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AN UPPER LIMIT FOR THE ELECTRON ANTI-NEUTRINO MASS FROM TRITIUM β DECAY

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An upper limit for the electron anti-neutrino mass from tritium β decay *

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ABSTRACT - The end point region of the tritium β-spectrum is measured using a double focusing magnetic spectrometer. For the electron anti-neutrino mass an upper limit of $m_\nu < 12.1$ eV at 95%C.L. is obtained.

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1 INTRODUCTION

For more than fifty years physicists have paid considerable attention to whether a neutrino has rest mass or not, an important problem in the fields of particle physics and astro-physics. Because of the difficulties in experiments, only the upper limits of the neutrino mass were reported.

In 1980, the ITEP group[1] published the evidence for non-zero m_ν. In their later work, they proceeded improve their experimental instruments and methods, and came to the same conclusion — the electron anti-neutrino has finite mass, and a value of 17 eV < m_ν < 40 eV was reported in their latest paper[2]. The same experiment has been repeated using different magnetic spectrometers in different laboratories [3-7], none of them has got a result, indicating a finite neutrino mass.

Since 1981, the neutrino mass experiment has been in its development in CIAE. A new iron-core 255° double focusing magnetic separator was reconstructed as a high resolution β spectrometer with high luminosity for our measurement. The preliminary result of our measurement was reported in 1986 at Osaka symposium[8]. Since then, some calibration experiments have been performed and the experimental data have been re-processed. This paper is the final report of our measurement.

2 THE MEASURING INSTALLATION

The central trajectory radius of the CIAE double focusing β spectrometer is r_0=40 cm, the gap height 25 cm and the corresponding focusing angle is θ_f=255°. The initial

horizontal and vertical angles of the electron beam are within the ranges of ± 9 ° and ± 1.5 °, respectively and are defined by five apertures at different places, with a corresponding transmission coefficient of 0.13% and a momentum resolution of 0.02% in theory for monoenergetic linelike electron source[9].

For raising the luminosity of the spectrometer, we used Bergkvist[10] method of an extended source of 10 × 9 cm^2 with both energy and geometry compensation on the basis of electron optics. It was shown that the electrostatic potential distribution on the source surface and the geometry of the source should meet some requirements. As shown in Fig. 1. the incline angle between the source surface and the θ=0° plane at r=r_0 is 48°. The electrostatic potential with special distribution is applied on the source surface. To meet the above mentioned requirements, in theoretic calculation, we diveded the β source into a series of narrow strips each 0.05 cm in width. These strips were curved in the radius of curvature of about 16 cm, concaved to the centre of the spectrometer, so as to obtain a straight image on the detector. Under these conditions. the theoretical momentum resolution of the spectrometer was about 0.1% and the luminosity was 0.12 cm^2 [11].

The instability of the current to drive the magnet is less than 10^{-4} in a two-day's run. A point-like electron gun of 18.6 keV was used for calibration[12]. In the case of optimum resolution condition the momentum resolution was 0.02%, which is in agreement with the theoretical calculaton. Seventeen monoenergetic lines from ^{170}Tm, ^{169}Yb and ^{182}Ta were measured so that the linearity of the spectrometer could be tested.

A tritium labelled [3, 4, 5, 6-3H]PAD ($C_{14}H_{15}T_3O_2N_3$) of high specific activity was prepared. This tritium source is ~ 2$\mu g/cm^2$ thick which was measured by backscattering method[13] and 9.0 × 8.0 cm^2 in effective dimensions with the total strength of the source is about 70 mCi. The source backing is a high resistive film of $10^7\Omega$, through which the compensation potential is applied.

In order to measure the resolution function accurately, reference sources of monoenergetic internal conversion lines of ^{169}Yb and ^{170}Tm were used. The sources were vacuum evaporated on a pure aluminium backing and were cut into arc-like strips each 0.05 cm in width and 16 cm in radius of curvature. The source thickness is about 2$\mu g/cm^2$, and the radioactivity is about 100 $\mu Ci/cm^2$, while the non-uniformity is less than 10% [14]. The strips of Yb and Tm sources were uniformly distributed on the high resistive backing which was similar to the backing of the tritium source.

The detector[15] is a thin window proportional counter with P10 gas as working gas at a pressure of 3.3×10^4 Pa. The window is made of two or three layers of Formvar foils each in the thickness of 100 $\mu g/cm^2$. For the 23 keV electrons. the energy loss in the window is less than 2 keV, and the transmission factor is more than 95%. The data acquisition was performed by using a system composed of a low-noise charge-sensitive preamplifier, a linear amplifier and a multichannel analyzer. The energy resolution for the photo-peak of 5.9 keV X-rays of ^{55}Fe is 18%.

3 MEASURING METHOD AND RESOLUTION FUNCTION

Electrostatic scanning with constant magnetic field was used for measurement

of spectra , so that the hysteresis effect of the iron core of the spectrometer and the correction of the detector efficiency were avoided. However, the accepting solid angle of the spectrometer is a function of the scanning potential and was corrected experimentally by using ^{169}Yb-M and ^{170}Tm-K coversion lines with different scanning potentials[16].

The electrons emitted from the central line of the extended source were accelerated to 22.9 keV such that the pulse height of the tritium β spectrum in the end point region is larger than most of the background. In the most sensitive region for m_ν (in 100 eV range below the end point energy of the tritium β spectrum), the signal to background ratio is approximately 1:1.

Generally, neutrino mass is calculated according to the spectral shape around the end of the tritium β decay spectrum obtained by a magnetic spectrometer. But a β spectrometer itself has electron optical resolution function and the β source suffers energy loss and backscattering, they both may make the β energy spectrum distorted, and hence, have a serious influence in the neutrino mass estimation. It is this account that a careful analysis was carried out theoretically and experimentally on the total resolution function[17].

The procedure for acquiring the total resolution function theoretically is shown in Eq. (1)

$$R_{th} = R_l \ominus (\Gamma \oplus EL \oplus SUO) \oplus ELS \qquad (1)$$

where, R_l is the internal conversion spectrum for 18.437 keV electrons of ^{169}Yb-M1 line obtained under the same geometrical condition for the tritium β source. The measured spectra for Yb-M1, M2 and M3 lines as shown in Fig. 2; Γ, EL and ELS are the natural width of ^{169}Yb-M1 line and the energy loss spectra for monoenergetic electrons in Yb source and for the tritium β source, respectively, calculated by Monte Carlo simulation [18]; SUO is the spectrum of the shake up/off effect of Yb source[19]. $\ominus$ and $\oplus$ stand for the calculation procedures of deconvolution and convolution.

Equation (2) gives the procedure for obtaining the total resolution function by experimentation.

$$R_{exp} = R_l \ominus R_s \oplus R_{ph} \oplus ELS \qquad (2)$$

Here $R_l \ominus R_s$ stands for the deconvoluting narrow strip (0.05×8.0cm^2) from the large area (9×8 cm^2) internal conversion electron spectrum of ^{169}Yb and ^{170}Tm obtained experimentally; R_{ph} is the narrow photoelectron spectrum. The electron spectra of R_l and R_s are supposed to have the same Γ, SUO and EL in Eq. (2). The total resolution functions from ^{169}Yb-M1 and ^{170}Tm-K internal conversion electron spectra, as based on Eq.(1) and (2), are shown in Fig 3. respectively.

Comparing the above mentioned total resolution functions from the two methods, we see that the FWHM of the total resolution functions is $30\pm$ 2eV and the spectra are well comparable at the high energy side. At the low energy side the tail is higher for the theoretically calculated spectrum.

Obviously, the experimental method can avoid a lot of errors and uncertainties from theoretical calculation. This is just the distinction of the experimental method in which we acquired the total resolution functions. While neutrino mass is calulated by fitting m_ν^2, the difference between the values of m_ν^2 from R_{th} and R_{exp} is acounted into the systematic error at the next section.

4 DATA ACQUISITION AND ANALYSIS

The tritium β spectra were measured in the energy ranges of 17.4 – 23 keV or 17.8 – 23 keV. Fig. 4 is a typical ^{3}H-β pulse height spectrum of the proportional counter for the energy point of 17.85 keV. The small peak on the right hand side is the pulse height spectrum of ^{3}H-β rays. The high peak on the left is the pulse height spectrum of ^{55}Fe-X (5.895 keV) source monitoring the stability of the counting system. The tritium spectrum is about 70 data points for each run which spent about 20 hrs., and the total acquisition time is about 2500 hrs.

The neutrino mass was estimated by least squares fitting of the following theoretical expression of $N_{th}(E)$ to the measured spectrum:

$$N_{th}(E) = A\epsilon(E)\sum_i \{F(Z,E_i)pE_i[1+\alpha(E_0-E_i)^2]\sum_j W_j n(E_i,E_j)\} \times R(E,E_i) + BG \qquad (3)$$

$$n(E_i,E_j) = (E_0-E_i-E_j)[(E_0-E_i-E_j)^2 - m_\nu^2]^{1/2}$$

where, A is the normalization constant; $F(Z,E_i)$ is the Fermi function. Z is the daughter nuclear charge; p, E and E_i are the momentum, kinetic and total energy of β rays, respectively; $\epsilon(E)$ is the correction for the accepting solid angle due to scanning potential[16]; $R(E,E_i)$ is the total resolution function; α is the empirical shape correction factor used by Ref. [10]; W_j and E_j are the branching ratio and excitation energy of the final state, taken from Ref. [20-22]; m_ν^2 refers to (neutrino mass)^2; BG represents the background; A, E_0, α, m_ν^2 and BG were free parameters in the fitting program[23].

Table 1 shows the effects of different final state structures(FSS). From this table, the differences among tritium containing molecules and tritium molecules in FSS effect are not remarkable; the m_ν^2 values deduced from T-atom and T-nuclei deviate much from zero. The measuring data for runs added into seven series and the fitting results of FSS of CH_3T[20] are shown in Table 2.

Fig. 5 shows the Kurie plots of the series 1-5, where the solid lines are the corresponding best fit for the data points. Fig. 6-a is the deviation of the best fit from data and the Fig. 6-b is that of the fit with m_ν^2=900 (eV^2), divided by the standard deviation. It is seen that m_ν^2=900 (eV^2) gives a poor fit.

Systematic errors were investigated by varying the input parameters. These are the different resolution functions of R_{th} and R_{exp}, the effective average source thickness and the final states parameters W_0, E_j.

1. The effect of different resolution functions of R_{th} and R_{exp} is to shift the resulting

m_ν^2 by an amount of 27 (eV^2).

2. The error of the effective average source thickness is 16%. This results is an effect of 29 (eV^2) on m_ν^2.

3. The uncertainties from the final state parameters W_0 and E_j were taken to be the maximum variation in the results for CH_3T [20]. That of W_0 and E_j are 2% and 6%, respectively. The effect of varying each input parameter separately is to shift the fitted m_ν^2 by an amount of 11 (eV^2) and 24 (eV^2), respectively.

All of the above mentioned shifts of m_ν^2 were added in quadrature to yield systematic error as $m_\nu^2(\text{syst.}) = \pm 48$ (eV^2). The seven series of data sets are combined by taking a weighted average to obtain

$$m_\nu^2 = -31 \pm 75 \pm 48 \ (eV^2)$$

The statistical and systematic errors added in quadrature and for m_ν^2 at 95% confidence level arrive at the final result as the upper limit on m_ν^2

$$m_\nu^2 < 155 \ (eV^2) \text{ or } m_\nu < 12.4 \ (eV), \ E_0 = 18578.3 \pm 5.1 \ (eV).$$

where an error of 5.1 eV was obtined by linearly adding with the statistical error (0.4 eV) and the systematic errors of the source aligument(1.4 eV) and the energy uncertainty of ^{169}Yb-M_1 line.

5 CONCLUSION

As mentioned above, the fitting results are sensitive to the FSS of the β source. So

the results of T-atom and T-nuclei are different from the FSS of our tritium-containing molecule source. But all the fitting based on the FSS have some systematic negative m_ν^2 values, which will be discussed in our next paper[25]. Some of the recent results of neutrino mass measurement are listed in Table 3. As can be seen, the last five results do not indicate any serious discrepancy among them, and all of them are disagreed with the finite neutrino mass of $17 < m_\nu < 40$ eV reported by the ITEP group[2]. Up to now, whether the neutrino mass equals zero or not is still an open problem.

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Table 1. Results of the final state structures of β spectrum

FSS	No. of Levels	W_0	E_1[21] (eV)	χ^2/DOF	$E_0 - 18500$ (eV)	m_ν^2 $(eV)^2$
CH_3T	2	0.6056	48.80	1.141	78.6	-71
CH_3T[20]	7	0.6056		1.141	78.3	-31
CH_2=CHT	2	0.6006	47.48	1.145	79.7	-51
CH_3-CHT-CH_3	2	0.6030	48.46	1.144	79.9	-43
VALINE II	2	0.6291	50.90	1.140	78.9	-141
T molecule	2	0.5820	44.98	1.148	79.9	-68
T molecule[22]	12	0.5822		1.145	77.6	-177
T atom	2	0.7020	45.65	1.146	75.2	-191
T nuclei	1	1.000		1.158	67.2	-237

Table 2. Summary of the fitting results

series	χ^2/DOF	E_0-18500 (eV)	α ($\times 10^{-3}$) (eV^{-2})	m_ν^2 (eV^2)
1	73/61	77.2 ± 1.1	0.85 ± 0.40	-99 ± 169
2	74/58	78.7 ± 1.1	0.78 ± 0.84	-287 ± 282
3	61/61	79.4 ± 1.3	-2.43 ± 0.92	364 ± 165
4	77/55	75.9 ± 1.1	-1.12 ± 0.47	-100 ± 154
5	67/59	79.8 ± 1.2	-1.61 ± 0.49	-109 ± 239
6	73/64	77.2 ± 1.2	0.98 ± 0.46	-14 ± 237
7	81/64	80.8 ± 1.2	-3.52 ± 0.52	-369 ± 262

Table 3. Electron anti-neutrino mass

Reference		m_ν^2 (eV^2)	m_ν^2 Errors (eV^2)		Quoted upper 95% m_ν limit (eV)
			Statistical	Systematic	
ITEP[2]	1987	919	60	150	$17 < m_\nu < 40$
Zurich[3]	1986	-11	63	178	18
INS[4]	1991	-65	85	65	13
LANL[5]	1991	-147	68	41	9.3
Zurich[24]	1992	-24	48	61	11
CIAE	1992	-31	75	18	12.4

Figure captions

Fig. 1. The construction of the spectrometer and electron beam layout, where S-β source. D-detector.

Fig. 2. Internal convertion lines of ^{169}Yb-M obtained at proper compensation potential.

Fig. 3. The total resolution.

Fig. 4. Pulse height spectra for ^{3}H-β and ^{55}Fe-X.

Fig. 5. The Kurie plot for series 1-5.

Fig. 6. The deviation of a - the best fit and b - the fit with m_ν^2 =900 (eV^2), divided by the standard deviation.

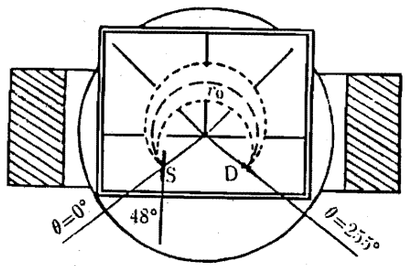

Fig.1 The constraction of the spectrometer and electron beam layout. S-source, D-detector.

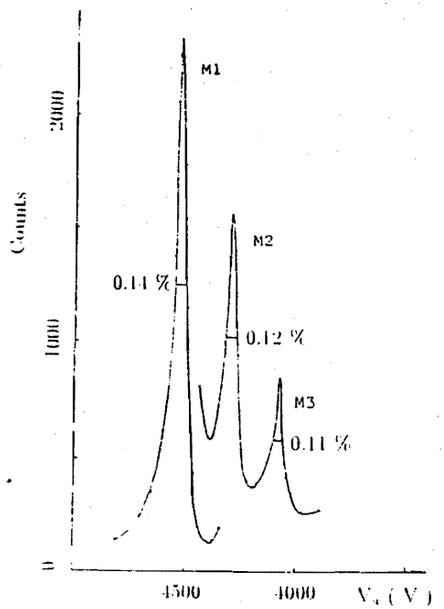

Fig.2 Internal conversion lines of ^{169}Yb-M obtained at proper compensation potential.

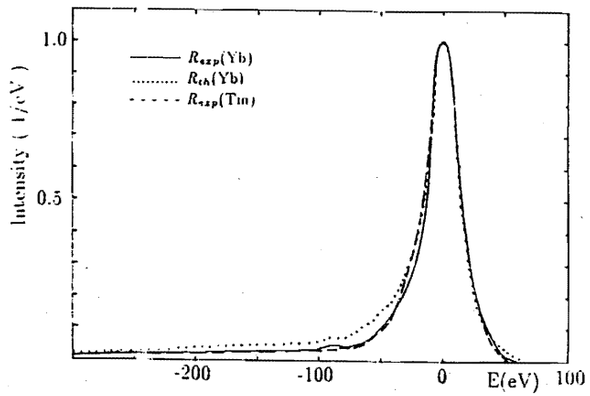

Fig.3 The total resulution function

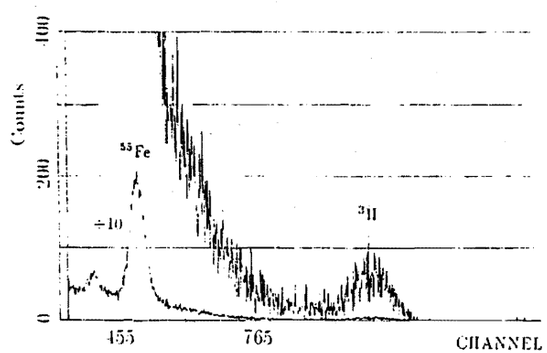

Fig. 4 Pulse height spectra for ^{3}H-β and ^{55}Fe-X.

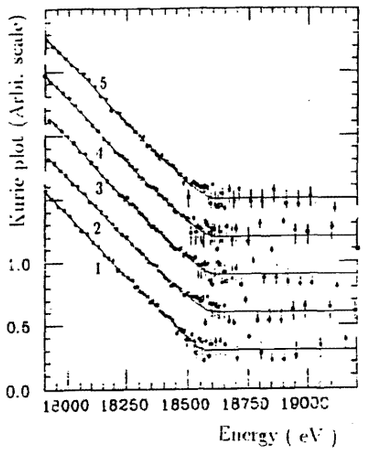

Fig.5 The Kurie plot for series 1 - 5

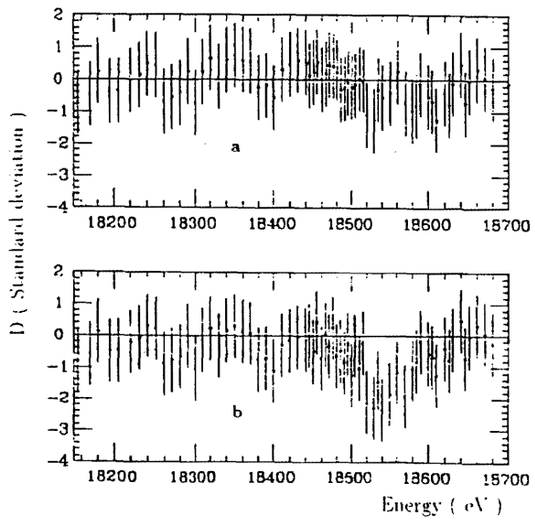

Fig.6 The deviation of a - the best fit and b - the fit with m_ν^2=900 (eV^2). divided by the standard deviation.