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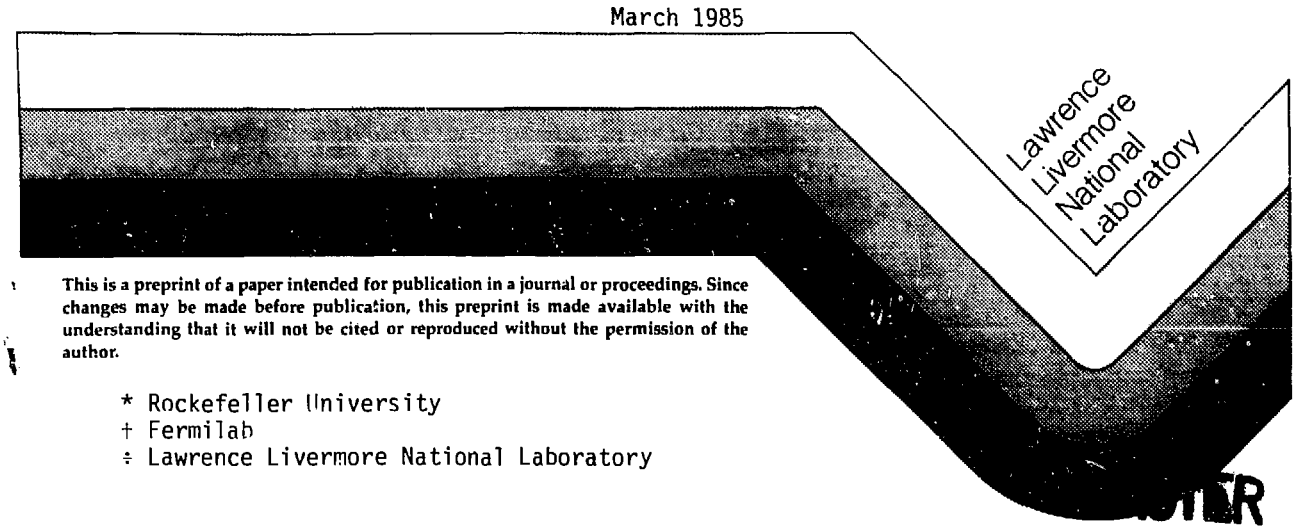

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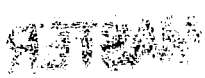

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ABSTRACT

We are performing an experiment to determine the electron neutrino mass with the precision of a few eV by measuring the tritium beta decay energy distribution near the endpoint. Key features of the experiment are a 2 eV resolution electrostatic spectrometer and a high-activity frozen tritium source. It is important that the source have electronic wavefunctions which can be accurately calculated. These calculations can be precisely made for tritium and the HeT^+ daughter ion and allow determination of branching fractions to 0.1% and energy of the excited states to 0.1 eV. We discuss the excited final molecular state calculations and describe the experimental apparatus.

The goal of our experiment is to measure the neutrino mass to better than 2 eV. If the neutrino mass is finite, the tritium beta decay energy distribution changes appreciably only within a few neutrino masses from the endpoint (see Figure 1). For a zero neutrino mass, the fraction of decays within 2 eV of the endpoint is only 2.6×10^{-12}. This small fraction dictates a low-background high-resolution spectrometer with large acceptance. After beta decay, the resulting atom or molecule can be left in one of many excited states. These excited states take energy from the emerging beta and give rise to a number of branches in the Kurie plot each with a different endpoint energy (see Figure 1). The sum of these branches results in the observed Kurie plot. A believable physics result emerges only if one knows the occupation fractions and energies of these final excited states and hence, the expected shape of the measured distribution. In addition, the spectrometer resolution function must be well understood. Long tails in this function can introduce a significant smearing in the tritium beta decay spectrum. Such effects greatly complicate the interpretation of the data. Finally, the emerging electrons undergo a dE/dx loss in the source itself. Ideally, a measurement of the dE/dx loss is made and a consistant neutrino mass is determined in sources of different thicknesses.

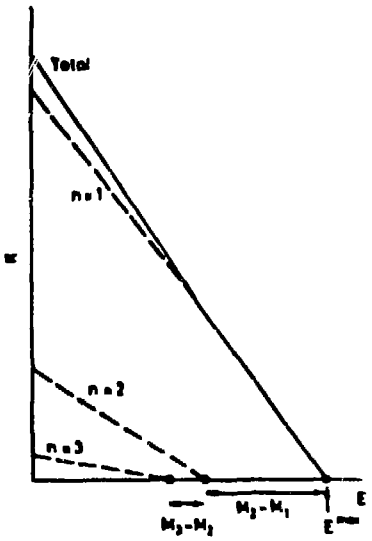

Fig. 1a

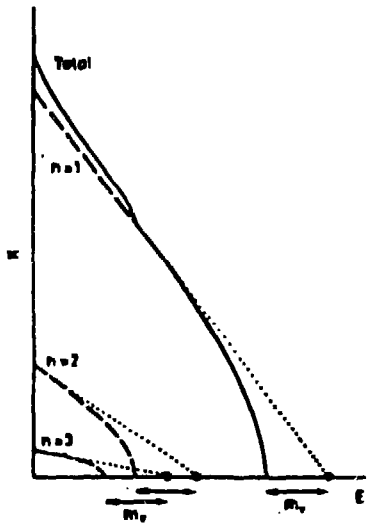

Fig. 1b

Fig. 1. A finite neutrino mass affects the shape of the Kurie plot only within a few m_ν of the endpoint as shown by contrasting Fig. 1a for zero neutrino mass and in Fig. 1b for finite neutrino mass m_ν. In addition, the effects of three final states on the Kurie plot are shown.

For most complex molecules or tritium binding processes, the final state effects are not calculable with sufficient precision. However, molecular tritium (T_2) at liquid helium temperatures is ideal because the low intermolecular binding energy (on the order of 1/400 eV) means it essentially has the electronic wavefunction of the free T_2 molecule. Two independent groups are performing the final state calculations for molecular tritium. Each group has a quite different approach. N. Winter[1] determines the electronic wavefunction from a complete configuration interaction calculation. W. Kolos[2] and his coworkers determine the electronic wavefunctions by minimizing the energies using 100 to 200 term elliptic wavefunctions. Both groups determine the nuclear wavefunctions by solving Schroedinger's equation for the potential energy curve for each of these electronic states. For the bound states, the nuclear wavefunctions are determined for each vibrational and rotational quantum state. As will be discussed below, the initial state for the molecule can be accurately taken as the ground electronic state and the ground nuclear motion state. On the other hand there will be a distribution of final states in each degree of freedom.

The lowest electronic states for the HeT^+ daughter ion as a function of the helium-tritium internuclear distance are plotted in Figure 2. The transition probabilities to each of these states are shown as a function of the HeT^+ internuclear separation in Figure 3. This figure shows that most of these states have the wrong electronic configuration to have any appreciable transition probability. With the initial T_2 internuclear separation of 1.4 A. U., there are only five electronic states, including the ground state, which have sufficiently large transition probabilities to give rise to distinct branches in the Kurie plot. As is expected from the closeness of the T_2 and the HeT^+ ground state internuclear separations, most of the probability occurs for a transition to the HeT^+ ground state. The probability of finding the HeT^+ ion in the ground state after the decay is approximately 60% which is to be compared with 70% in the decay of an isolated tritium atom.

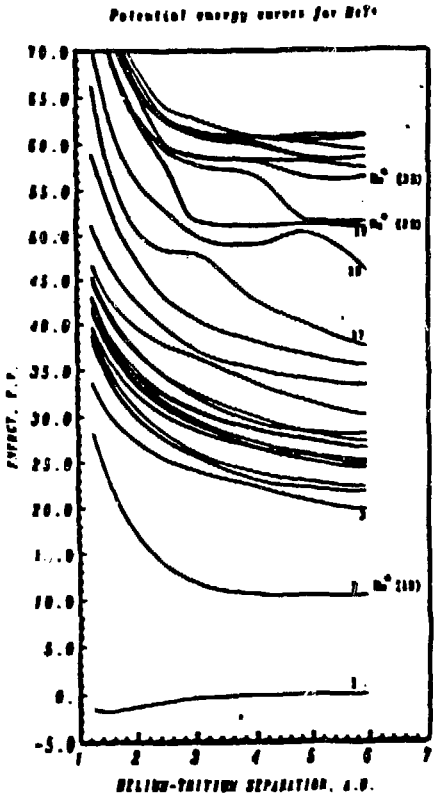

Fig. 2. The lowest 28 electronic states for the HeT^+ daughter ion as a function of the helium-tritium internuclear distance.

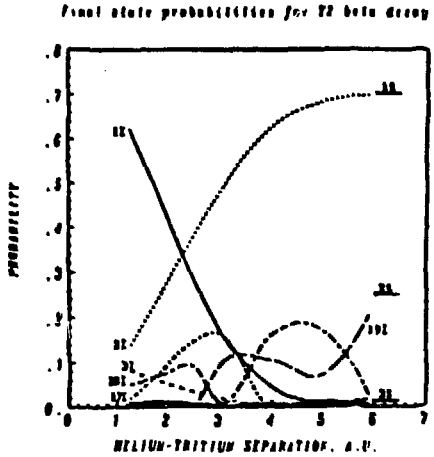

Fig. 3. The transition probabilities states from the T_2 state to the HeT^+ daughter ion states as a function of internuclear separation. For an initial separation of 1.4 A.U., only 5 states have significant probability.

Unlike the atom, however, the HeT^+ ion in its ground state has both vibrational and rotational degrees of freedom which can absorb energy from the decay beta. At the liquid helium temperature of our source, only the lowest vibrational and rotational states are populated. However, after the decay, when one of the atoms has been given an impulse from the decay beta, most of the possible vibrational and rotational states will be populated. Fortunately, even near the endpoint of the beta decay spectrum where the maximum energy transfer to the nucleus can occur, the energy transferred to the nucleus is too small to dissociate the HeT^+ daughter ion an appreciable fraction of the time.

The HeT^+ is primarily excited to a high vibrational state when, near the endpoint of the beta decay distribution, the decay beta is emitted nearly aligned with the internuclear axis. Conversely, the HeT^+ ion is left in a highly excited rotational state when the decay beta is emitted nearly perpendicular to the internuclear axis. This coupling between the beta decay and the vibrational and rotational states gives a high density of states near the top of the potential well (see Figure 4). The full width of this distribution is about 2 eV and the full width at half height is on the order of 1 eV. As a consequence of this small spread, the ground state branch in the Kurie plot is smeared by only an average of 1 eV. This additional spread is a small penalty to pay for the ease of using molecular rather than atomic tritium.

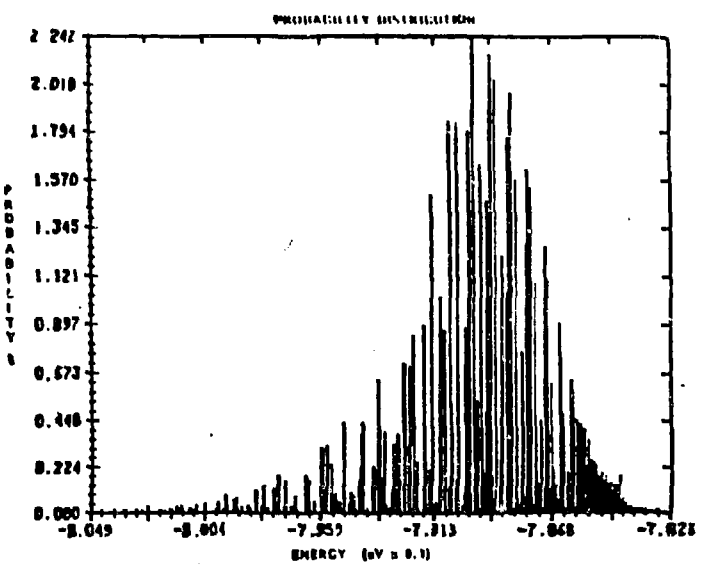

Fig 4. Probability distribution of ending up in various states for the HeT^+ electronic ground state due to rotational and vibrational excitations. The full width at half height is about 1 eV.

Our source is actually solid tritium rather than a free molecule. Nevertheless, the tritium molecular wavefunction in the frozen solid is very close to the molecular wavefunction of the free molecule. We can understand this qualitatively by noting that the tritium melting temperature implies that the intermolecular binding energy is very much less than the orbital electron binding energy. Consequently, we can expect a very small perturbation on the molecular wavefunction because of intermolecular binding forces. Quantitively, the electron probability density halfway to the nearest molecular neighbor is approximately 3×10^{-4} of the maximum. This small electronic overlap gives rise to a negligible distortion of the molecular wavefunction. The depth of the internuclear potential well is approximately 1,600 times deeper than the intermolecular potential well. This difference in binding energies also indicates a very small perturbation of the molecular wavefunction in the solid.

A theoretical calculation of the change in the T_2 electronic wavefunction resulting from the effects of binding tritium in the crystal lattice was done by L. Stolarczyk, Warsaw (reported to us by H. Monkhorst, University of Florida). He symmetrically orthogonalized the wavefunctions and found that the fractional change in the wavefunction, $\Delta\psi/\psi$, is approximately 0.07%. This small change is not surprising since the inductive forces which bind the tritium molecules in the solid are typically one to two orders of magnitude smaller than the exchange forces which govern molecular binding.

The experimental evidence for a very small change in the electronic wavefunction resulting from the binding in the solid comes from Raman spectra in gaseous and solid hydrogen. The vibrational energy levels are determined by the shape of the internuclear potential well and the shape of this well is determined by the electronic wavefunction. The typical measured shift in the vibrational energy levels resulting from the binding in solid hydrogen is about 1/2000 eV. Since this energy shift is very small compared with the typical vibrational energy level spacing of about 0.1 eV, this is evidence for a very small perturbation in the molecular wavefunctions resulting from the intermolecular binding in the solid. Furthermore, the molecular binding forces are so weak that the rotational states are hardly perturbed and the molecules can rotate as though they were nearly free. Hence, we conclude that the uncertainty in the transition probabilities due to intermolecular binding in the solid is less than 0.1% and about 0.1 eV for the energy level uncertainties.

The experimental apparatus is shown in Figure 5. It is contained in a vacuum tank 0.9 m in diameter and 7 m long. The tank is passively shielded by 2 concentric magnetic shields giving a residual field less than 2 milligauss in the active region. The source is a liquid helium cooled plate on which tritium is frozen. Varying the amount of tritium gas introduced allows

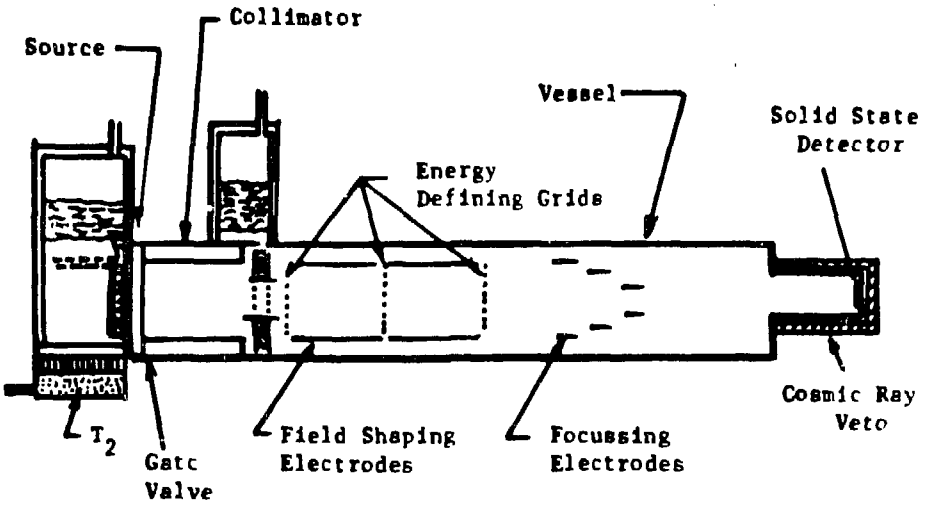

Fig. 5. Schematic view of the apparatus. The source at the left rotates from its vertical position to a horizontal position as shown by dotted lines.

source thickness variation from a few monolayers up to any thickness. Following the source, a variable-length collimater defines the angular acceptance of the electrons. The spectrometer consists of three equally spaced grid planes with field shaping electrodes around the axis. We measure the integral number of electrons whose energies are higher than the center grid potential. Electrons leaving the spectrometer pass through an electrostatic lens which focusses them onto a solid state detector. This detector simply counts the electrons but does have a 1 kev energy resolution which aids in rejecting low energy electrons and photons.

The experimental apparatus was tested in early fall by looking at the 7.3 keV electron conversion electrons from ^{57}Co. This line has an intrinsic HWHM of 0.6 eV. Our measurement of this line showed a HWHM of 2 eV. This measured distribuion is shown in Figure 6. The tail on the low energy side is due to the occurance of close-lying satellites of the conversion lines produced by accompanying shake-off excitations.

In conclusion, we have discussed why frozen tritium is an ideal source offering the highest activity per dE/dx of any material and offering fully calculable final state effects. These final state effects contribute less than 0.2 eV of uncertainty to the final possible determination of the neutrino mass. In addition, we have built a spectrometer with a measured resolution of better than 2 eV. As we complete the cryogenic components of the experiment, our Monte Carlo studies show that our frozen source and our apparatus will be able to determine the neutrino mass to better than 2 eV.

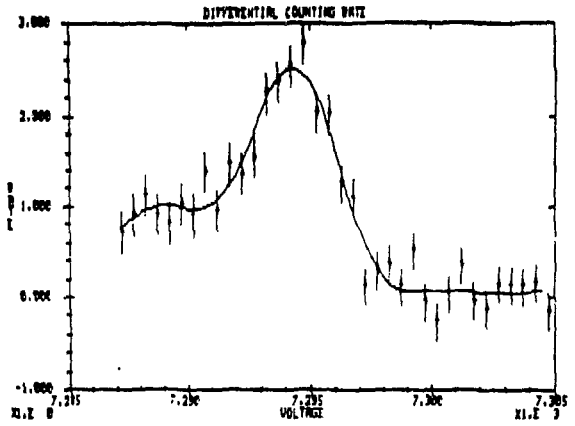

Fig. 6. Measured distribution of the 7.3 KeV conversion electrons from a ^{57}Co source. This line has an intrinsic HWHH of 0.6 eV. Our measurement has a HWHH of 2 eV.

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REFERENCES

1) N. Winter, Lawrence Livermore National Lab., and O. Fackler, to be published.
2) W. Kolos, B. Jeziorski, K. Szalewicz, H. Monkhorst, to be published.