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The logo of the Lawrence Livermore National Laboratory, featuring a stylized 'U' shape composed of three horizontal bars of increasing length, followed by the text 'Lawrence Livermore National Laboratory' in a sans-serif font, all contained within a white rectangular box that is part of a larger graphic element.

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AN EXPERIMENT TO MEASURE THE ELECTRON NEUTRINO MASS  
USING FROZEN TRITIUM\*

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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. To make this measurement, we have built a spectrometer with a resolution of 2 eV. Our source is frozen tritium since tritium and the  $\text{HeT}^+$  daughter ion have electronic wavefunctions that can be calculated with high accuracy. We describe the experiment and discuss the excited final molecular state calculations.

The goal of our experiment is to measure the neutrino mass to better than 2 eV. For a finite neutrino mass, the tritium beta decay energy distribution changes most noticeably in an energy range only a few neutrino masses from the endpoint. For a zero neutrino mass, the fraction of decays within 2 eV of the endpoint is only  $2.6 \times 10^{-12}$ . This small fraction dictates a low background high resolution spectrometer with large acceptance. After beta decay, the resulting atom or molecule is 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 different endpoint energies. The sum of these branches is what is measured. A believable physics result emerges only if one knows the occupation fractions and energies of these final excited states. In addition, the measuring apparatus must be well understood. 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 consistent neutrino mass is determined in sources of different thicknesses.

For most complex molecules or tritium binding processes, the final state effects are not calculable with sufficient precision. However, molecular tritium ( $\text{T}_2$ ) at liquid helium temperatures is ideal because the low intermolecular binding energy means it essentially has the electronic wavefunction of the free  $\text{T}_2$  molecule. Two independent groups are performing the final state calculations for molecular tritium. The calculational approach is quite different. N. Winter<sup>1</sup> determines the electronic wavefunction from a complete configuration interaction calculation. W. Kolos and his coworkers<sup>2</sup> determine the electronic wavefunctions by minimizing the energies using 100 to 200 term elliptic wavefunctions. Both groups determine the nuclear wavefunctions for each of these electronic states by solving Schrodinger's equation for that potential energy

function. For the bound states, the nuclear wavefunctions are determined for each vibrational and rotational quantum state. As will be discussed later, 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.

Considering the states for the  $\text{HeT}^+$  daughter ion as a function of the helium tritium interaction distance shows that most of these states have the wrong electronic configuration to have any appreciable transition probability. With the initial  $\text{T}_2$  internuclear separation, 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  $\text{T}_2$  and the  $\text{HeT}^+$  ground state internuclear separations, most of the probability occurs for a transition to the  $\text{HeT}^+$  ground state. The probability of finding the  $\text{HeT}^+$  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.

Unlike the atom, however, the  $\text{HeT}^+$  molecule 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 the lowest rotational states of the  $\text{T}_2$  molecule 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 of the  $\text{HeT}^+$  ion will be populated.

The  $\text{HeT}^+$  ion is primarily excited to a high vibrational state when, near the endpoint of the beta decay distribution, the decay beta is

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emitted nearly aligned with the internuclear axis. Conversely, the  $\text{HeT}^+$  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. The full width at half height of this distribution is about 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.

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 fact 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. Quantitatively, the electron probability density halfway to the nearest molecular neighbor is approximately  $3 \times 10^{-4}$  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 conservatively that the uncertainty in the transition probabilities due to intermolecular binding in the solid is less than 0.5% and much smaller for the energy level uncertainties.

The experiment 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 helium-cooled plate with tritium frozen on it. Varying the amount of tritium gas introduced allows source thickness variation from a few up to hundreds of monolayers. Downstream of the source, a variable-length collimator defines the angular acceptance of the electrons. The electrons then pass through a spectrometer which 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 focuses them onto a solid state detector.

The experimental apparatus was tested in early fall by looking at the 7.3 keV electron conversion electrons from  $^{57}\text{Co}$ . As a result of this test, we conclude that the spectrometer has a resolution which is better than 2 eV.

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 1 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.

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

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