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# Proposal to isolate the origin of the 17-keV kink in the $\beta$ spectrum

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An experiment is proposed which can definitively test for the presence of a 17-keV neutrino in $\beta$ decay. By measuring the recoil ion direction and energy in coincidence with the emitted electron, the neutrino mass may be reconstructed. This method can also distinguish among more exotic explanations for a 17-keV threshold, such as radiative or Coulomb corrections, a nuclear excitation, or a fourth particle in the decay. Some details of a possible experiment using $^{35}$S are discussed.

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There has been much excitement generated by the recent measurements of a kink 17 keV below the end point in $\beta$ spectra. Positive results have been reported for the $\beta$ decay spectra of $^{3}$H, $^{35}$S, and $^{14}$C [1-4], and for the inner bremsstrahlung spectra of $\beta$ capture in $^{71}$Ge and $^{55}$Fe [5,6]. These results seem to confirm Simpson's 1985 report of a similar measurement in $^{3}$H [7], and may indicate that the electron antineutrino contains ~1% admixture of a 17-keV mass eigenstate. However, a number of experiments using $^{35}$S [8-12] and one with $^{63}$Ni [13] found no evidence for such a mixing. In a reanalysis of some of these earlier experiments, Simpson claims to find a 17-keV kink of approximately the expected magnitude [14,15]. Given the conflicting results, it is desirable to have an alternate method with which to search for the presence of a heavy neutrino in $\beta$ decay. In this paper a method is proposed which can give a definitive test.

In the $\beta$ decay of an atom there are three particles in the final state: the antineutrino, electron, and recoil ion. In a three-body decay, with the application of energy-momentum conservation, the mass of one of the final-state particles may be determined from a measurement of the four-momenta of the decaying particle and the other two final-state particles. The proposal is therefore simply to measure the three-momenta of the electron and recoil ion in the decay rest frame. Given the masses of the decaying atom, recoil ion, and electron, the antineutrino mass may be uniquely reconstructed.

Although a heavy neutrino has been the most popular explanation for the reported deviations in the $\beta$ spectra, there may be more exotic possibilities. The alternate interpretations entertained here are the following. (1) There is a small branching ratio for an excitation in the final-state nucleus. The additional rest mass in the final state in this branch would result in a threshold (~17 keV) below the end-point energy. (2) There is a small branch in which an additional particle or particles are emitted. A finite rest mass for the additional particle(s) would again result in a threshold below the end point. (3) The deviation from the expected spectra is a structure function effect inherent in the decay, such as due to radiative or Coulomb corrections. (4) Perhaps the least exotic possibility is that the deviations are due to systematic effects in the experiments rather than in the $\beta$ decay. Of course none of these alternatives would modify the $\beta$ spectrum in precisely the same way as a heavy neutrino. But, as discussed below, the method proposed here of measuring the recoil ion in coincidence with the electron can distinguish between a heavy neutrino and the above alternatives.

The necessity of measuring the recoil ion from the decay introduces some experimental complexity. The typical recoil ion kinetic energy is only a few eV. A gas phase source is therefore desirable in order that the ion escape the decay region unimpeded. If the kinematics are to be reconstructed from the electron and ion trajectories, the decay volume must be small with respect to the analyzing devices described below, and the source must be translationally cold relative to the recoil ion kinetic energy. One possibility which satisfies these three constraints is to use a supersonic beam of radioactive gas seeded with He. With the proper Laval nozzle, a very cold (~few K translationally) jet of relatively high density ($\sim 10^{14}$ cm$^{-3}$) can be formed [16]. The jet transports the sample gas through a small decay region of ~10 mm$^{3}$ viewed by the detectors (see Fig. 1).

An electron spectrometer defines a direction for the decay electron and measures its energy. There are several suitable detector configurations. Here a truncated spherical deflection electrostatic analyzer [17] (SDA) is considered. Such a spectrometer can have a relatively large acceptance of 1° in polar angle by a 20° azimuthal angle, relative to the gas jet. A scintillator in conjunction with a charged coupled device (CCD) array at the focus of the SDA detects the electrons. Only the azimuthal angle is resolved, giving a tolerable uncertainty in the electron direction of ±0.5°. It is reasonable to expect an energy resolution of ±500 eV in the region of interest for $^{35}$S

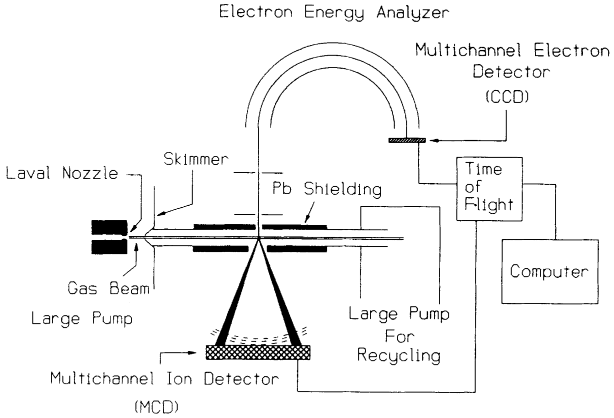

FIG. 1. Schematic of the proposed experiment.

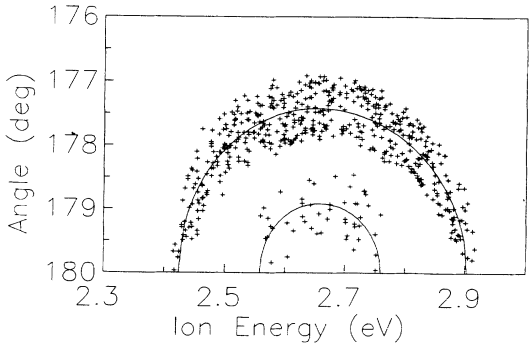

FIG. 2. Monte Carlo data of electron-ion angle vs ion energy for $^{35}$S decay. The upper branch is for $m_\nu=0$ and the lower branch is for a 10% (for clarity) mixing probability of $m_\nu=17$ keV. Electron energy is $148\pm0.5$ keV, angular uncertainty is $\pm0.5°$, and ion energy fractional uncertainty is $\pm8\times10^{-3}$.

around ~150 keV (see below). The spectrometer can simultaneously record events in a 15-keV window in electron energy around the kink.

The recoil ion is detected in coincidence with the electron by a multichannel detector (MCD). The electron-ion angle is determined from the position sensitivity of the MCD. The ion energy is given by the time of flight as determined by the difference in arrival times of the electron and ion at the respective detectors. For the MCD 25 cm from the decay volume, a typical ion time of flight from a $^{35}$S decay in the energy range of interest (see below) is ~65 μs. The largest uncertainty in the time of flight is expected to be due to the finite decay volume, rather than any intrinsic timing limitation. Given the small kinetic energy of the recoil ions (a few eV), electrostatic potentials must be well controlled within the experiment. This can be accomplished by avoiding contact potentials and with proper grounding. A schematic of the proposed experiment is shown in Fig. 1.

In order to demonstrate the utility of the proposed experiment, Monte Carlo data for $^{35}$S decay with $m_\nu=0$ and $m_\nu=17$ keV were generated. The standard weak decay matrix element with $g_A/g_V=1$ was assumed. The data were modified to include uncertainties in (1) electron-ion angle and electron energy due to the finite resolution of the electron spectrometer, and (2) ion energy due to the finite decay volume. The separation of heavy neutrino events was found to be most evident in plots of electron-ion angle versus ion energy. Such a scatter plot is shown in Fig. 2 for an electron energy of $148\pm0.5$ keV with an uncertainty in angle of $\pm0.5°$, and an ion energy fractional uncertainty of $\pm8\times10^{-3}$. For clarity the branching ratio of the heavy neutrino has been increased to 10%, and the solid curves are the constraints of energy-momentum conservation without experimental uncertainty. As can be seen, the heavy neutrino events in the lower branch are well separated from the massless events in the upper branch. In this example the electron energy is about 2 keV below the threshold for the heavy neutrino. As the electron energy approaches the heavy neutrino threshold from below, the lower branch in Fig. 2 becomes smaller, disappearing at the threshold. For electron energies well below the threshold, the effect of the finite neutrino mass on the kinematics is somewhat reduced. For the uncertainties given above, the two branches in fact begin to overlap at about 140 keV. With the SDA described above, this entire range plus a 5-keV window above the threshold can be recorded simultaneously. It should be noted that most of the scatter in Fig. 2 is due to the geometric acceptance of the electron spectrometer (this is the source of the sharp cutoff in the event distribution in Fig. 2). This uncertainty could be reduced by decreasing the angular acceptance of the electron spectrometer, but at the price of reduced event rate.

For the SDA described above, the coincidence event rate for a 1% branching ratio to the heavy neutrino is about 8 $h^{-1}$ over the 10-keV range in electron energy below the threshold in which the two branches are well separated. If the MCD is to detect all the coincident ions from heavy neutrino events in this range, it must subtend approximately 10° in polar angle by 30° in azimuthal angle relative to the gas jet. With such a relatively large detector and low coincidence signal rate, potential backgrounds must be well controlled. Accidental coincidences from multiple decays within the decay region turn out to be unimportant. By triggering on electrons and using angle and timing information, multiple decays give an average $S/N\sim20$ on the heavy neutrino branch. The magnitude of other backgrounds such as spurious electrons from high-voltage electrodes, decay products from adsorbed sulfur, and detector noise are harder to predict. But, for an average $S/N\sim1$ it is estimated that the *product* of the total uncorrelated background rates on the CCD and MCD must be less than ~50 $s^{-2}$. We believe background rates of this level are attainable. Active measures can help to reduce noise rates. For example, a negatively biased grid in front on the MCD can eliminate a large fraction of the spurious electron rate on the MCD.

As stated above, a heavy neutrino can be distinguished from other possible explanations for a deviation in the β spectrum. A nuclear excitation can mimic a heavy neutrino at a given electron energy, but the energy dependence is very different. For example, the Monte Carlo data of Fig. 2 is very well fit by a nuclear excitation of 9.7 keV. But in this case the threshold would be ~10 keV from the end point, which is easily distinguished from the heavy neutrino. If there are additional particles in the final state, the constraint of energy-momentum conservation between electron-ion angle and ion energy no longer holds (as for the three-body decay). The region below the lower branch would therefore be expected to fill in with some distribution. A structure function effect would of course not give the lower branch in Fig. 2. Rather, the expected number of data points on the massless branch would vary slightly with electron energy. Of course, if the reported deviations are due to experimental systematics in the previous experiments, only the massless branch would be seen. It might be noteworthy that if interesting events are observed, the Lorentz structure of these decays could be determined by spin polarizing the initial state or by measuring the electron polarization.

Finally, some comments about the choice of a radioactive source gas. The only atomic source with a low enough vapor pressure to be suitable for the present application is probably $^{35}$S. Atomic sulfur however poses some problems. The Laval nozzle must be heated to a high temperature since sulfur vaporizes as $S_8$ and only excess heat and catalytic help from the metal walls guarantees an atomic beam. The radioactive gas must also be recirculated to avoid a prohibitively large total radioactivity in the apparatus. This could be accomplished by condensing the sulfur on a thin flexible metal band which is cooled, through rollers, to liquid $N_2$ temperature. The metal band then transports the condensate to a heated chamber where the sulfur is revaporized and mixed with He to be expanded in the nozzle.

The other possibility is to use a molecular source such as $H_2\,{}^{35}S$. In this case the Laval nozzle could remain at moderate temperatures; and the sample gas could be recirculated with more conventional pumping techniques. However, reconstructing the recoil ion energy and direction is now more problematic. After the decay to $H_2Cl^+$ there is $\sim$400 eV of excess energy in the atomic electron distribution due to the additional nuclear charge. This energy is released in less than $\sim 10^{-16}$ s by the emission of some number of Auger electrons with $\sim$90% probability, or x rays with $\sim$10% probability [18]. For the former decay modes the momentum kick from the Auger electron(s) is enough to wash out the separation between the two branches in Fig. 2. In addition, the multiply charged ions $H_2Cl^{n+}$ dissociate to $H^+ + HCl^{(n-1)+}$. The Auger decay modes must therefore be separated from those with x rays, for which the momentum kick is negligible and the recoil ion $H_2Cl^+$ is stable. The multiply charged decay products can be rejected by a set of biased grids in front of the MCD. The singly charged $H^+$ and $HCl^+$ from the Auger branch turn out to be well separated by timing from the region of interest in Fig. 2. This leaves only the x-ray decay mode as signal. Although the accepted signal is now reduced by a factor $\sim$10, the background is also reduced by a similar amount.

In conclusion it should be noted that since the interesting decay events are well separated from the massless ones, the method described in this paper does not require a precise characterization of the detector efficiencies and background counts as a function of energy, as do the $\beta$ spectrum experiments. It is therefore especially well suited to resolve the current controversy surrounding the reported deviations in the $\beta$ spectrum.

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