Evidence of Heavy-Neutrino Emission in Beta Decay

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The observation of a distortion of the β spectrum of tritium is reported. This distortion is consistent with the emission of a neutrino of mass about 17.1 keV and a mixing probability of 3%.

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There is considerable interest today in whether neutrinos have mass or not. Since it has been known for some time that the energy spectra of β particles will show a distortion at the threshold energy for the emission of a heavy neutrino[1,2] the spectra can be used to look for a massive neutrino and to determine the amplitude of mixing with the predominantly emitted light neutrino. This might be the only viable way, in the forseeable future, for determination of the mass of the muon neutrino (i.e., the mass of the neutrino which is dominant in π-μ decay) if it is much less than the present limit of 500 keV.[3] At least two dedicated experiments to search for neutrinos in the mass ranges 100 eV–10 keV and 30–460 keV using tritium[4] and ^{64}Cu β decay[5] have been carried out with negative results. This paper presents evidence for a distortion of the β spectrum of tritium which is consistent with the emission of a heavy neutrino of mass about 17.1 keV and with a mixing probability of about 3%.

The experiment consisted of the study of the β spectrum of ^{3}H implanted in a Si(Li) x-ray detector. The general method has been described in detail previously[6] and only a general description and differences from Ref. 6 will be presented here.

Tritium accelerated in an FN tandem Van de Graaff accelerator was implanted at energies from 10.5 to 15 MeV in a Si(Li) detector (Ortec model, 200 mm^2 area) using a rastered beam to achieve uniform implantation over the central portion of the detector. The estimated depth of the tritium in the silicon is from 0.25 to 0.45 mm. The β count rate after implantation was about 300/s, and the resolution function for 6-keV x rays was about 220 eV. Various experiments have indicated that tritium is very strongly bound in the detector after implantation and does not diffuse even at room temperature. (See Ref. 6 and references quoted therein.) The decay of tritium has been followed with this detector over a period of four years and the half-life has been determined[7] to be 12.35 ± 0.03 yr, in very good agreement with published values.[8]

The recording of the β spectrum was carried out in a manner similar to that described in Ref. 6, with the exception that x rays from Br as well as Cu and Mo were used for calibration, the zero level of the analog-to-digital converter (ADC) was stabilized with a precision pulser (BNC model PB-4), and the gain was stabilized on the Mo $K\alpha$ x rays. The x rays which were incident upon the detector through the slot in an x-ray chopper wheel intermittently with a period of a minute were analyzed by the same ADC (Tracor Northern TN-1242) as the β spectra but routed to the second half of memory of a multichannel analyzer. The integral linearity of the preamplifier, amplifier, and ADC was tested with the precision pulser and the ADC differential linearity with a ramp pulser.

The amplifier used was an Ortec model 572 operating with 6-μs shaping time constant to achieve a compromise between resolution and avoidance of spectral distortion (pileup) resulting from the chance occurrence of two nearly simultaneous β decays. In one run a pile-up rejection signal from the amplifier was used to veto piled-up pulses, and in two others this was not done in order to check that the rejection process did not create an artifact in the spectrum. The spectra were recorded with a dispersion of about 9 eV/channel over 2048 channels.

Figure 1 shows a portion of the β spectrum from just above the noise of the detector to about 5.5 keV in which a marked distortion is evident at about 1.5 keV and below. Figure 2 shows a portion of the Kurie plot. The Kurie plot is defined by $K = (N/pEF)^{1/2}$ vs T, the kinetic energy of the β particles. Here N is the number of β particles at an energy E and momentum p. The Fermi function F used is given below. Because of the difficulty of energy calibrating an x-ray detector below about 6 keV the calibration was established in the following way. The x rays of Cu and Br, and the Mo $K\alpha$ x ray were used to determine a linear calibration (with a typical rms deviation of 6 eV). The precision pulser was then used to measure the pulse-height response over the whole ADC range. This was combined with the x-ray calibration to determine a calibration curve over the whole energy range. At low energy there was a slight nonlinearity amounting to a deviation of about 20 eV at an energy of 1 keV from the prediction of the linear calibration curve based on the x-ray energies. The nonlinearity was accounted for by the addition of a small quadratic term to the calibration curve. The number of counts was then corrected for the changing dispersion.

The data were analyzed by fitting the β spectra in the region from about 0.7 keV to 3.2 keV to a theoreti-

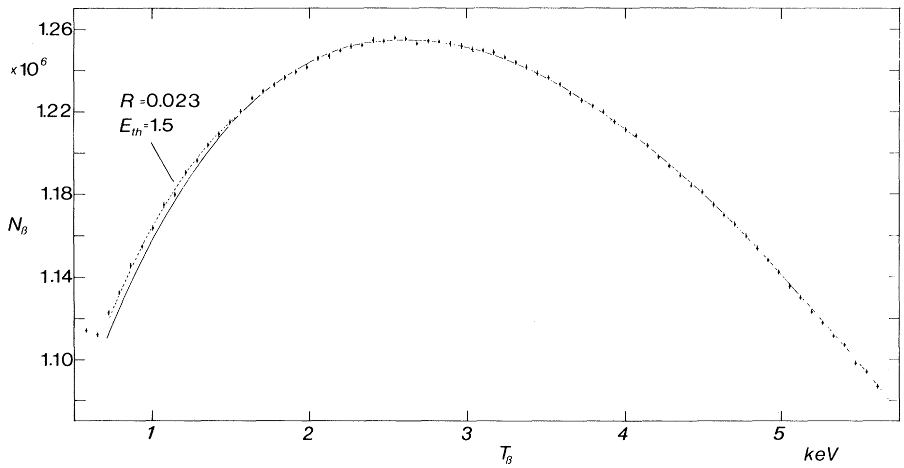

FIG. 1. A portion of the β spectrum of tritium. The next point to the left of the lowest energy point plotted is off scale at 1.6×10^6 counts. The smooth curve is the β spectrum without a massive neutrino and the dashed curve shows the change associated with a heavy neutrino.

cal spectrum of the form

$$N_\beta(E,Z)=N_\beta(E,Z,M_1)+RN_\beta(E,Z,M_2), \quad (1)$$

where $N_\beta(E,Z,M)$ is the usual β energy spectrum for the emission of a neutrino of mass M,

$$N_\beta(E,Z,M)\propto pE[(Q-E)^2-M^2]^{1/2} \times (Q-E)F(E,Z). \quad (2)$$

Here, Q is the total energy available for the transition and R measures the intensity of the second neutrino branch. Each term holds only for $(Q-E)>M$. The mass M_1 was set equal to zero. A nonrelativistic Fermi function $F(E,Z)$, given in Ref. 6, was used but with the addition of the screening correction of Rose.[9,10] The theoretical β spectrum was convolved with a Gaussian resolution function of width 220 eV as determined by the pulser. The background, measured prior to implantation, amounts to about 10^{-4} of the β counts in this region and has been subtracted.

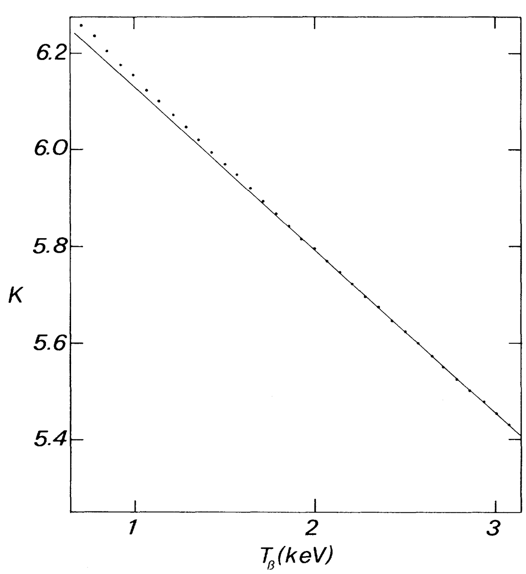

FIG. 2. A portion of the Kurie plot as a function of β kinetic energy of tritium (run a). The errors are the size of the plotted points.

In fitting, Q, M_2, R, and an overall normalization were varied. While Q is now well determined[11] to lie between about 18.57 and 18.61 keV, it was necessary to allow it to vary to achieve a good fit in the energy range of interest which is a long way from the end point. Incomplete pile-up rejection, inadequacy of the screening correction to $F(E,Z)$, and any remaining inaccuracies of the energy calibration could account for obtaining a Q value different from the true one. [In fact, as Table I shows, the end-point energy determined by the fit in the experiment with active pile-up rejection (run a) is quite close to the true value, and is closer than when no rejection is used, suggesting that incomplete pile-up rejection is probably the dominant error.]

The results are shown in Table I and Fig. 3. In the

TABLE I. Parameters giving reasonable fits with two neutrinos to the β spectrum of tritium.

Run	Q (keV)	End-point energy for second neutrino (keV)	R	Minimum χ^2/ν
a	18.7–18.9	1.4–1.8	0.020–0.030	38/34
b	19.0–19.3	1.2–1.6	0.030–0.050	49/34
c	19.1–19.3	1.4–1.8	0.017–0.028	43/34

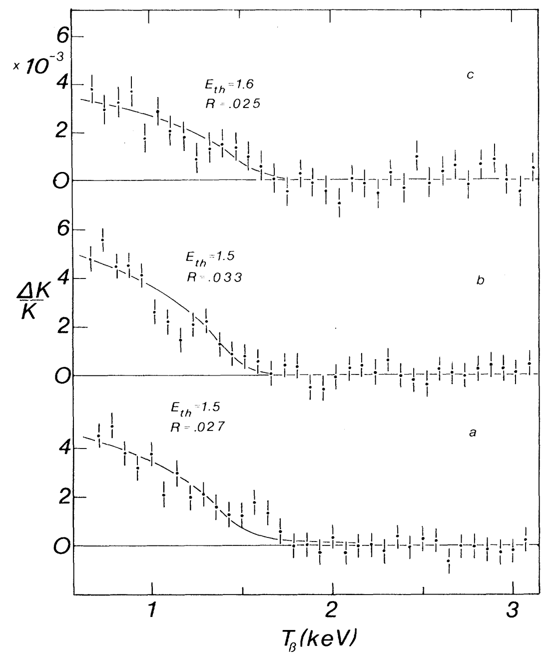

FIG. 3. The data of three runs presented as $\Delta K/K$ vs the kinetic energy of the β particles. The smooth curves are representative examples derived from the fitted β spectra including effects of the resolution function. E_{th} is the threshold or end-point energy in kiloelectronvolts. Run a included active pile-up rejection, b used no pile-up rejection, and c was the same as b except that the detector was housed in a sound-proof box.

latter the deviation ΔK of the Kurie plot K with nonzero M_2 from that with $M_2=0$, divided by K, is plotted versus energy. It can be shown that, neglecting resolution effects,

$$\Delta K/K \sim R[1-M_2^2/(Q-E)^2]^{1/2},$$

and consequently all experiments should show about the same deviation. This is seen to be adequately represented by the data in Fig. 3. The smooth curves in Fig. 3 are representative calculations of $\Delta K/K$ derived from the fitted β spectra, including resolution-function smearing. The experiments favor a threshold for the emission of a heavy neutrino at about 1.5 ± 0.2 keV, with R in the range from about 2% to 4%, larger threshold energies being correlated with smaller values of R. Taking the end-point energy of tritium as 18.6 keV gives a neutrino mass of 17.1 ± 0.2 keV. To my knowledge, this result is not in conflict with any previous experimental limits for heavy-neutrino emission from β-spectra searches[1,4,5] or searches for neutrino oscillations at reactors.[12]

There are many implications of such a massive neutrino:

(1) If this neutrino is the dominant neutrino associated with the muon or the τ lepton then it will be extremely difficult to measure its mass by conventional means.

(2) The value of R corresponds to a mixing amplitude $\sin\theta$ of about 0.14 to 0.20 if

$$|\nu_e\rangle = |\nu_1\rangle\cos\theta + |\nu_2\rangle\sin\theta \qquad (3)$$

is the electron neutrino wave function. This value is quite close to that of the Cabibbo angle in the quark sector.

(3) If Eq. (3) represents the dominant components of the electron neutrino, then neutrino oscillations cannot account for missing solar neutrinos.

(4) If neutrinos are Majorana particles, Eq. (3) would imply that neutrinoless double-β decay should go at a rate approximately 2000 times the present limit. This tends to suggest that neutrinos are Dirac particles although a possible alternative has been discussed.[13] There will also be implications in other areas such as cosmology.

In summary, the β spectrum of tritium recorded in the present experiment is consistent with the emission of a heavy neutrino of mass about 17.1 keV and a mixing probability of about 3%. The effects of such neutrinos should be seen in all β spectra for which their emission is energetically allowed.

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