THE
PHYSICAL REVIEW

A journal of experimental and theoretical physics established by E. L. Nichols in 1893

SECOND SERIES, VOL. 88, NO. 4 NOVEMBER 15, 1952

The Beta-Spectrum of Tritium and the Mass of the Neutrino*

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(Received June 23, 1952)

A direct determination of the beta-spectrum of H^3 has been made in a high resolution magnetic spectrometer. The experimental data are fitted by a straight line Fermi plot from 5.5 kev to the maximum energy at 17.95±0.10 kev. An upper limit of 250 volts or 0.05 percent of the mass of the electron is obtained for the rest mass of the neutrino. New estimates are obtained for the H^3 comparative half-life, the neutron half-life, and the value of the Fermi universal constant of beta-decay.

INTRODUCTION

EVER since it was first realized that tritium is radioactive, the measurement of the beta-spectrum emitted in the transition to He^3 has offered a fascinating challenge. Because of the exceedingly small amount of kinetic energy available for the electron, the measurement of an undistorted negatron spectrum has, until recently, been beyond the capabilities of ordinary beta-spectrometer techniques. It is, moreover, this very low energy release which adds interest to the problem, since the shape of this spectrum is expected therefore to be most sensitive to the influence of any finite rest mass for the neutrino. Furthermore, since the initial and final states of this "super allowed" or "favored" transition involve only the simplest of nuclear structures, an exact determination of the energy released in the transition is important for the detailed understanding of the beta-decay process. This is particularly so if the true law of beta-decay involves a linear combination of the scalar, tensor and pseudoscalar interactions.[1] The $H^3 \rightarrow He^3$ comparative half-life (ft value) is then a measure of the relative amounts of scalar and tensor present.

There are two serious difficulties which up to now have stood in the way of a direct magnetic spectrometer determination of the tritium momentum spectrum. Because of the low energy of the electrons, it is necessary to use an extremely thin and completely uniform source in order to avoid distortions of the spectrum arising from absorption and scattering. It is also required that the support for the source be vanishingly thin, or electrons reflected with loss of energy will further distort the distribution. The second obstacle has been that of obtaining a suitable detector whose sensitivity is independent of electron energy over an appreciable part of the distribution, without requiring large empirical corrections.

Because of these difficulties previous investigations have avoided the use of the spectrometer. The other methods employed have, in turn, involved inherent poor resolution which has in most cases necessitated the application of corrections of the same order of magnitude as the effect being investigated. In addition, from the scatter of the reported values for the maximum energy, it is apparent that other perturbations have been present.

Most of the results of earlier attempts to determine the end-point energy of the spectrum are summarized in the review article by Hornyak *et al.*[2] The methods employed were magnetic field cutoff, absorption of the electrons or of bremsstrahlung, cloud chambers, and proportional counters. The end-point energies reported spread from 11±2 kev to 18.9±0.5 kev. Recently, another measurement has been reported[3] of 19.4±0.4 kev, based on work with an electrostatic integral spectrograph. This last determination as well as those made with proportional counters[4,5] attempt to set an

* This work was assisted by a grant from the Frederick Gardner Cottrell Fund of the Research Corporation and by the joint program of the ONR and AEC.

[1] E. J. Konopinski and L. M. Langer, Annual Review of Nuclear Science (to be published).

[2] Hornyak, Lauritsen, Morrison, and Fowler, Revs. Modern Phys. **22**, 291 (1950).

[3] Hamilton, Alford, and Gross, Phys. Rev. **83**, 215 (1952).

[4] G. Hanna and B. Pontecorvo, Phys. Rev. **75**, 983 (1949).

[5] Curran, Angus, and Cockroft, Phil. Mag. **50**, 53 (1949) and Phys. Rev. **76**, 853 (1949).

upper limit on the rest mass of the neutrino from the shape of the spectrum near the end point. The values obtained are lower than the 5-kev limit which was possible from the shape of the higher energy S^{35} spectrum.[6] All these results are not inconsistent with a neutrino rest mass of zero, although the experiments of Curran *et al.* were interpreted as indicative of a finite neutrino mass of between zero and 1 kev.

In the present investigation, the effort has been to develop source preparation and detector techniques which would make possible a straightforward, precise spectrometer determination of the tritium beta-momentum distribution. Operating the spectrometer at 0.7-percent resolution, it has thus been possible to obtain results which, without requiring the application of any large and perhaps ambiguous corrections, are capable of yielding a more precise determination of the maximum energy of the spectrum and set a closer limit on the rest mass of the neutrino.

Estimates of the half-life of tritium have varied from 10.7 ± 2 to 31 ± 8 years.[2] The most recent and probably most accurate value is 12.46 ± 0.2 years.[7] When this value of the half-life is combined with the present energy measurement, one obtains a somewhat different value for the comparative half-life and the universal Fermi constant. An estimate of the half-life of the neutron is also obtained.

EXPERIMENTAL PROCEDURE

Spectrometer

The tritium beta-spectrum was studied in the high resolution, 40-cm radius of curvature, shaped magnetic field spectrometer.[8] Although this instrument was designed for general use with electrons as high as 10 Mev, many of its features, such as the freedom from scattering, were particularly applicable to this low energy problem. Because of the low energies of the tritium electrons, certain modifications and improvements were incorporated. These modifications, which are related to the important problem of keeping the source at ground potential, to detection, and to measurement of the low magnetic field strength, are discussed below.

With 0.6-cm source and detector slit widths, the momentum resolution for thin internal conversion sources is measured as 0.7 percent for the full width at half-maximum. Thus, a correction was needed, only for points recorded within 2 percent of the maximum energy. These corrections (see Fig. 4) amount to only about 0.2 percent in momentum and are small compared to the effect in spectral shape which was being studied.

Detector

A small side window G-M counter was used as a detector. The counter consists of a cylindrical, oxidized copper cathode of 0.5-in. i.d. and 1.6-in. length, with a 0.005-in. tungsten anode mounted on the axis. The electrons enter the counter through a 2.5-cm by 0.6-cm opening along the length of the counter wall. The opening is covered by a 1.5-microgram/cm^2 Zapon window which is supported by a fine grid of Lektromesh.[9] This grid is 0.0005 in. thick, has 150 openings to the inch, and 56 percent transmission. Such a grid should introduce no distortion of an electron distribution below about 90 kev.

A mixture of 5 parts argon to 1 part ethylene at a total pressure of 2.5-cm Hg was used as the filling gas. With this arrangement, a plateau of about 80 volts is obtained in the neighborhood of 650 volts.

In spite of the low pressure, a small amount of the gas mixture diffuses through the extremely thin counter window, into the evacuated spectrometer chamber. A modified Cartesian manostat[10] is used to regulate the counter pressure within 0.01-cm Hg. An oil diffusion pump maintains the vacuum in the spectrometer chamber at better than 5×10^{-6}-mm Hg. The pulses from the GM tube were constantly monitored on a cathode-ray oscilloscope and showed complete uniformity of amplitude and constancy throughout a spectrum run.

Because of the high specific ionization by the low energy electrons, essentially 100 percent detection efficiency is obtained even with the low pressure used in the counter. Tests were made by varying the counter gas mixture from 2:1 to the more nearly conventional 5:1, and by varying the total gas pressure.

Source

The nature of this problem requires that the source be extremely thin and uniform. Significant data on spectral shapes can be obtained only in the energy interval for which neither the source nor the support introduce energy degeneration because of inelastic scattering. The demand for a thin, uniform source suggests thermal evaporation in vacuum[11] of some suitable tritiated compound onto a thin support. The requirements on the compound are that it must be stable in high vacuum at ambient temperatures, yet must evaporate without decomposition at a temperature low enough to avoid thermal damage of the thin support. Further, the specific activity must be high. Tritiated succinic acid was the final choice. This compound is quite stable at room temperature, sublimes readily at 150°C, and, as prepared,[12] had a specific activity of 0.9 mC/μg.

[6] Cook, Langer, and Price, Phys. Rev. **73**, 1395 (1948); and Phys. Rev. **74**, 548 (1948).
[7] Jenks, Ghormley, and Sweeton, Phys. Rev. **75**, 701 (1949).
[8] L. M. Langer and C. S. Cook, Rev. Sci. Instr. **19**, 247 (1948).
[9] Langer, Motz, and Price, Phys. Rev. **77**, 798 (1950).
[10] L. M. Langer and R. D. Moffat, Phys. Rev. **80**, 651 (1950).
[11] Langer, Moffat, and Price, Phys. Rev. **76**, 1725 (1949).
[12] We are grateful to E. S. Robinson and J. G. Povelites of the Los Alamos Scientific Laboratory for their cooperation in preparing the succinic acid sources.

Several sources were prepared by evaporating a 2.5-cm by 0.6-cm rectangle of succinic acid onto a 4 $\mu g/cm^2$ Zapon support. The Zapon is held by a 1.125-in. stainless steel ring which then is mounted in the spectrometer source holder.

The deposits were invisible except for a slight contrast in reflectivity which could be detected at glancing incidence in subdued light. They were estimated to be about 0.5 $\mu g/cm^2$ thick. Counting rates obtained at the peak of the beta-spectrum were between 2000 and 10,000 counts per minute.

Autoradiographs made by exposing the sources to x-ray film, showed complete uniformity of activity and proper localization of the material in the rectangular source region.

Grounding of the Source

Two methods were used for grounding the sources to prevent electrostatic charging. First, a thin band of copper 1 cm wide and about 2-$\mu g/cm^2$ thick was evaporated thermally in vacuum onto the reverse side of the zapon support. This band extended beyond the edge of the source so as to make contact with the stainless steel ring. Such copper deposits have been measured in this laboratory to have a resistance of the order of 10^8 ohms. This is sufficiently low to insure good grounding. The second method consists of installing an oxide coated cathode-filament assembly (from an 879 tube) just below the source in the spectrometer. The cathode was heated to normal emission temperature so that any tendency of the source to charge positive would be neutralized by electrons attracted from the emitting cathode. The emission of the cathode was checked by measuring the current to ground when the cathode potential was lowered by 45 volts.

By varying the filament temperature, spectrum runs were obtained with the cathode emission differing by a factor of 100. These were found to give the same results.

Each grounding method alone, as well as the combination of copper backing plus emitting cathode, gave spectra with identical end points. As might be expected, the additional mass of the copper grounding layer resulted in increased scattering which caused the Fermi plot of the data to deviate from a straight line at a higher energy (10 kev) than was otherwise observed (5.5 kev). With no provision for grounding, the sources appeared to charge to about 460 volts as indicated by the lower curve of Fig. 2.

The stability of the sources was checked by measuring the bremsstrahlung in a standard geometry with a thin, mica window GM counter. In spite of repeated and prolonged exposure to high vacuum, no measureable change in activity was detected. Further, repeated spectrometer runs with a given source were found to agree without need for intensity adjustments.

Magnetic Field

The current for the magnet is supplied by an electronically stabilized source and was monitored by periodically reading the value on a type K potentiometer. The current was stable to better than 1 part in 10,000 during the time required for any point.

Special apparatus was constructed for the measurement of the magnetic field intensity. This experiment required operating in the range of 3.5–15 gauss and the usual field measuring apparatus[13] was not sufficiently sensitive. It was found satisfactory to measure the voltage generated by a coil rotating in the magnetic field. A small coil of 1-cm diameter was driven by an 1800-rpm synchronous motor. The 30-cycle pick-up voltage was brought out through a rotating primary transformer[13] and fed through a narrow band filter and a stabilized amplifier and read on a voltmeter of 0.5 percent accuracy. By appropriate settings of a precision high impedance voltage divider, readings of 10–20 volts were obtained for the region under investigation.

This system was intercalibrated with the deflections from a conventional ballistic galvanometer, flip coil, and standard mutual inductance arrangement. A slight nonlinearity of the amplifier system was overcome by interpreting the voltmeter readings in terms of the appropriate ballistic galvanometer deflection.

The magnetic field shape was carefully checked to insure that there was no variation of the gradient with field intensity. The rotating search coil was mounted so that its position between the pole faces could be varied. Measurements of the field strength relative to the value at the mean radius of 40.32 cm were made as a function of radial position for various field intensities. These measurements included the region from the inside of the beam to the point outside the beam at which the rotating coil was finally located. It was found that cycling of the magnet on the proper hysteresis curve insured reproducibility of the proper field shape. The data were all obtained by successively increasing the energizing current always in the same direction.

Calibration

Immediately before and after each tritium run, a calibration of the spectrometer was made in terms of the "A" line of thorium C''. The momentum of this line has been obtained[14] with high accuracy as $H\rho = 533.66 \pm 0.12$. It was selected because it lies close to the end point of the tritium beta-spectrum.

Sources of ThB in equilibrium with its products were prepared by electrostatically collecting the recoil atoms from Th active deposit. The 0.6 cm wide, 0.015-g/cm^2 Al strip used as a collector was then employed as a grounded source of the Th "A" line electrons. The extrapolation of the high energy edge of this line's

[13] L. M. Langer and F. R. Scott, Rev. Sci. Instr. **21**, 522 (1950).

[14] H. Craig, Phys. Rev. **85**, 688 (1952); see also, J. Surugue, Ann. phys. **11**, 8, 484 (1937).

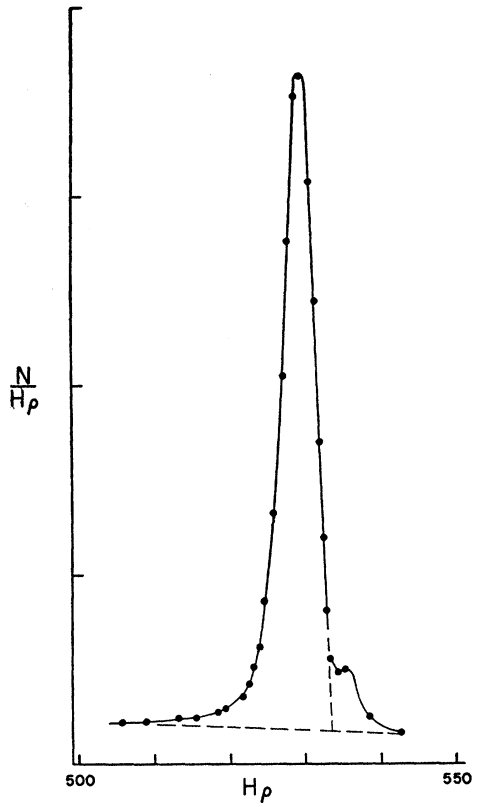

FIG. 1. Typical momentum profile obtained for the "A" line of ThC'' used for calibration.

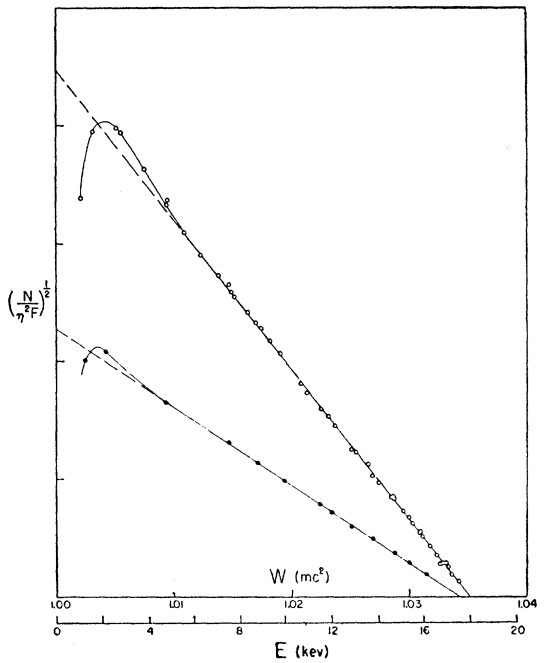

FIG. 2. Fermi plots of the tritium beta-spectrum. The upper curve is for a source grounded by an emitting cathode. The lower curve is for an ungrounded source.

profile was used as a calibration point. Figure 1 shows a typical run. The "A" line arises from internal conversion in the L_I shell. The line resulting from the much less frequent conversion in the L_{II} shell does not interfere with the calibration. Because of broadening by the thick Al backing, the line obtained with these sources had a width at half-maximum of 0.9 percent. This broadening does not affect the calibration if the high energy edge extrapolation is used. Correction was made for the fact that this edge corresponds to electrons which have traversed a trajectory with an effective radius, $\rho=\rho_0-\frac{1}{4}(S+\delta)$, where ρ_0 is the nominal mean radius and S and δ are the source and counter slit widths, respectively.

Small corrections for finite geometrical resolution were applied to those points on the tritium spectrum which fall in the immediate neighborhood of the end point.

RESULTS AND CONCLUSIONS

The Beta-Spectrum and End Point

The upper curve of Fig. 2 shows a typical Fermi plot of the tritium electron spectrum. The data are fitted well by a straight line from the maximum energy down to 5.5 kev, where the effect of source and backing thickness begin to produce a noticeable excess of low energy electrons. The falling portion of the curve below 2 kev shows the result of attenuation by the thin Zapon counter window. Extrapolation of the straight line, which is the theoretical curve for zero neutrino rest mass, yields an end point of 17.95±0.10 kev. This curve was obtained with a source which was prevented from charging only with the heated cathode. The lower curve of Fig. 2 shows the effect of no provision for grounding the source. Here the whole spectrum appears to be shifted so that the maximum energy appears at 17.49 kev, or 460 volts lower than obtained with a grounded source. Figure 3 shows the result of evaporating 2 μg/cm^2 of copper behind the same source as used for obtaining the data of Fig. 2. As might be expected, the end point remains unchanged, since either method of grounding seems to be sufficient in itself. However, the deviation from the straight line, because of the additional mass of copper, occurs at the higher energy of 10 kev.

In another series of experiments, the sources were mounted so that the 4 μg/cm^2 Zapon support came between the succinic acid deposit and the detector. In general, the results of these experiments shown in Fig. 4 are the same as for those obtained for sources mounted in the normal manner, except for the fact that the curves are shifted so as to appear to give an end point about 250 volts lower. The deviations from the straight line again set in at higher energies. Curve B is for the cathode-emission grounded source, curve A for a copper deposit grounded source. Curve C is for an ungrounded source. It is apparent from these experiments that there is no appreciable penetration of the

succinic acid into the Zapon support—the sort of thing one might expect with sources prepared by adsorption of tritium gas.

Neutrino Rest Mass

The phenomenological definition of the neutrino and Fermi's use of it in his formulation of the theory of beta-decay make no stipulation about the rest mass of the neutrino other than that it is probably small. It has been shown[15] that if the neutrino were to have a finite rest mass, ν, it would become manifest in its influence on the momentum distribution of the electrons in beta-decay. In that case, the distribution formula for electrons of momentum η may be written as

$$Nd\eta = \text{const}F(Z, W)\eta^2K(K^2-\nu^2)^{\frac{1}{2}}(1\mp\nu/WK)d\eta,$$

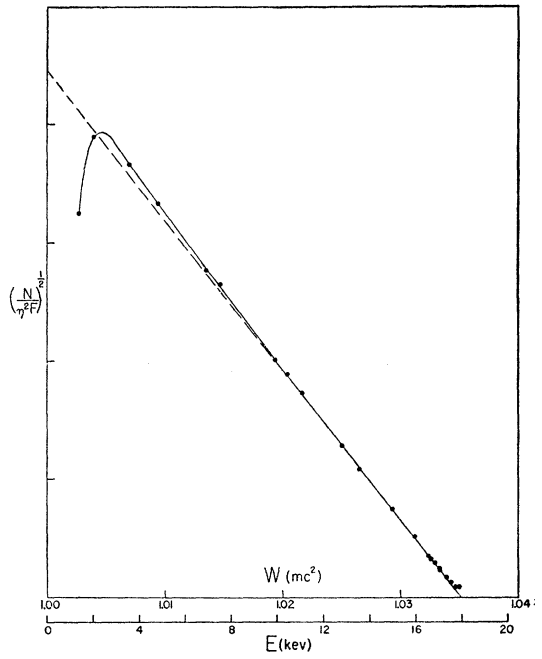

FIG. 3. Fermi plot of the tritium spectrum data obtained with a source which was grounded by a 2μ g/cm² Cu deposit on the backing.

where N is the number of electrons in unit momentum interval, F is the Coulomb factor, K is the neutrino energy and $W=(1+\eta^2)^{\frac{1}{2}}$ is the electron energy, in units of mc^2.[16] The negative sign applies if it is a Dirac antineutrino which accompanies negatron emission. The plus sign would apply to Fermi's original formulation of the theory in which the neutrino accompanies negatron emission. The possible validity of such a formulation was substantiated by the considerations of Yang and Tiomno.[17]

The influence of a finite neutrino mass is most pronounced near the maximum energy of the beta-spectrum. The Fermi plot then is no longer a straight line. Instead, it turns sharply towards the energy axis. The distance between the theoretical true end point and the point, defined by the usual straight line extrapolation of the negatron spectrum obtained at low energies, turns out then to be equal to $\nu/2$ or to $3\nu/2$, depending on whether it is the Dirac anti-neutrino or neutrino which is emitted in the process. If a Majorana neutrino were emitted, this distance would be equal to ν. Recent theoretical considerations[18] suggest that the neutrino is a Dirac rather than a Majorana particle. In the following, the negative sign is assumed corresponding to a Dirac antineutrino going with negatron emission. A Fermi plot of the data in the region near the end point is shown in Fig. 5. Both vertical and horizontal scales have been enlarged to show greater detail. The theoretical curves for various neutrino rest energies are shown for comparison with the data. These curves have all been normalized to the observed

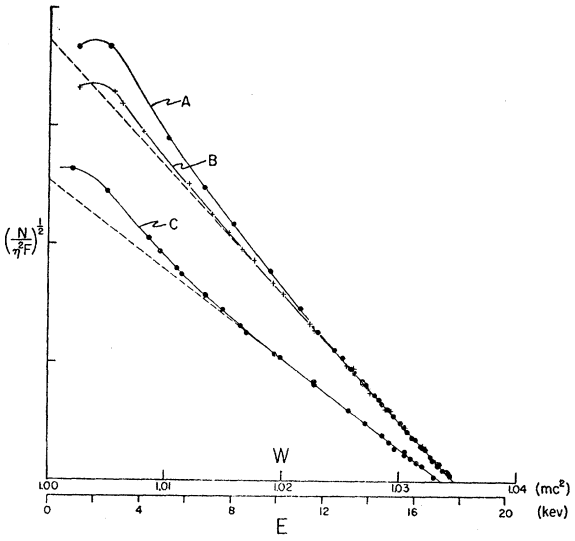

FIG. 4. Fermi plots obtained with sources reversed so that the Zapon support was between the activity and the detector.

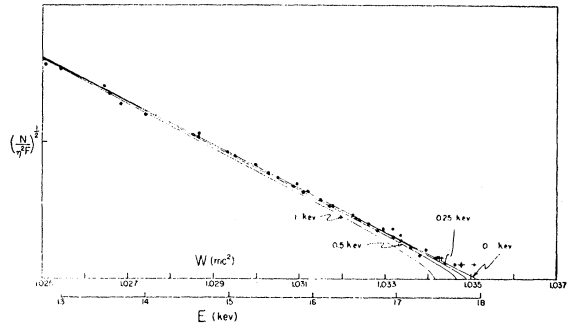

FIG. 5. Expanded Fermi plot of the tritium spectrum in the region near the end point. The curves are the theoretical plots expected for the indicated rest mass of the neutrino.

[15] O. Kofoed-Hansen, Phys. Rev. **71**, 451 (1947).
[16] J. R. Pruett, Phys. Rev. **73**, 1219 (1948); see also reference 6.
[17] C. Yang and J. Tiomno, Phys. Rev. **79**, 485 (1950).
[18] E. R. Caianiello, Phys. Rev. **86**, 564 (1952).

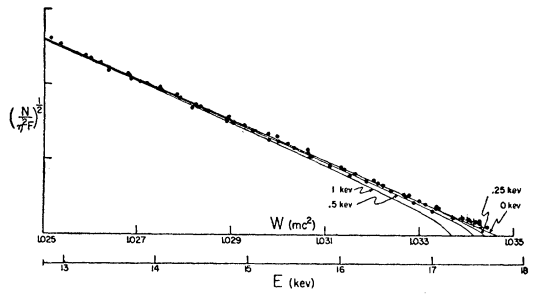

FIG. 6. Like Fig. 5, except for data obtained with the sources reversed.

intensity at 10.5 kev. The small magnitude of the resolution correction required in the immediate neighborhood of the end point is shown by the displacement of the circles to the position of the crosses. Figure 6 shows a similar plot for the data obtained with the source reversed.

The data are consistent with a Dirac neutrino rest mass of zero and set an upper limit on any finite rest mass of 250 volts or 0.05 percent of the rest mass of the electron.

Comparative Half-Life

The value of 17.95±0.10 kev for the beta-maximum energy, together with the half-life of 12.46±0.2 years,[7] permit a more precise evaluation of the comparative half-life of the super allowed $H^3 \rightarrow He^3$ transition. The result is $ft = 1014 \pm 20$ sec or $\log ft = 3.006$.[19]

[19] The value of f was calculated from Eqs. A6 and A7 given by E. Feenberg and G. Trigg, Revs. Modern Phys. 22, 404 (1950).

Neutron Half-Life

If one assumes that the comparative half-life for the neutron decay is the same as for that of H^3, one can combine the present results with the measured energy of 0.782±0.002 Mev for the neutron decay[20] to get an estimate of the neutron half-life. The value so obtained is 10.4±0.6 minutes. This value is in good agreement with the experimental value obtained by Robson of 12.8±2.5 minutes.

Universal Fermi Constant

The H^3 decay is an $S_{\frac{1}{2}} \rightarrow S_{\frac{1}{2}}$ transition. If the law of beta-decay is indeed a linear combination of the Fermi and Gamow-Teller forms of interaction,[1] then the universal constant G of beta-decay is given by the relation

$$ft = 5.57 \times 10^{-20} G^{-2} \left[\left| \int \boldsymbol{\sigma} \right|^2 + K^2 \left| \int 1 \right|^2 \right]^{-1} = 1014 \text{ sec},$$

if G is in units of $mc^2(\hbar/mc)^3 = 4.73 \times 10^{-38}$ erg cm³. Here, $|\int \boldsymbol{\sigma}|$ and $|\int 1|$ are matrix elements and $K = G_F/G_{G-T}$ is the ratio of the strengths of the Fermi and Gamow-Teller parts of the interaction.

If $[|\int \boldsymbol{\sigma}|^2 + K^2 |\int 1|^2]$ is normalized to unity, then

$$G = 7.41 \times 10^{-12} = 3.50 \times 10^{-49} \text{ erg cm}^3.$$

The authors are indebted to Professor E. J. Konopinski for many helpful discussions. They also wish to acknowledge the cooperation of Mr. E. Plassmann and Dr. H. C. Price in assisting with some preliminary experiments.

[20] See reference 2; also, J. Robson, Phys. Rev. 83, 349 (1951).