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MEASUREMENT OF THE β-SPECTRUM OF ^{3}H WITH A Si(Li) DETECTOR FOR DETERMINING $m_{\bar{\nu}_e}$

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ABSTRACT

An experiment to measure the β-energy spectrum of tritium implanted in a Si(Li) X-ray detector has been investigated as a method to determine the mass of the electron anti-neutrino and the ^{3}H-^{3}He atomic mass difference. Present results imply a mass < 65 eV with 95% confidence and an end-point energy of 18567 ± 5 eV.

INTRODUCTION

An experiment has been carried out using tritium implanted in a Si(Li) X-ray detector to determine the mass $m_{\bar{\nu}}$ of the electron anti-neutrino in tritium β-decay and the atomic mass difference between ^{3}H and ^{3}He. Compared to magnetic spectrometer methods of determining the same quantities[1,2], this method has the advantage that the whole β-energy spectrum can be recorded simultaneously and at the same time as calibration spectra, and that final state effects do not complicate the analysis as much. This advantage is paid for by the rather worse energy resolution of the Si(Li) detector than of a magnetic spectrometer. However, the measurement of a large part of the β-spectrum permits an analysis procedure which can compensate for the worsened resolution. (This work was first reported at Neutrino '79, Bergen[3].)

EXPERIMENT

The experimental details are briefly as follows. (A full report will be published in Physical Review D.) A defocussed beam of tritons (0.25 nA) from the McMaster FN tandem accelerator was implanted into a commercially obtained Si(Li) detector (80 mm^2 in area) in steps of 100 keV from 8 MeV to 9.1 MeV as shown in fig. 1. Implantation was stopped when a worsening of resolution became apparent.

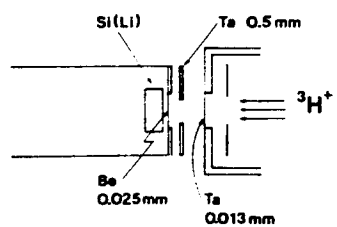

Fig. 1. Implantation of ^{3}H into a Si(Li) detector.

The energy spectrum of the β-particles was routed into one half of a multi-channel analyzer memory and a spectrum including Cu, Mo and Ag X-rays which were intermittently shone on the detector every

few seconds was routed through the same ADC into the second half (see fig. 2). The X-rays were used for gain stabilization and calibration.

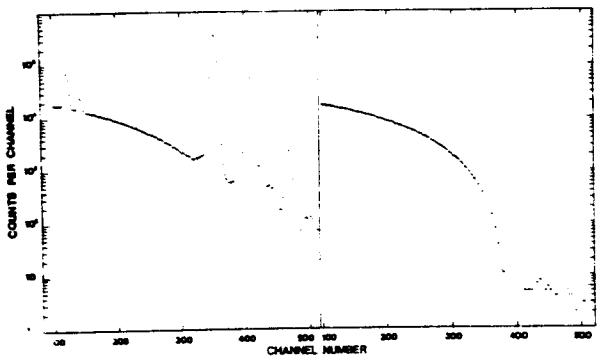

Fig. 2. Typical spectrum of ^3H β-decay. The left half shows the spectrum with the calibration X-rays included and the right half the β-spectrum only.

Pulse pile-up rejection was also used. After four spectrum recordings were made (one at a different detector bias), an annealing procedure was carried out which returned the resolution to its pre-implanted shape with no apparent loss of tritium. Three further recordings were carried out after this. In fig. 3 is shown the Mo K_α doublet obtained prior to annealing (a) and after annealing (b). The smooth curves are the fitted resolution functions used in the data analysis.

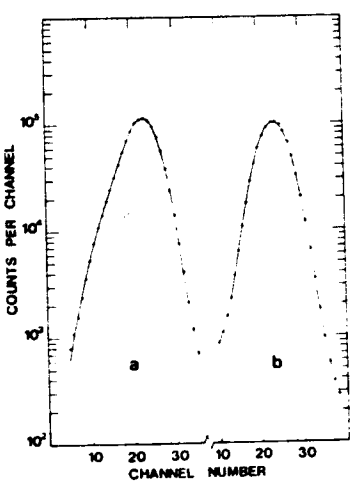

Fig. 3. Mo K_α doublet (E = 17.443 keV) recorded in the detector simultaneously with the β-spectrum.

RESULTS

The data were analyzed by folding the resolution function determined from the X-ray spectra with the theoretical spectrum for allowed β-decay, correcting for the finite width of the K X-rays, fitting the result to the data in the region from about 9.5 keV to 17 keV, and searching for a minimum in χ^2 as a function of β-end-point energy. Background determined from the region above the end-point had been subtracted. All fits were good and no systematic deviations from the allowed shape were found (fig. 4). The normalized χ^2 minimum was 0.95, corresponding to a 90% confidence level.

The region of the end-point was then analyzed for $m_{\bar{\nu}}$. This was done by determining a ratio $R(m_{\bar{\nu}})$ of the total number of counts in the β-spectrum in the most sensitive region (∿ 18.1 - 18.7 keV) relative to the number expected for $m_{\bar{\nu}} = 0$ from the best fit to the spectrum in the region 9.5 to 17 keV. Fig. 5 shows representative Kurie plots (a) for a pre-annealing run and (b) for a post-annealing run. Note that the theoretical curves have not been fitted in the end region. Fig. 6 shows the ratio $R(m_{\bar{\nu}})$ measured experimentally (data points) and expected theoretically as a function of $m_{\bar{\nu}}$.

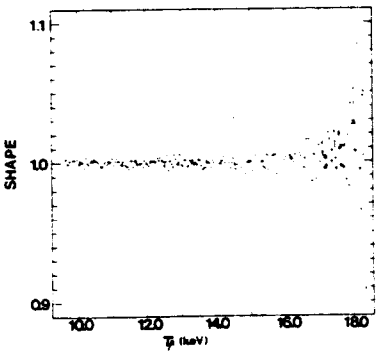

Fig. 4. Shape spectrum of tritium β-decay. The ordinate is the experimental number of counts divided by the theoretical after least squares fitting. The abscissa is the kinetic energy of the β-particles.

The average value of $R(m_{\bar{\nu}})$ from the pre-annealing runs is 1.002 ± 0.017 and from the post-annealing runs is 0.996 ± 0.013. Averaging these together gives a ratio $R(m_{\bar{\nu}})$ of 0.998 ± 0.011 implying $m_{\bar{\nu}} <$ 65 eV with 95% confidence and a best value of 20 eV which is however only 0.2 S.D. from a mass of zero.

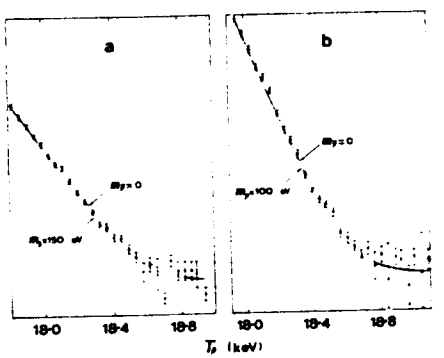

Fig. 5. Kurie plots. The theoretical (smooth) curves are not fitted but extrapolated from the fitting region (see text).

Previous 90% confidence levels on $m_{\bar{\nu}}$ are 55 eV[1] and 35 eV[2]. Recently however a report[4] gives a value of 34 ± 4 eV (1 S.D.) for $m_{\bar{\nu}}$ and a 99% confidence limit of $14 < m_{\bar{\nu}} < 46$ eV. Unfortunately, the authors do not comment on the apparent discrepancy between this new result and their earlier result[2].

One advantage of the present method is that there is only one final atomic state, ^3He neutral in its ground state in a silicon lattice, compared to the multiplicity of ionic states, $^3He^+$ (1s), $^3He^+$ (2s) etc. which in the case of β-spectrometer measurements leads to a spread of β-energies of about 40 eV. The reason for the unique final state is that the charge collection time in a Si(Li) detector is long (many μs) compared to the neutralization and de-excitation times of $^3He^+$ ions in silicon and hence the energy released in these processes is added to the β-energy. Therefore the initial and final state can be considered to be a free ^3H atom and a free ^3He atom and the end-point energy will give the ^3H-^3He atomic mass difference directly. The post-annealing end-point energy is 18567 ± 5 eV. There may however be corrections of a few eV to this for effects such as the binding of ^3H to the silicon lattice. The present value of the ^3H-^3He atomic mass difference is considerably lower than Bergkvist's value[1] of 18651 ± 16 eV and somewhat lower than the mass-spectrometer measurement of Smith and Wapstra[4] of 18600 ± 7 eV.

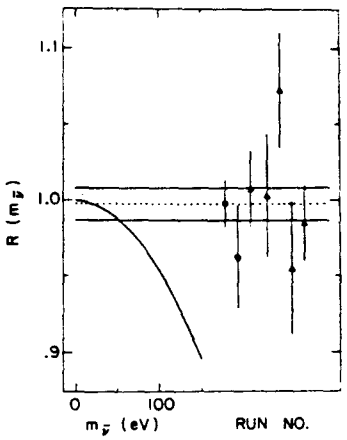

Fig. 6. The final results on $m_{\bar{\nu}}$. The ordinate is the number of counts in the sensitive region divided by the number expected for $m_{\bar{\nu}} = 0$. On the right are shown the results of the various runs (pre-annealing ▲ , post-annealing •). The horizontal dashed line is the weighted average of all runs, with a standard deviation shown by the horizontal continuous lines. On the left the smooth curve shows the variation of $R(m_{\bar{\nu}})$ with $m_{\bar{\nu}}$.

CONCLUSION

Can the present method achieve a lower limit? One can show (Phys. Rev. D, to be published), assuming the neutrino mass to be zero, that the time to achieve an upper limit $m_{\bar{\nu}}$ on the mass requires a time t of counting which is given by

$$t \propto \frac{\Delta E}{D m_{\bar{\nu}}^4}$$

Here, ΔE is the detector resolution and D is the dose of tritium in the detector. Consequently, to lower the limit by a factor of two requires sixteen times longer counting period for the same D and ΔE, and hence efforts must go into increasing D by a factor of ten or so since unfortunately variation in ΔE is small for commercially available detectors. One could do this by increasing the number of detectors, or by increasing the dose per detector (or a combination of both). An advantage to increasing the dose per detector is that background will be less important. However, one must guard against effects of radiation damage or of changing impurity concentration in the detector.

From a strictly statistical view the present method can probably confirm a neutrino mass of 35 eV at the 95% confidence limit and a new experiment with a data acquisition rate an order of magnitude larger than the experiment described here is now in progress. However, experimental features will have to be carefully examined. Probably the most important is the resolution function for an internal β-ray source. In the present work the assumption has been made that the β-ray resolution function is given by the full energy peak of a spectrum of a photon of the same energy as the β-ray. This assumption is based on the fact that these photons primarily interact through the photoelectric effect thus generating photoelectrons which interact the same as β-particles, and on the observation that Si(Li) detectors are extremely linear in energy response down to very low energies (∿200 eV) thus indicating independence of the full energy peak of surface effects. Radiation damage, for example, might alter the situation because X-rays, unlike β-rays, sample more than just the implanted region (see fig. 3) and it is therefore desirable to limit or rid the detector of, if possible, radiation damage.

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