Energy of the 32-keV transition of $^{83}Kr^m$ and the atomic mass difference between ^3H and ^3He

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The energy of a gamma transition in the decay of $^{83}Kr^m$ has been determined to be 32 147.3(16) eV in a comparison with transitions in ^{241}Am decay. This value, substantially more precise than previous ones, leads to a corresponding improvement in precision in the atomic mass difference between ^3H and ^3He as determined from an experiment on the beta decay of free molecular tritium. The mass difference, 18 589.0(26) eV, is in agreement with some independent determinations but disagrees with others, most notably with some recent ion-cyclotron-resonance data. The latter disagreement calls into question the 17-eV lower limit on the mass of the electron antineutrino claimed by Boris *et al.*

I. INTRODUCTION

Laboratory experiments searching for limits on the electron antineutrino mass by examining tritium beta decay spectra[1] also produce a value for the endpoint energy, E_0, of the beta spectrum. Since this endpoint energy is equal to the atomic mass difference between ^3H and ^3He, ΔM, plus a small correction term involving molecular binding, ionization, and recoil energies, its value may also be determined by independent means. For example, the mass difference has been measured by ion-cyclotron-resonance (ICR) mass spectrometry,[2] and the correction term has been calculated[3] to a fraction of an electron volt. Thus, the value of E_0 determined in a given tritium beta decay experiment provides a check against systematic errors in the experiment or the data analysis.

The Los Alamos National Laboratory tritium beta decay experiment (which has been described in detail elsewhere[4]), as well as another experiment now under construction at Lawrence Livermore National Laboratory,[5] use a K-conversion electron line from gaseous $^{83}Kr^m$ to calibrate the energy scale of the spectrometer. The energy of this electron line, 17 835 eV, was previously known[6–8] to only 20 eV, corresponding to the uncertainty in the energy, E_{32}, of the gamma transition at 32 160(20) eV. A 20-eV uncertainty is thus introduced into the resultant value of E_0, although there is no effect on the neutrino mass. A more precise measurement of E_{32} would allow comparison between the Los Alamos E_0, and thus ΔM, and ΔM obtained by independent means. With this motivation, the authors have undertaken a new measurement of E_{32} of $^{83}Kr^m$.

II. EXPERIMENTAL METHOD

Measurements of E_{32} were carried out in two separate experimental studies (series I and II). Sources of $^{83}Kr^m$ were obtained by cryosorption of $^{83}Kr^m$ gas onto charcoal granules at liquid-nitrogen temperatures. The krypton emanated from a mixed Na-Rb stearate[9] that contained ^{83}Rb. The sources, with strengths between approximately 1 and 15 millicuries, were contained in an aluminum cell with a window 0.013 cm thick. The cell was cooled by conduction through a copper coil immersed in a glass dewar of liquid nitrogen. Gammas emerging from the source cell were detected in a 28.3 $mm^2 \times 5$ mm Princeton Gamma-Tech Si(Li) solid-state detector. At 33 keV, the energy resolution was 330 eV full width at half maximum (FWHM).

Sources of ^{241}Am, one 18 μCi and a second 20 μCi, were used to calibrate the detector. The isotope ^{241}Am has lines at 26 345.0(10) eV and 59 537.0(10) eV whose energies have been measured by crystal diffraction spectrometry.[10,11] A third, crossover, transition exists with an energy equal to the difference between the other two, i.e., 33 192.0(14) eV. This 33-keV line is fortuitously placed for this measurement: it is as close to the krypton line of interest as possible while still being completely resolved. Spectra from the two ^{241}Am sources are shown in Fig. 1. The 18-μCi americium source contained a small ^{137}Cs impurity (as well as other unidentified impurities), resulting in the presence of a weak doublet of $^{137}Ba^m$ x rays in the americium spectrum, with energies of 31.8 and 32.2 keV. The ratio of the peak heights of the 32.2-keV barium line and the krypton line was determined to be less than 1:20. The correction made in series I for this cesium contamination is discussed below.

Data runs were taken with ^{241}Am and $^{83}Kr^m$ both in place. The americium was placed between the $^{83}Kr^m$ cell and the detector window. That scattering in the Am source did not disturb the Kr line shape within uncertainties was verified by interposing a further 1.5 mm of Al (about 5 times the thickness of the Am source backing) in some runs. Some runs were taken at different gain settings, as a check for differential nonlinearity. The relative intensities of the Kr and Am lines were varied over a 4:1 range to reveal possible sensitivities of the fitting algorithms to intensity. As a further check of the analysis methods, runs were taken with a ^{137}Cs source and ^{241}Am, and the $^{137}Ba^m$ x-ray doublet was fit in an analogous fashion to the $^{83}Kr^m$ line. Examples of the four types of spectra are shown in Fig. 2.

III. RESULTS

A. First experimental series

The six ^{241}Am and ^{83}Kr^m runs were analyzed with the aid of the SAMPO gamma-ray analysis code.[12] The code fits Gaussians with exponential tails to peaks and allows for either a linear or a quadratic background. We used a quadratic background, but the result from a linear background differed by less than 0.5 eV from a quadratic one in a test case. The energy calibration was based on the three precisely known ^{241}Am gamma lines, to which a quadratic was fitted as discussed below in Sec. III C.

Initially, we fit the ^{83}Kr^m line and the 33-keV ^{241}Am line as a doublet, but in the final analysis singlets were used because the fits were somewhat better. However, because of the proximity of the two peaks, we felt it prudent to ascertain that the presence of its neighbor did not affect the position of either peak. To do so, we independently fit the ^{83}Kr^m peak in the spectrum containing only ^{83}Kr^m and the ^{241}Am peaks in a spectrum containing only ^{241}Am, and then added the two spectra together, and refit the combined spectrum. The centroids obtained in this manner were in good agreement with each other, differing by 2 eV or less. (Part of this small residual is attributable to slight differences in the peak shapes between the two spectra, a result of grain drifts.) As a further check, we subtracted the ^{83}Kr^m spectrum from one of the spectra containing both ^{83}Kr^m and ^{241}Am, and compared the positions of the ^{241}Am lines before and after the subtraction. The shifts observed in this test (which is insensitive to gain drifts) were less than 0.03 eV.

The corrections for the cesium contamination were made by subtracting an appropriate fraction of the spectrum taken with the cesium and americium sources both in place from each of the six spectra containing ^{83}Kr^m and ^{241}Am. The resultant spectra were those actually

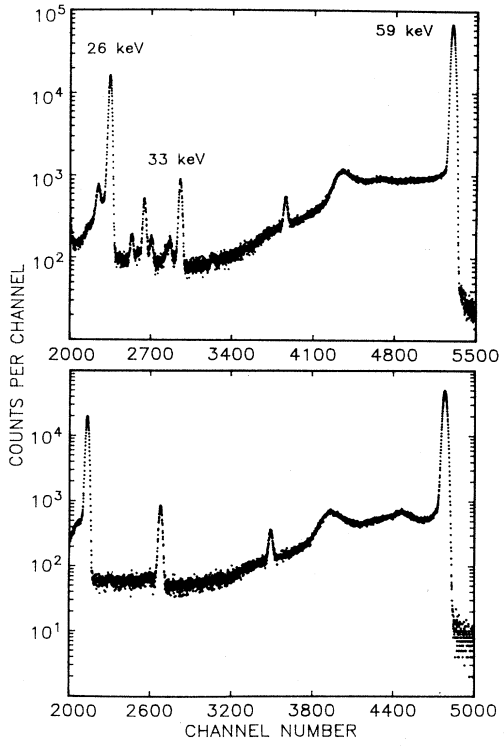

FIG. 1. Spectra of ^{241}Am sources. Top—18-μCi source, which was not radiopure. Bottom—20-μCi source used in second series of experiments, with no evidence of radiochemical impurities.

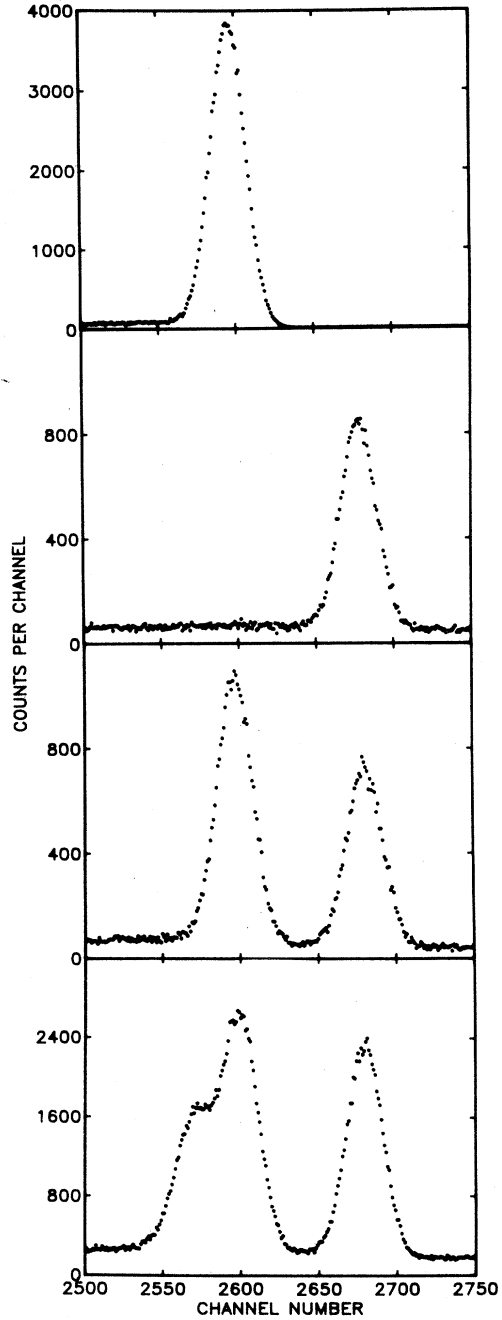

FIG. 2. Partial spectrum in the vicinity of 33 keV of (from the top) ^{83}Kr^m, ^{241}Am, ^{83}Kr^m+^{241}Am, and ^{137}Cs+^{241}Am from experiment series II.

used to calculate E_{32} of the $^{83}Kr^m$. The shifts resulting from these corrections were small, ranging from 0.1 to 1.1 eV. We assigned an uncertainty to the correction process equal to the average correction term, 0.5 eV.

The energy of the $^{83}Kr^m$ line was influenced by the size of the windows used in the fitting process. For each run, we varied the window sizes until the fits became clearly unacceptable to the eye, and then calculated an uncertainty for this effect from the scatter in the centroid positions for acceptable fits.

Figure 3 shows one of the final fits, and the results for E_{32} from the six data sets are summarized in Table I. Also shown for each run in Table I is the quantity

$$\sigma=[\sigma_1^2/N_1+\sigma_2^2/N_2]^{1/2} ,$$

where $\sigma_{1,2}$ are the standard widths of the Gaussian parts of the 32-keV Kr and 33-keV Am peaks and $N_{1,2}$ are the numbers of counts in the peaks. This represents a minimum statistical uncertainty in the Kr line energy. Because additional statistical uncertainty is introduced by background, whose amplitude and spectral shape are determined by relatively poor-statistics data on the wings of the peaks, we used sample scatter as the uncertainty estimator and considered it to encompass the statistical uncertainties. The uncertainty in the mean is then 1.8 eV.

To obtain the final uncertainty in the series I result, we added in quadrature the contributions from the cesium correction, from window size sensitivity, and from sample scatter. The result, 1.9 eV, represents one standard deviation, and includes no contribution from the uncertainties in the energies of the ^{241}Am calibration lines.

The results for the measurement of the two barium x rays are displayed in Table II. Here the uncertainty, 3.9 eV, was calculated by considering the uncertainties from sample for an individual run for the $^{83}Kr^m$ case (3.6 eV), the window sensitivity (0.4 eV), and calibration (1.4 eV). The energies obtained agree well with the literature values.[13] We did not include the Lorentzian components to the line shape of the barium x rays, as the full width at half maximum for the Lorentzian component for these x rays is[14] only $\sim$20 eV.

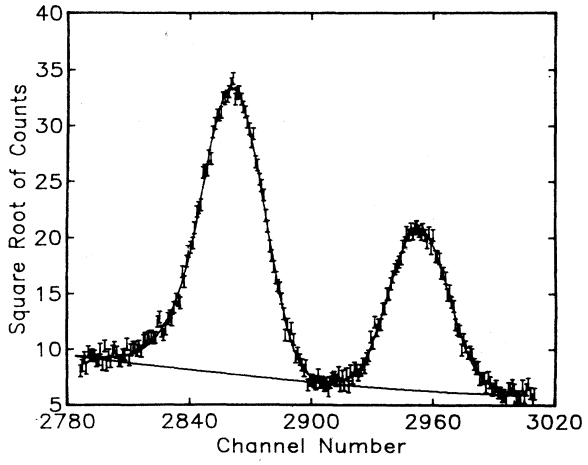

FIG. 3. Data (points) and fits to peaks and background (curves) for Run 11, series I. The fits are generated by the code SAMPO. The peak at the left is the 32147-eV $^{83}Kr^m$ line, and the one at the right is the 33192-eV ^{241}Am line.

B. Second experimental series

Data were taken with the same detector and electronics as in Series I, but the 20-μCi ^{241}Am source (free of contaminants: see Fig. 1) was used and the analysis of the data differed.

Rather than parametrize the peak shape as a Gaussian with exponential tails, which fits the data well in the region of interest but which diverges quickly outside that region, a physically motivated description of the line shape was adopted. The gamma spectrum incident on the detector may be described as a delta function at the emission energy plus a weak continuous distribution arising from scattering into the detector from surrounding material ("backscatter"). Compton scattering out from the detector does not contribute intensity in the region near the photopeak and may be neglected. As may be seen from Fig. 1 (for example, near the 59-keV line), the backscatter component has some structure, but is reasonably flat as it merges with the photopeak. Thus a simple, but remarkably accurate, description of the spectrum can be obtained by convoluting a delta function and an adjoined rectangular distribution with the Gaussian detec-

TABLE I. Compilation of the results for E_{32} for the six data sets of series I and 17 sets of series II.

Run	E_{32} (eV)	σ (eV)
	Series I	
8	32 148.3	2.1
11	32 151.2	1.6
12	32 149.2	1.2
20	32 145.7	2.1
21	32 142.1	2.2
22	32 149.1	1.4
Average	32 147.6	1.8
	Series II	
19	32 149.4	2.5
20	32 147.2	1.3
21	32 148.9	2.3
22	32 149.6	1.8
23	32 146.7	1.5
24	32 144.3	1.5
25	32 148.1	1.3
26	32 143.8	3.3
27	32 149.1	2.0
28	32 148.0	1.7
29	32 142.8	2.5
30	32 147.7	2.0
31	32 146.0	2.2
32	32 145.6	2.8
33	32 147.7	1.4
34	32 149.8	1.4
35	32 147.2	1.8
Average	32 147.2	0.5

TABLE II. Energies of the $^{137}Ba^{m}$ x-ray doublet.

Siegbahn designation	Present value[a] (eV)	Literature value[b] (eV)
$K_{\alpha 1}$	32 191.8(39)	32 193.6(5)
	32 193.4(25)	
$K_{\alpha 2}$	31 817.8(39)	31 817.1(5)
	31 816.4(29)	

[a]From series I and II experiments, respectively.
[b]Reference 13.

tor response. A linear background is added to the result.

The nonlinear minimization code[15] MINUIT was used to implement this scheme. The quality of fit was excellent, as indicated in Fig. 4. Values of χ^2 were in every case consistent with counting statistics. In fitting the 32-keV doublet the height of the backscatter pedestal was set at the same fraction of the photopeak for both lines. That the peak and pedestal shapes were indeed the same (apart from the monotonic increase in peak width with energy) was confirmed by fits to the spectra containing only one peak. No systematic sensitivity to window size was noted for variations of 30 channels. Nevertheless, to be conservative, we allow for the possibility of a 0.5-eV uncertainty as in series I. The energies derived from a quadratic energy calibration as described in the preceding section are listed in Table I. The average value for E_{32} from series II is 32 147.2(5) eV, in good agreement with the result from series I. Similarly, the series II energies for the Ba x rays from a ^{137}Cs source are in agreement with the literature values[13] (Table II).

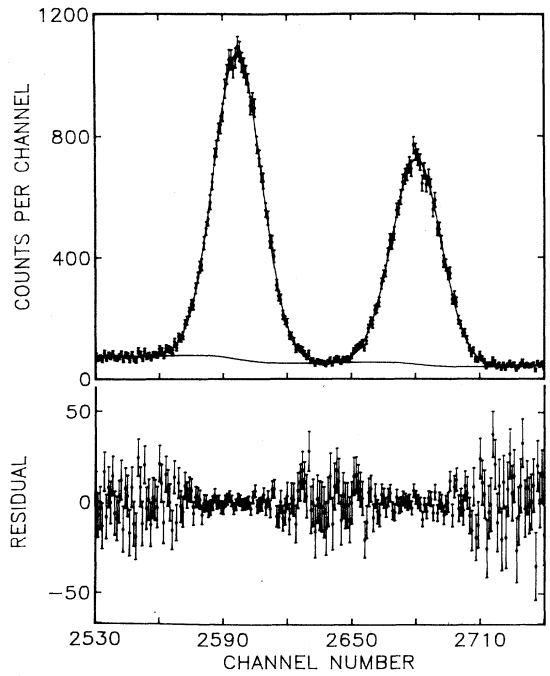

FIG. 4. Data (points) and fits to peaks and background (curves) for Run 25, series II. The background shown is the combination of a linear background and the backscatter pedestals (which are convoluted with the Gaussian detector response). The residuals shown below are the excess of the data value over the fit value expressed as a percentage of the fit value. The fits are generated by the code MINUIT.

C. Combined results

The quoted uncertainties[10,11] for both the 26-keV and the 59-keV calibration lines are 1 eV. If these uncertainties are fully correlated, then the uncertainty for the 33-keV line would also be 1 eV. If they are completely uncorrelated, then the 33-keV energy uncertainty would be 1.4 eV. We elected to use the latter. The uncertainty in the 33-keV line energy dominates the calibration uncertainty for the nearby Kr line. The energy calibration of the spectra was based on the three precisely known ^{241}Am lines, and only linear and quadratic fits are possible. Perfect linearity is not expected, but because the effect on the $^{83}Kr^{m}$ energy of adding a second order term to the energy calibration was less than 5 eV (1 part in 6000), we have assumed that terms of order 3 or higher are completely negligible. The data on the ^{137}Ba x rays are consistent with this assumption within the 2-eV combined uncertainty, and even the imprecisely known 42 423(20)-eV ^{241}Am line (Fig. 1) is sufficient to constrain the effect of a cubic term on the $^{83}Kr^{m}$ line to less than 3 eV.

Combining the results from series I and II and adding the calibration uncertainty in quadrature, one obtains the final result for E_{32}, 32 147.3(16) eV.

As may be seen in Table III, the measurement reported here is in good agreement with previous work, while considerably more precise. The value of 32 147.3(16) eV for E_{32} of $^{83}Kr^{m}$ implies[16] a conversion electron energy of 17 820.1(18) eV, and an endpoint energy for molecular tritium decay of 18 568.9(26) eV from the Los Alamos experiment.[17]

TABLE III. Summary of the results presented in this paper and a comparison with previous results.

Description	Value (eV)	Reference
E_{32}	32 140.0(500)	6
(previous	32 160.0(200)	7
experiments)	32 160.0(300)[a]	8
	32 180.0(500)	8
E_{32} (present)	32 147.3(16)	
K-shell binding energy	14 327.2(8)	16
K-shell conversion electron energy[b]	17 820.1(18)	
Los Alamos tritium endpoint energy[b,c] E_0'	18 568.9(26)	17
Correction term[c] ΔU	38.79	3
ΔM from Los Alamos tritium experiment[b,c]	18 589.0(26)	17

[a]From ^{83}Br decay.
[b]Revised with data from present work.
[c]$\langle V_i \rangle = 18.62$ eV.

IV. KRYPTON-TRITIUM EXPERIMENT

As discussed below, the new $^{83}Kr^m$ datum leads to a ΔM significantly lower than that measured by the ICR technique of Lippmaa *et al.*[2] In view of this, we decided to perform a subsidiary experiment to explore the possibility of a systematic error in the Los Alamos tritium beta-decay experiment which would tend to shift the endpoint energy (and thus the mass difference) downward; namely, the presence of space-charge buildup from trapped $^3He^+$ and other ions, which could effectively decelerate the electrons emerging from the source. The krypton calibration peak would not be affected by this space charge because the activity of the krypton source is much lower than that of the tritium source, and the krypton data are taken separately from the tritium data. The possibility of this effect was recognized when the apparatus was designed, and the solution was to neutralize the (positive) space charge by installing a hot tungsten filament at the end of the source farthest from the spectrometer. However, experimental confirmation of the success of this strategy was lacking, and thus we decided to measure the sensitivity of the position of the $^{83}Kr^m$ calibration peak to the presence of tritium in the source.

Repeated measurements of the centroid of the $^{83}Kr^m$ peak were made in the presence and absence of tritium in the source tube. The Los Alamos tritium beta-decay experimental apparatus was used for the measurements. (For further description of the apparatus, see Refs. 4 and 17.) The spectrometer was set nominally at 26.0 keV so that the maximum of the $^{83}Kr^m$ peak occurred for an accelerating voltage of 8024 volts. When tritium was present in the system, we took points at 7800 volts, 9200 volts, and 9500 volts in addition to scanning the region of the krypton peak. These points were used to strip the tritium contribution from the data and isolate the $^{83}Kr^m$ peak.

It was observed that the $^{83}Kr^m$ peak was shifted 0.65(36) eV to higher accelerating voltages when tritium was present with respect to when it was not. The tritium pressure in the source was comparable to that used during the earlier measurements described in Ref. 17. Some centroid shift to lower electron energies (higher accelerating voltages) is expected owing to energy loss in the tritium gas. A classical calculation of the shift expected from energy loss gives ~ 0.5 eV. Since the shift that we measured is of the same magnitude, and could be due entirely to energy loss, and since we see no evidence for other systematic effects, we make no additional correction to the endpoint energy (and thus ΔM) cited above for the Los Alamos tritium experiment.

V. DISCUSSION

Tritium beta-decay experiments yield an endpoint energy $E_{\rm exp}$ which may be related to the ^3H-^3He atomic mass difference ΔM through calculations of the average excitation $\langle V_i \rangle$ imparted to the daughter molecule in the decay. The electron spectral density dN/dE in allowed Fermi beta decay is given by

$$\frac{dN}{dE} = CFpE \sum w_i (E_0 - E - V_i)^2 \left[1 - \frac{m_\nu^2 c^4}{(E_0 - E - V_i)^2} \right]^{1/2} \times \Theta(E_0 - E - V_i - m_\nu c^2) , \quad (1)$$

where C is a constant, F the Fermi function $F(Z,E)$, p the electron momentum, E the electron total energy, E_0 the maximum value of E (in the absence of neutrino mass), V_i the excitation energy of the ith state in the daughter molecule ($V_0 = 0$), w_i the branching ratio to that state, m_ν the neutrino mass, and Θ the Heaviside function. For present purposes we may consider the neutrino mass to be zero and neglect the role of the Heaviside function, since they affect only the region near the endpoint. Then the summation in (1) may be carried out

$$\frac{dN}{dE} = CFpE (E_0 - E - \langle V_i \rangle)^2 \left[1 + \frac{\langle V_i^2 \rangle - \langle V_i \rangle^2}{(E_0 - E - \langle V_i \rangle)^2} \right] . \quad (2)$$

The similarity in form between Eqs. (1) and (2) is significant because it means that an incorrect variance of the final state spectrum ($\langle V_i^2 \rangle - \langle V_i \rangle^2$) can result in an incorrect neutrino mass without affecting the quality of fit to an experimental spectrum. Equation (2) is strictly valid only when E lies so far below E_0 that all excited state energies V_i are included. Actual analyses of the endpoint are therefore made with a detailed model of the final states.

The last factor in Eq. (2) again affects the spectrum only near the endpoint, and the experimental endpoint energy found by fitting data from lower energies is

$$E_{\rm exp} = E_0' - \langle V_i \rangle ,$$

where $E_0' = E_0 - m_e c^2$. Then the atomic mass difference is given by

$$\Delta M = E_0' - B(T) + B(\mathrm{He}) - B(R:\mathrm{He}^+) + B(R:T) + E_{\rm rec} , \quad (3)$$

where $B(x)$ is the total electronic binding energy of the molecule x in its ground state, and R signifies a molecular fragment appropriate to a particular source molecule. Generally it is $E_0' = E_{\rm exp} + \langle V_i \rangle$ that is quoted by experimental groups as the "endpoint energy." The recoil energy $E_{\rm rec}$ may be taken to be the free-atom recoil energy at the endpoint, 3.4(1) eV, provided that molecular rotational and vibrational excitation is not treated separately (which leads to double counting).[18]

Three groups[3,19–22] have reported calculations in the sudden approximation of the final-state spectrum of the THe^+ ion (or HHe^+) produced in the beta decay of T_2 (or HT). The desired quantity,

$$\langle \Delta E \rangle = B(R:\mathrm{He}^+) - \langle V_i \rangle - B(R:T) ,$$

may be obtained from the explicitly calculated final-state spectrum and branching ratios, or it may be evaluated directly from the initial ground-state wave function:

$$\langle \Delta E \rangle = \langle \Psi_0(R:T) | H(R:T) - H(R:\mathrm{He}^+) | \Psi_0(R:T) \rangle .$$

The latter "sum rule" method can be expected to be highly reliable, being independent of details of the excitation spectrum. Kaplan and Smelov[3] find $\langle \Delta E \rangle = 30.03$ eV, which leads to the 38.79-eV correction term, ΔU, shown in Table III:

$$\Delta U \equiv \Delta M - E_{\text{exp}}$$
$$= B(\text{He}) - B(T) - \langle \Delta E \rangle + E_{\text{rec}} .$$

In Table IV are summarized the available calculations for $\langle V_i \rangle$ (which similarly may be made in two ways). There is generally good agreement between the different methods of calculation, but the importance of very highly excited states may be seen. In the analysis of Ref. 17, a discretized spectrum with $\langle V_i \rangle = 17.67$ eV was used, whereas the sum rule correction of Kaplan and Smelov gives 18.62 eV. The 1-eV difference arises in part from highly excited states (above 94 eV) to which Eq. (2) is less applicable. An uncertainty of approximately 0.1 eV is contributed by the lack of detailed knowledge of the distribution of this strength. The value of ΔM from the Los Alamos experiment becomes 18 589.0(26) eV.

VI. CONCLUSIONS

The resultant ^{3}H-^{3}He mass difference from the Los Alamos tritium beta-decay experiment, 18 589.0(26) eV, is in good agreement with several other measurements of ΔM. For example, with the corrections suggested by Audi *et al.*,[23] the radio-frequency mass spectrometry work of Smith[24] gives 18 595(10) eV and 18 579(12) eV. There is fair agreement with the ICR measurement by Talrose and Nikolaev[25] [18 582(3) eV] and with the recent tritium experiment of Fritschi *et al.*[26] [18 602(10) eV]. The Si-detector measurement by Simpson *et al.*[27] yielded 18 580(7) eV, and Redondo and Robertson[18] have shown, by calculation of previously neglected chemical effects, that this result should be corrected upward by 10(3) eV.

However, the Los Alamos ΔM is not within 2 standard deviations of the ICR measurement reported by Lippmaa *et al.*[2] [18 599(2) eV] and two other modern tritium experiments: Boris *et al.*[28] [18 598.9(40) eV], and Kawakami *et al.*[29] [18 603(5) eV]. It must be further noted that although the two ICR measurements are very precise, they are not in agreement with each other. (Here and below, we mean by "standard deviation" the published uncertainty, which generally has both statistical and systematic components.)

Boris *et al.*[28] have recently reported the status of the tritium beta-decay experiment at the Institute for Theoretical and Experimental Physics in Moscow (ITEP). They conclude that the ν_e mass is 26 eV and that it must lie within a "model-independent" range of 17–40 eV. The range is a reflection of the fact that the spectrum of final states[3] is somewhat uncertain and strongly affects the neutrino mass extracted from the data. The ITEP group explored this matter by using a variety of different theoretical final-state spectra A change in the final-state spectrum not only affects the derived neutrino mass, but also shifts the derived value of ΔM and at some point spoils the good agreement between the ITEP result, 18 598.9(40) eV, and the ICR result of Lippmaa *et al.*,[2] 18 599(2) eV. The argument is illustrated graphically in Fig. 5, which is patterned on the one given by Lyubimov.[30] The range 17–40 eV is obtained by requiring that the two determinations of ΔM not disagree by more than 6 eV (1.3 standard deviations in the difference).[30] There is a complication not considered by the ITEP group. The connection between the scale of ΔM on which the Lippmaa *et al.* measurement rests and the E_0' scale of tritium β decay can only be made through Eq. (3). Particular assumptions for the initial and final ground states lead to different offsets between the two scales, as tabulated in Table V and illustrated in Fig. 5. Quite apart from any experimental issue relating to the actual mass difference, this effect weakens the argument for a model-independent lower limit.

An error in the Lippmaa *et al.* result of a magnitude

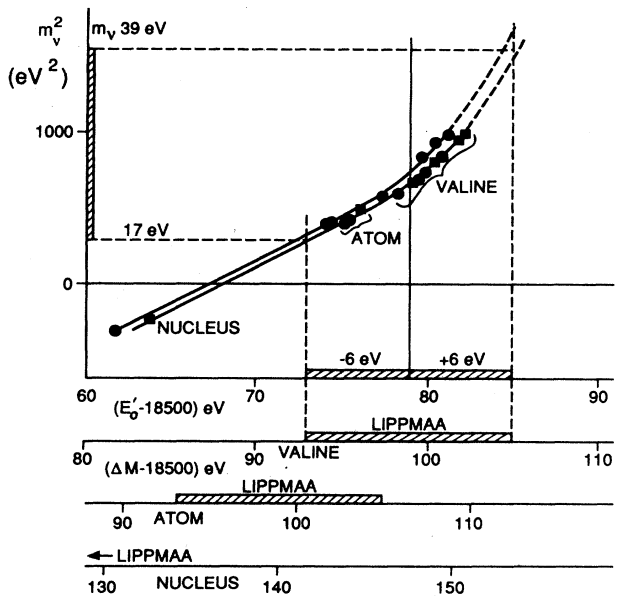

FIG. 5. Effect of different choices of final-state distribution on the results from the ITEP tritium experiment (Refs. 28 and 30). The ordinate is the square of the derived neutrino mass, and the abscissa is the endpoint energy. The ITEP group found that all choices tried lay within the band indicated. Fixing the endpoint energy to be within 6 eV of the value obtained by Lippmaa *et al.* (Ref. 2) then constrained the neutrino mass to be greater than 17 eV. The scales at the bottom show the equivalent values of the ^{3}H-^{3}He mass difference for various assumptions about the molecular ground states involved in the tritium decay.

TABLE IV. Calculated values of the average excitation energy, $\langle V_i \rangle$.

Authors	Reference	Truncation point (eV)	$\langle V_i \rangle$ (eV)
Fackler *et al.*	21	164	18.05
Fackler *et al.*	21	94	17.36
Martin and Cohern	19	94	17.05
Kaplan and Smelov	3	sum rule	18.62

TABLE V. Values of $\Delta M - E_0'$ for various molecules (from Ref. 3).

Molecule	$\Delta M - E_0'$ (eV)
Valine	19.79
CH_3T	19.30
HT	20.07
T	27.92
T^+	68.72

suggested by our own data would reduce the 17-eV "model-independent" lower limit on the neutrino mass to 0. That does not necessarily mean, however, that there is an error in the ITEP central value ($m_\nu = 26$ eV), because an error in the ITEP value for ΔM could simply arise from an energy-calibration error. A systematic error in the final-state distribution, the energy-loss distribution, or the resolution function would have different consequences. In general, errors in these distributions affect both the endpoint energy (through the first moment of the distribution) and the derived neutrino mass (through the second moment). If that is the origin of the discrepancy, it would imply that the central value of Boris *et al.*[28] for the neutrino mass, 26 eV, is somewhat overestimated, although a quantitative correction is not feasible since there is no general relation connecting the first and second moments of a distribution.

In conclusion, the new calibration of the endpoint energy measured in the beta decay of gaseous T_2 does not support a claimed model-independent lower limit for the electron neutrino mass. At the same time, a nonzero mass in the range found by the ITEP collaboration is in no sense ruled out. It is to be hoped that new experimental data on tritium beta decay and on the ^3H-^3He mass difference will soon allow a resolution of the discrepancy identified here.

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