Beta Decay Energy of Tritium*

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The extrapolated end point from Kurie plots of the tritium beta spectrum between 14 and 18 kev has been measured as 18.61±0.02 kev (internal consistency) on the Argonne double-lens beta spectrometer. Composite sources of tritiated estradiol and 10-hr thorium B (Pb^{212}) and its daughters allow calibration at 25 kev (the "*A*" line) as well as some check on the effect of the source thickness on the "*A*" line. A review of other measurements, including mass difference data, average energy determination, and proportional counter work, shows agreement with the present magnetic spectrometer result, 18.6±0.1 kev (this error includes some estimate of possible systematic effects). Two notable exceptions give lower values, 18.2 and 18.0 kev—one an average energy determination, the other a magnetic spectrometer result. The 18.6-kev decay energy and a half-life of 12.43 years give $ft=1137\pm20$ sec.

I. INTRODUCTION

RECENTLY the spread in the values of tritium decay energy appearing in the literature has been pointed out again by Friedman and Smith[1] in their publication of the mass difference H^3-He^3, obtained by mass "synchrometer" technique. The present work is not directed to the question of the neutrino mass or the shape of the spectrum but rather to the "extrapolated end point" which, as Sakurai[2] has re-emphasized, should be just equal to the mass difference. An accurate value for the decay energy of H^3 and hence for the *ft* product for the beta decay is of interest in connection with the relative size of the Gamow-Teller and Fermi coupling constants.

II. EXPERIMENTAL PROCEDURE AND RESULTS

Because another addition to the list of values might justly be regarded as further confusion, the features of this measurement must be examined carefully. They are the following:

(1) "built-in" low-energy calibration using a combined-source technique in which Pb^{212} (ThB) and the tritiated material are put on the same source;

(2) an iron-free double lens spectrometer[3] whose linearity down to 2 kev has been demonstrated[4];

(3) sublimated sources with thicknesses estimated at 0.3 to 0.03 $\mu g/cm^2$;

(4) aluminum foil backings 400 $\mu g/cm^2$, while too thick for shape measurements at the low energies, give certain electrical grounding without affecting the shape at the high-energy end of the spectrum.

The procedure consists of collecting the 10-hr ThB (recoils from the α decay $Em^{220}\rightarrow Po^{216}\rightarrow Pb^{212}$) electrostatically on a 200 $\mu g/cm^2$ Al foil over an area of $\frac{3}{16}$-inch diameter. The holder is designed to insure that no emanation can reach the back of the foil. Tritiated estradiol[5] is then sublimated[6] from a warm filament in vacuum onto a $\frac{1}{4}$-inch area overlapping the thorium B deposit. A $\frac{1}{8}$-inch diameter disk is then cut out of the center (the tool is much like a small cork borer) and fastened with an extremely dilute glyptal drop to another 200-$\mu g/cm^2$ Al foil on a standard source holder. This cut-out technique was adopted so that both thorium B and tritium were deposited on the same area without worrying about the effectiveness and the alignment of the masks. The deposits are quite invisible. The specific activity of the material and the actual count on the samples in the spectrometer leads to surface densities of 0.3 $\mu g/cm^2$ for the strongest sources and 0.03 $\mu g/cm^2$ for the weakest source. Ohmmeter checks with a fine wire touching the $\frac{1}{8}$-inch source disk showed electrical contact on all the sources.

The flow-type proportional counter window (formvar supported by Lectromesh, 150 mesh, 50% open) has a cutoff of 1.2 kev. It was operated at 5 cm Hg pressure and has a background of 3 counts/min. The spectrometer was operated at 1.6% resolution and 1% transmission. Counting rates on the peak of the spectrum with the strong sources were 600 counts/min. From 30–50 counts/min on the "*A*" line was sufficient for a suitable measurement on the line in 3 or 4 hours. A minimum of ThB was used so that the tritium spectrum near the end point could be run without waiting for the 10 hr ThB to decay completely. The prominence of the

* Based on work performed under the auspices of the U. S. Atomic Energy Commission.

[1] L. Friedman and L. G. Smith, Phys. Rev. **109**, 2214 (1958).

[2] J. J. Sakurai, Phys. Rev. Letters **1**, 40 (1958).

[3] Porter, Freedman, Novey, and Wagner, Phys. Rev. **103**, 921 (1956); Porter, Wagner, and Freedman, Phys. Rev. **107**, 135 (1957).

[4] Freedman, Porter, Wagner, and Day, Phys. Rev. **108**, 836 (1957).

[5] This material was prepared by a group at the Ben May Laboratory for Cancer Research of the University of Chicago, H. I. Jacobson, L. Closs, G. N. Gupta, and E. V. Jensen, with the facilities and cooperation of K. E. Wilzbach of Argonne National Laboratory. The method involved catalytic hydrogenation with 88% pure tritium (to be published). The specific activity, determined by enzymatic assay for the quantity of estradiol in a sample of known activity, was ~200 $\mu C/\mu g$.

[6] A range of volatility was observed using this material (there are radiation decomposition products in the solution). The most volatile fractions could be shown to pump off slowly even at room temperature at 10^{-5} mm Hg pressure. The less volatile fractions (coming off the filament at temperatures not known accurately but in the range 100–300 C°) were used for the spectrometer sources and showed no detectable pump-off at the spectrometer pressure of 10^{-5} mm Hg.

"A" line and the fact that the Th(B+C+C′+C″) beta spectrum is quite featureless between 410 and 488 gauss-cm make it convenient in this respect. Two of the runs (3b and 4) were started 20–24 hours after the line was measured showing that the presence of ThB was not affecting the result.

The tritium data were taken from 14.5 to 18.5 kev in half-kilovolt steps. Alternate points were taken with increasing and the others with decreasing current. Points at 19, 19.5, and 20.5 kev were included in the cycles and the average of these taken as background. The background at these points above the spectrum includes 1 to 2 counts/min of the thorium beta continuum if the run was made before the thorium decayed. When the thorium has decayed, the background above the spectrum is indistinguishable and from the background at zero current or from that with the source removed. The error flags (and the weights used in the least squares fits) include the uncertainty in the background.

The effect of the resolution correction (Owen-Primakoff-Hinman approach)[7] cannot be seen on the Kurie plots except for the 18.4-kev point. Since the fiducial point on the line is taken as the middle of the width at half height, the first moment of the transmission curve is very small and no large first moment shift in the spectrum occurs in the correction. Thus the plots in Fig. 1 are the data with no resolution correction. The weighted least-squares fits of a straight line to the Kurie plots were made excluding the 18.4-kev point both because the resolution correction is appreciable for this point and (with an open mind) because possible finite neutrino mass effects might influence the extrapolated end-point determination. These results are summarized in Table I.

The "A" line $H\rho$ value[8] used here is 534.21±0.03 gauss-cm. It is the L_{I} line of a 40-kev transition in Tl^{208}. The L_{II} line of the same transition has an intensity of $\frac{1}{10}$ the L_{I} line and is not resolved in these experiments. Its presence can be seen in the line asymmetry, and in obtaining the calibration constants the small L_{II} peak was unfolded from the large one (see inset of Fig. 1). The shift in the fiducial point due to this unfolding of the line was 5 parts in 10 000. Reversing the current in the spectrometer coils showed that the uncompensated[9] axial component of the earth's magnetic field introduces much smaller effects than could be seen at the precision of these experiments (0.1% in momentum).

The most important systematic bias that can arise in a measurement of this type is due to the source thickness. Note that the ThB recoils are collected first, that the "A" line electrons penetrate the entire source

TABLE I. Summary of the data on tritium decay energy with volatilized sources.

Source	Relative strength	Calibration constant gauss-cm/mv	Least squares $E_0 \pm \sigma(E_0)$ kev
1	12	(13.19_5)[c]	18.70±0.11
2	1	13.20_0±0.01	18.66±0.35
3[a]	3	13.19_3±0.01	18.56±0.04
[b]			18.71±0.07
			(18.71±0.07)[d]
4	11	13.19_0±0.01	18.61±0.03
		Weighted average	18.61±0.02[e]

[a,b] Different runs of same source, b about 24 hr later.
[c] Source No. 1 was directly volatilized with $\frac{1}{8}$-in. mask on 200-μg/cm² Al, no calibration line. This is an average based on the other sources.
[d] Run 3b with resolution correction showing no effect at this level of precision.
[e] $\sigma(\bar{E}_0) = (\Sigma w_i)^{-\frac{1}{2}} = 0.022$ kev; $\sigma(\bar{E}_0) = [(k-1)^{-1} \Sigma w_i \Delta_i^2 / \Sigma w_i]^{\frac{1}{2}} = 0.024$ kev, where $w_i = 1/\sigma_i^2$, $\Delta_i = \bar{E}_0 - E_i$, $k = 5$.

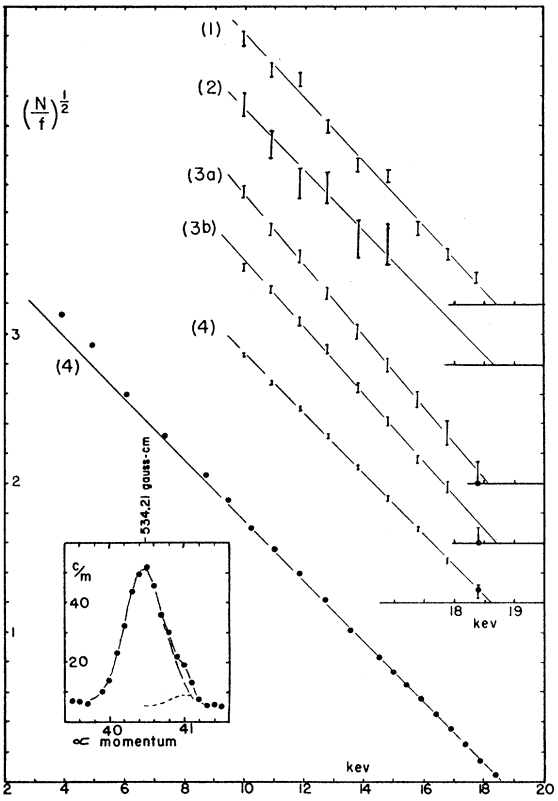

FIG. 1. Kurie plots of the tritium beta spectrum with several volatilized sources. The upper plots, on an expanded energy scale, show only the region near the end point. The points from 14.5 to 18 kev inclusive were used in weighted least-squares fits to a straight line to obtain the extrapolated end points. One source (4) is shown including the lower energy region of the spectrum. Table I gives the differences in the sources and the numerical results. The inset shows the "A" line of the Th decay chain which was incorporated in composite sources with the tritiated material to provide for calibration and for probing the source effects.

[7] G. E. Owen and H. Primakoff, Phys. Rev. **74**, 1406 (1948); Rev. Sci. Instr. **21**, 447 (1950); G. W. Hinman, Carnegie Institute of Technology Report No. NYO-91, Appendix VII, 1951 (unpublished); see also Appendix I of Argonne National Laboratory Report ANL-5525 (unpublished).

[8] K. Siegbahn and K. Edvarson, Nuclear Phys. **1**, 137 (1956).

[9] The components of the earth's magnetic field transverse to the axis of the spectrometer are degaussed to the extent that 500-volt electrons (special 1-meter-long oscilloscope tube) suffer 0±1 mm deflection in traveling along the axis of the spectrometer. This corresponds to an average field of <1.4 milligauss over the trajectory.

TABLE II. A summary of several methods yielding the total decay energy of tritium.

Reference	Method	Tritium decay energy (kev)	Comments
Friedman and Smith[a]	Mass synchrometer	18.6±0.2	
Jenks, Sweeton, and Ghormley[b]	Calorimetry average energy (kev) $\bar{E}=5.69\pm0.04$	18.6±0.1[h]	
Popov *et al.*[c]	$\bar{E}=5.52\pm0.01$	18.21±0.03	
Curran, Angus, and Cockcroft[d]	Gas sample proportional counter	18.6(±0.5)	Resolution near the end point ~8–13% in energy. No Kurie plots
Hanna and Pontecorvo[e]		18.9±0.5	Both this and above calibrated with external beam Mo $K\alpha$ x-rays at 17.4 kev
Hamilton, Alford, and Gross[f]	Electrostatic integral spectrometer	17.6±0.4	Calibration troubles
Langer and Moffat[g]	Magnetic spectrometer	17.95±0.1	Calibrated with "A" line on separate sources
Present work		18.61±0.1	

[a] See reference 1.
[b] See reference 14.
[c] See reference 13.
[d] Phys. Rev. **76**, 853 (1949).
[e] Phys. Rev. **75**, 983 (1949).
[f] See reference 12.
[g] See reference 16.
[h] Slack, Owen, and Primakoff, Phys. Rev. **75**, 1448 (1949) obtained this value from the $\bar{E}$ of Jenks *et al.* The other is obtained by the same procedure.

thickness of the tritiated compound. This offers a direct probe of the source effects on these 25-kev electrons by comparing the "A" line $H\rho$ with that of the "F" line (K line of a 238-kev transition in Bi^{212}) at an electron energy of 150 kev. This ratio was obtained on one of the thicker sources (No. 4) and the result, with considerably less precision, is the same as the Siegbahn and Edvarson[8] value.

$H\rho(F)/H\rho(A)=2.59907\pm0.00025$ (Siegbahn and Edvarson),

$H\rho(F)/H\rho(A)=2.599\pm0.003$ (present work).

This implies[10] a shift of less than 60 ev in the peak of the A line after passing through the thickest source.

Further one can examine the results on the different sources. Certainly a factor of 3 or 4 in source thickness is not affecting the results, and with a lower confidence level a factor of 10 in source thickness is not affecting the results.

The deviation of the Kurie plot from linearity can qualitatively be ascribed to the thick backing but no quantitative statement can be made.

Finally we mention briefly a series of preliminary experiments in which the idea of the combined source was tried out except that 50 times lower specific activity tritiated thymadine was deposited by evaporating a liquid drop on the Al source backing. These sources showed crystalline structure (under microscopic examination) of very nonuniform character. The results for the tritium end point on six runs on three sources ranged from 17.7 to 18.4 kev and the "A" line calibration constants showed variation of 0.6%. These results are not surprising in view of the source preparation and are in marked contrast to the consistency of the results in Table I.

[10] Assuming the most probable energy loss/$\mu g/cm^2$ for 25-kev electrons is 4 to 5 times that for 150-kev electrons.

III. REVIEW OF OTHER DETERMINATIONS OF BETA DECAY ENERGY OF H^3

In the summary of Table II many of the measurements with cloud chambers, absorption, etc.,[11] have not been included, but there remain representatives from several approaches. It appears that with three exceptions the value 18.6 kev would be included in all the other measurements. In this writer's opinion the end-point value of Hamilton, Alford, and Gross[12] from the electrostatic spectrometer should not have great weight. The absolute value of the end point was not their primary objective but rather the shape of the spectrum in the last kev occupied their efforts so that no checks on the absolute calibration with their 100-$\mu g/cm^2$ source were described.

One of the remaining two exceptions in a recent calorimetric determination of the average energy in the tritium decay by Popov *et al.*[13] whose quoted precision is very good (0.2%), but whose result appears disparate with the earlier result of Jenks *et al.*[14,15] The other is the well-known work of Langer and Moffat[16] on the large shaped-field 180° spectrometer. No explanation of the disparity in either the $\bar{E}$ measurements or the magnetic spectrometer measurements is at hand.

If we take 18.6±0.1 kev (this error includes some

[11] Some of these may be traced in the review article by Hornyak, Lauritsen, Morrison, and Fowler, Revs. Modern Phys. **22**, 291 (1950).
[12] Hamilton, Alford, and Gross, Phys. Rev. **92**, 1521 (1953).
[13] Popov, Gagarinskii, Senin, Mikhalenko, and Morozov, Atomnaya Energiya **4**, 296 (1958).
[14] Jenks, Sweeton, and Ghormley, Phys. Rev. **80**, 990 (1950).
[15] There would be considerable interest if future work shows a real discrepancy between the average energy and, say, spectrometer values for the end point, because the two are related by the theoretical expression for the shape of the spectrum about which we know very little below 3 or 4 kev.
[16] L. M. Langer and R. J. D. Moffat, Phys. Rev. **88**, 689 (1952).

estimate of possible systematic effects) for the decay energy of tritium and the Jones[17] half-life of 12.262 ±0.004 years, the *ft* value[18] of H^3 is 1122±20 sec. Popov *et al.*[13] report a longer lifetime 12.58±0.18 years and give an average (which includes the value of Jenks *et al.*[14] as well as that of Jones[17]) of 12.43±0.04 years. This average along with 18.6±0.1 kev gives $ft=1137\pm20$ sec.

Some recent comments on the problem of the ratio of Gamow-Teller to Fermi coupling constants were made by Kistner and Rustad[19] at the Gatlinburg Conference on Weak Interactions. Using $E_0(H^3)=18.6$ kev from the mass difference work, and magnetic moment data to correct $|\int\sigma|^2$, they pointed out that H^3, O^{15}, and F^{17} are consistent with $C_{GT}^2/C_F^2=1.16\pm0.05$ while the neutron data (along with the average of $0\rightarrow0$ transitions) point to a higher value (1.4) for this ratio. However, if the uncorrected single-particle value for $|\int\sigma|^2$ is used for H^3, then tritium and the neutron are consistent with $C_{GT}^2/C_F^2\simeq1.45$.

[17] W. M. Jones, Phys. Rev. **100**, 124 (1955).
[18] E. Feenberg and G. Trigg, Revs. Modern Phys. **22**, 399 (1950), Eqs. (A6) and (A7) for *f*.
[19] O. C. Kistner and B. M. Rustad, Bull. Am. Phys. Soc. Ser. II, **4**, 79 (1958); and private communication of work to be published.

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Magnetic Moments of Strongly Deformed Odd-Odd Nuclei*

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The strong-coupling magnetic moment relation for odd-odd nuclei is evaluated with the use of Nilsson wave functions for finite values of core distortion. The theoretical predictions are compared with all of the data available on odd-odd nuclei in the strong-coupling region. There is no evidence for appreciable error having been introduced by the assumption of no interaction between the odd proton and odd neutron.

I. INTRODUCTION

THE magnetic moments of odd-odd nuclei have been calculated using a variety of approaches. The simplest model to meet with some success is the *j-j* coupling scheme wherein one assumes that the magnetic moment arises from an odd proton and odd neutron, each in its appropriate shell-model state.[1] An improvement in agreement of theory with experiment[2] was obtained when Schwartz[3] suggested that, still using the *j-j* coupling scheme, the *g*-factors for the odd proton and neutron states could be obtained empirically from nearby odd-even nuclei where the shell-model states being occupied are presumably the same as in the odd-odd nucleus under consideration. Caine[4] has shown that this semiempirical approach is successful because it takes into account a large part of the effects resulting from configuration mixing.

The work described above is based on the assumption that the particles are in a spherically symmetrical potential well. Calculations of the magnetic moments of distorted core, odd-odd nuclei were performed first by Bohr and Mottelson.[5] The odd proton and odd neutron were assumed to be coupled strongly to an ellipsoidal core, but both nucleons were considered to be in pure *j*-states. The effects of *j*-mixing arising from the noncentral potential were considered qualitatively. Recently, Gallagher and Moszkowski[6] have calculated moments of odd-odd nuclei using the "asymptotic wave functions" obtained by Nilsson.[7] These are wave functions for particles so tightly coupled to the distorted core that the effects of spin-orbit coupling are insignificant. Thus these calculations represent the opposite extreme from those based on the spherical-core shell model.

Nilsson, however, has solved exactly a Hamiltonian which includes both the spin-orbit and particle-core couplings, so that for each value of the core distortion parameter one is given a level order and corresponding

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[1] E. Feenberg, Phys. Rev. **76**, 1275 (1949).
[2] R. J. Blin-Stoyle, *Theories of Nuclear Moments* (Oxford University Press, London, 1957), p. 68.
[3] H. M. Schwartz, Phys. Rev. **89**, 1293 (1953).
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[6] C. J. Gallagher, Jr., and S. A. Moszkowski, Phys. Rev. **111**, 1282 (1958).
[7] S. G. Nilsson, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **29**, No. 16 (1955).