 from the 2775 MW reactor core, and detected the reaction

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

The target was liquid scintillator and was used to measure the positron energy to ≈ 20% FWHM. The neutron was detected also in delayed coincidence after thermalization in a $^3$He proportional counter. The detector is enclosed in a veto structure to eliminate cosmic rays and the experiment is largely background free. The principal experimental data is the positron energy spectrum which apart from small recoil effects is 1.8 MeV lower than the incident neutrino spectrum. This is a very high statistics experiment as reactor experiments go, because of the closeness of the detector and the high reactor power.

The reactor properties and the detector response are simulated in great detail, with a prediction of the shape and magnitude of the positron spectrum. The experimental accuracy is greatest in the measurement of the ratio of the spectra and this corrected ratio is significantly different from unity with the far position having a lower yield. The argument of $\sin^2(1.27\ \Delta m^2 \ell/E_\nu)$ is approximately 0.9 for $\Delta m^2 = 0.2\ eV^2$ which is nearly an optimum value, but at this wavelength there is not much distortion of the positron spectrum shape. So the experiment basically rests on the relative total yield of the two spectra, far and near.

Many checks have been made, and the experiment cannot be lightly dismissed. We await confirmation however before accepting the fact that neutrino oscillations do occur.

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