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Energy of the superallowed positron decay of ^{10}C

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The threshold energy for the ^{10}B$(p,n)^{10}$C reaction and the energy of the 720 keV gamma ray which follows the decay of ^{10}C have been measured to be 4876.91 ± 0.10 keV and 718.353 ± 0.011 keV, respectively. This has enabled the energy of the superallowed positron decay of ^{10}C to be determined to be 885.72 ± 0.09 keV, which is a necessary step in the deduction of an accurate *ft* value.

INTRODUCTION

The superallowed component of the positron decay of ^{10}C is a $0^+ \rightarrow 0^+$ decay between members of a $T=1$ isotopic spin triplet, and as such, the measurement of its *ft* value enables in principle the value of G_V, the vector-weak interaction coupling constant, to be determined. As has been pointed out by Marciano and Sirlin,[1] this decay has a special significance, since the contribution of Z-dependent radiative corrections to the *ft* value, an area of some theoretical uncertainty, should be the smallest of the nuclear cases. Until now, the main obstacle to the extraction of the *ft* value with a high accuracy (i.e., to better than, say, 0.2%) has been the accepted value of the branching ratio for the decay $1.465 \pm 0.014\%$,[2] but as this is currently being remeasured with the aim of reducing the error to close to 0.1%,[3] it is now worthwhile to remeasure the other parameters of the decay, viz. the total decay energy and the half-life. The present account deals with the former.

If the maximum positron energy in the superallowed decay is Q_β, then the f in the *ft* value is proportional approximately to Q_β^5, and thus in order to achieve an overall accuracy of less than 0.1%, Q_β must be obtained to better than 0.02%. In fact, the decay is to the second excited state of ^{10}B at 1.74 MeV, and Q_β is around 900 keV, so the desired precision is to at least ± 180 eV.

The value of Q_β is most easily obtained from a combination of the energy of the 1.74 MeV excited state with the Q value of the associated reaction $^{10}\mathrm{B}+p \rightarrow {}^{10}\mathrm{C}+n$. The relation is

$$Q_\beta = -Q_{pn} - (n - {}^1\mathrm{H} + 2e)c^2 - E_{1.74} ,$$

where the symbols in parentheses are the masses of the neutron, hydrogen atom, and electron, all three of which introduce negligible error into Q_β. In Ref. 4 is reported a measurement of $Q_{pn} = -4430.17 \pm 0.34$ keV. The present, improved version has followed essentially the same method as described there, but with greater attention to systematic errors and to the obtaining of higher statistical accuracy.

The energy of the 1.74-MeV state is most conveniently measured by studying its two deexcitation γ rays at 720 and 1020 keV. The energy of the latter was recently reported as 1021.646 ± 0.014 keV,[5] but the former, at 718.32 ± 0.04 keV,[6] is easily improved, and a new value has been measured.

THE ^{10}B$(p,n)^{10}$C THRESHOLD DETERMINATION

The Q_{pn} is most directly measured by determining the threshold energy for production of ^{10}C. Accordingly, targets of 99.5% ^{10}B, approximately 100 μg/cm^2 in thickness and evaporated on to a 99.999% gold backing, were bombarded with protons of about the threshold energy of 4.88 MeV. These protons had come as a beam from the tandem accelerator AURA2, and had passed in a tightly constricted 0° orbit round an Enge split-pole spectrograph, striking the target 10 cm beyond the image plane. The mean kinetic energy of the protons was held essentially fixed by fixing the spectrograph magnetic field. The reaction energy was altered by applying an offset potential of a few kilovolts to the target.

The ^{10}C produced has a half-life of 19 sec, and the yield is not very great, mainly because of the spin difference between the target and product, $3^+ \rightarrow 0^+$, so some effort was expended in trying to maximize the efficiency of the detection of the decay products. These are primarily a 720-keV γ ray (100%) and a positron of energy up to 1.9 MeV (98.5%). So, typically, the target was bombarded with 200 nA of protons for 20 sec. The beam was then mechanically interrupted 5 m upstream, and the target was moved 50 cm vertically downward in a 12-mm square tube by a magnetic coupling device, through the floor of the spectrograph, where the radiation emitted was observed for 30 sec. The target was then translated upwards again and the cycle repeated 20 times.

Of the various possible methods of identifying ^{10}C, it was felt that the best combination of sensitivity and cleanliness would be given by one of the following. Firstly the γ rays emitted by the target were looked at by three 7.5 cm × 7.5 cm NaI detectors in an any two-out-of-three coincidence arrangement. Unfortunately it was not possible to position all three detectors close to the target, and so this method had insufficient solid angle. Second, the positrons emerging through a 0.1-mm stainless-steel window in the side of the main tube were observed with a plastic scintillator $E - \partial E$ telescope, as a function of the time that had elapsed since the end of the bombardment period. This system had been quite successful for higher-energy positron emitters,[7] but did not in this case sufficiently discriminate between yields above and below threshold.

The method used finally was to detect the emitted 720-keV γ rays with a 22% Ge(Li) detector, placed axially as close as possible (11 mm) to the target. The resolution of the 720-keV peak was generally around 2.6 keV full width at half maximum (FWHM), and the total count rate never greater than 500 $\sec^{-1}$. A yield curve then consisted of values of the total number of detected full-energy 720-keV γ- rays, normalized to the number of incident protons which had produced them, taken for a series of target offset voltages. A measure of the number of protons was obtained by observing protons scattered at approximately 140° into a silicon semiconductor detector 250 mm from the target. A typical threshold curve is shown in Fig. 1. Also shown in Fig. 1 is the least-squares fit to the data points in terms of the function $Y_i = a(V_i - V_0)^{3/2} + b$, where b is a constant background, and V_0 is the offset voltage at threshold. This functional form is derived on the assumption that the neutrons emitted in the (p,n) reaction are s wave, and that the target is sufficiently thick that the energy of all incident protons has dropped below threshold before they emerge from the back of it. Both these conditions are straightforwardly obeyed in the present case.

The threshold energy for a particular run E_0 is then obtained as $E_0 = E_p - eV_0$, where E_p is the mean kinetic energy of the protons. To obtain this latter, every few hours the proton beam was stopped, and without altering the magnetic field in the spectrograph, a beam of singly charged ^{133}Cs ions from a subsidiary surface ionization source was accelerated to pass along the same path through the spectrograph as the protons had done. A measurement of the voltage through which these ions were accelerated gave their momentum and hence the mean momentum and energy E_p of the protons. Full details of the method, which enables the extraction of E_p to a few parts per million (ppm), are given in Ref. 8 and earlier references cited there.

A further improvement, not discussed in Ref. 8 has been the realization that temperature effects in the body of the spectrograph are not quite negligible and that a 30 ppm per Celsius degree linear effect in energy determinations is present and can be corrected for.[9] As temperature variations over the course of a whole run were almost negligible, each individual yield point has not been corrected, but rather an average proton kinetic energy has been calculated as the mean of the initial and final values.

There are two main differences in the treatments of the γ-ray yields between the previous experiment[4] and the present case. First, in order to increase the yield of the 720-keV γ rays, the entrance slit to the spectrograph was widened to enable more beam to be focused through, and this led to the proton beam energy distribution being wider than normal, approximately triangular in shape with a full width at half maximum (FWHM) of 150 ppm (0.74 keV). Second, in the γ-ray spectra, some care was devoted to establishing consistent criteria for the subtraction of a polynomial background from the 720-keV peak, although the spectra themselves were actually very clean. Indeed it might be expected that a satisfactory subtraction method would prove itself in that the subsequent analysis of the yield curves would find a background b which would be consistent with zero. Only in the eighth and last run was that not obviously true. Unfortunately, it had not been realized that the resolution of the detection system had been deteriorating during this run, being close to 4.5 keV at the end. This made the analysis of the spectra more uncertain than for the earlier data, and this is reflected in the final results.

RESULTS FOR THE THRESHOLD ENERGY

The results of the analysis of the eight runs, four for each of two targets, are shown in Table I. The yield points were analyzed, in terms of the function quoted above, using two independent, nonlinear iterative procedures. The first was essentially a "steepest descent method," and the second matrix inversion. Allowance

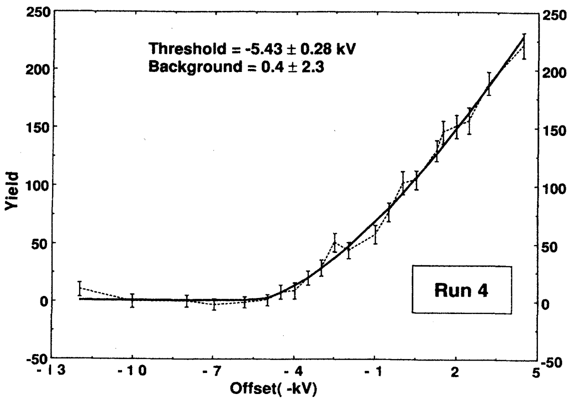

FIG. 1. A yield curve for the reaction ^{10}B$(p,n)^{10}$C as described in the text. The solid line is a fit to the function $Y_i = a(V_i - V_0)^{3/2} + b$.

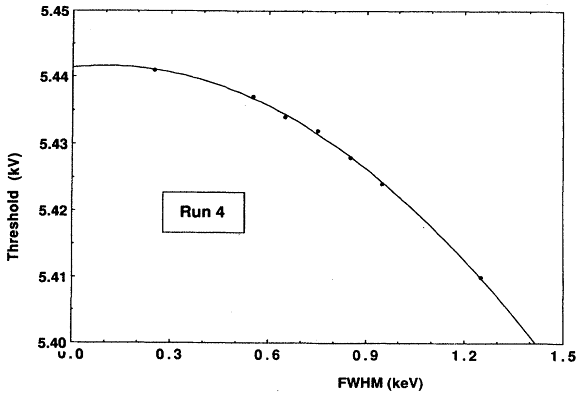

FIG. 2. The variation of the extracted threshold offset voltage for run 4, shown as the assumed FWHM of the beam-energy distribution is varied.

TABLE I. Analysis of the eight runs in terms of the function $Y_i = a(V_i - V_0)^{3/2} + b$ as described in the text. For the parameters, the figures in parenthesis represent the uncertainty in the same number of least significant digits in the parameter.

Run number	E_p (keV)	$-V_0$ (kV)	b	E_0 (keV)
1	4876.69	0.07(25)	−1.6(1.9)	4876.76(25)
2	4879.82	−2.90(30)	2.5(2.5)	4876.91(30)
3	4874.46	2.71(30)	1.7(2.1)	4877.17(30)
4	4882.22	−5.43(28)	0.4(2.3)	4876.79(28)
5	4879.08	−2.23(26)	−3.5(2.1)	4876.75(26)
6	4874.30	2.59(30)	0.3(2.1)	4876.88(30)
7	4880.20	−3.06(31)	−0.1(2.5)	4877.14(31)
8	4886.05	−8.62(31)	5.3(2.3)	4877.42(31)
		Weighted mean		4876.95(10)
		Unweighted mean		4876.98(09)

was made for a triangular beam energy distribution of 0.74 keV FWHM. The minimization parameters obtained were the same for both methods, but ascribed errors from the latter have been found to be more reliable in the past, and it is the results from the latter which are shown in the table. All the reduced χ^2_ν values for the fits were in the range 0.6–1.5 except for run 8, where it was 2.2. The fitted background values are included for the reasons indicated above, and except for run 8 they are obviously satisfactory. Even for that run the value is not sufficiently deviant to warrant exclusion of the result. The weighted mean of the eight runs is 4876.95±0.10 keV. Because errors derived from nonlinear fitting procedures are not infrequently open to suspicion, it is interesting to calculate the unweighted mean of the eight thresholds, particularly as the eight experiments were performed under similar conditions. This unweighted mean is 4876.98±0.09 keV, in good agreement.

In the extraction of the offset voltage at threshold from a yield curve, there is a slight dependence on the beam-energy distribution assumed. Generally this distribution is given entirely by the geometry of the beam-path collimation through the spectrograph, and this is true for the present case, in which the object and image slits were run slightly larger than normal, each being 0.08 mm wide. The actual energy shape can be determined straightforwardly from the caesium ion calibrations and was triangular with a FWHM of 150 ppm, as reported above. The analysis for one of the data sets, run 4, was carried out with a variety of assumed widths, and the results are shown in Fig. 2. Since the FWHM of the distribution is certainly known to better than 10%, any error introduced into the threshold analysis because of this uncertainty is negligible.

If the thickness of the boron target layer is insufficient to bring all the incident protons down to an energy below the threshold, then the simple analysis outlined above will be invalid. One fairly stringent test of this is to reanalyze a yield curve several times, successively omitting the highest energy points, and to look for an overall trend in the extracted thresholds. This process was carried out for runs 4 and 7 (one for each target) and the results for the latter are shown in Fig. 3. No evidence could be seen that the targets were insufficiently thick.

If one requires the background to be identically zero for the fits, as a check on the overall procedure, then the threshold values in Table II are obtained with weighted and unweighted means of 4876.95±0.08 and 4876.94±0.06 keV, respectively. For the final threshold value from this series of measurements we take the value

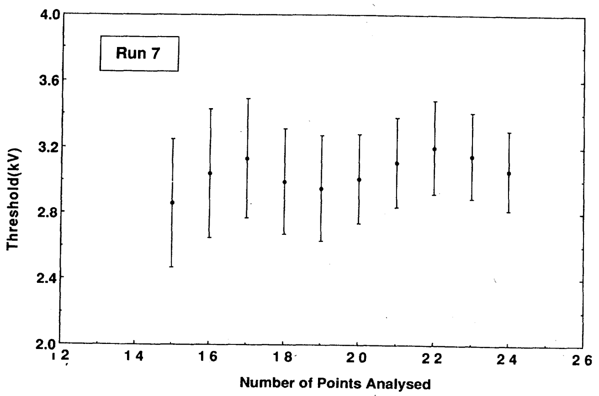

FIG. 3. The variation of the extracted threshold offset voltage for run 7, shown as the higher-energy points are successively and cumulatively omitted.

TABLE II. Analysis of the eight runs in terms of the function $Y_i = a(V_i - V_0)^{3/2} + b$ with the value of b fixed at zero, as described in the text.

Run number	E_p (keV)	$-V_0$ (kV)	E_0 (keV)
1	4876.69	0.23(20)	4876.92(20)
2	4879.82	−3.06(24)	4876.76(24)
3	4874.46	2.58(25)	4877.04(25)
4	4882.22	−5.46(22)	4876.76(22)
5	4879.08	−1.92(20)	4877.16(20)
6	4874.30	2.57(24)	4876.86(24)
7	4880.20	−3.06(25)	4877.14(25)
8	4886.05	−9.20(25)	4876.84(25)
	Weighted mean		4876.95(08)
	Unweighted mean		4876.94(06)

$E_0 = 4876.95 \pm 0.10$ keV.

In Tables I and II, there is no error given for the various quoted values of the mean proton kinetic energy. As explained in Ref. 8, when the mean magnetic rigidity of the particle orbit through the spectrograph is calibrated using caesium ions, a number (ME/f^2) is obtained (actually for caesium, a nonrelativistic calculation of mass multiplied by kinetic energy divided by the square of the frequency of the monitoring nuclear magnetic resonance system). This (ME/f^2) value varied by less than 50 ppm over the whole ten day period of the experiment, and the average difference between the values at the start and end of a complete run was 23 ppm. As the yield points were deliberately not taken in monotonic order of applied voltage, the effect of these small changes was negligible. The other, systematic errors in the determination of E_p, which are discussed in Ref. 8, and which are of the order of 5 ppm, are similarly negligible when combined with the 205 ppm quoted above.

THE 720-keV γ-RAY ENERGY

The methods used to determine the energy of the 720-keV γ ray which follows the decay of ^{10}C are essentially the same as are described in Ref. 5. In this case the primary calibration line was from a source of ^{137}Cs at 661.660 ± 0.003 keV, and secondary calibrations came from the two lines of ^{207}Bi at 569.702 ± 0.002 and 1063.662 ± 0.004 keV.[9]

A thin ^{10}B target similar to the one described above was bombarded with a 1–2 μA beam of 6.88-MeV protons for 5 sec, and then the target translated 50 cm down a tube where it came to rest approximately 15 cm from a 22% cylindrical Ge(Li) detector, at 90° to the detector's axis of symmetry. One second later, the spectrum of γ rays emitted from the target was taken by the detector for 5 sec, simultaneously with the γ rays from the ^{137}Cs and ^{207}Bi sources. The two last were placed within 5 mm of the target position to minimize the effects of any spatial dependence of the response of the Ge(Li) detector. The target was then translated upwards again, the beam chopper reopened and after a further 1 sec delay, the whole process repeated. The short bombard and count periods were to obviate effects due to variation of count rate in the detector and its electronics system, as explained in Ref. 5.

An additional feature was that surrounding the Ge(Li) detector was a 254 mm × 254 mm NaI suppressor. Of course, Compton suppression is not needed at all for this simple experiment, but since the apparatus had just been received, it was felt to be desirable to gain experience of its use in a real measurement. Accordingly all spectra were accumulated in two forms, suppressed and unsuppressed, using two independent ADC's. The suppression ratio was around four in the regions of interest.

The γ spectra were taken in 8192 channels with various dispersions of 0.1–0.2 keV/channel, and total count rates out of the amplifier were never greater than 1500/sec. The resolution of the detector system at 660 keV was approximately 1.9 keV FWHM.

For the analysis of the spectra, the same procedure was used as in Ref. 5. For each peak, a polynomial background, determined from 100 channels or so in its vicinity, was subtracted, and then a Gaussian function was fitted to the points which were above the half maximum, giving the Gaussian's center as the fiducial point of the peak. Then the slope of the energy calibration in the vicinity of the 660–720 keV doublet was evaluated using the two ^{207}Bi peaks, and the precise energy of the 660-keV line gave finally the energy of the 720-keV line.

As a check on this procedure, exactly the same method, except for the target cycling, was used to measure the energy of the 723-keV line in the decay of ^{108}Ag^m. Runs with this source were done under the same conditions as, and were interspersed with, the ^{10}C runs.

The mean value for the energy of the 723-keV line obtained was 722.943 ± 0.010 keV, where the results for both suppressed and unsuppressed spectra have been averaged, although account has been taken in the averaging of the fact that the two spectra are essentially the same data. No contribution has been folded in for the quoted errors on the calibration lines. The presently accepted value is 722.938 ± 0.008 keV.[10]

For the 720-keV line of ^{10}C, the average value from four runs was 718.353 ± 0.010 keV, and when the quoted error on the 662-keV line is folded in (the errors on the ^{207}Bi lines having a negligible effect), this remains the same.

THE SUPERALLOWED DECAY ENERGY Q_β

The value of the threshold energy obtained above, 4876.95 ± 0.10 keV, may be averaged with the value previously obtained in our laboratory,[4] 4876.90 ± 0.37 keV to give an unchanged final value of 4876.95 ± 0.10 keV. The γ-ray energy quoted above leads to an excitation energy for the first-excited state of ^{10}B of 718.380 ± 0.011 keV when the effect of nuclear recoil is taken into account.

There is one further effect which should be taken into account. It seems likely that the definition of the Josephson volt will shortly be revised upwards by 9 ppm.[11] Since our 1-V standard, which is the cornerstone of the kinetic energy determinations, was calibrated on the old value, we anticipate the change and lower E_0 by 9 ppm to 4876.91 ± 0.10 keV.

Using this value of E_0, the Q value Q_{pn} becomes -4430.20 ± 0.09 keV, where no allowance has been made for atomic effects or for the effects of nonuniform proton energy loss in the target, both of which are estimated to be small. The maximum positron energy in the superallowed transition is then

$$Q_\beta = (4430.20 \pm 0.09) - (718.38 \pm 0.01) - (1021.70 \pm 0.01) - (1804.40)\ \text{keV}$$

which leads to the final value of $Q_\beta = 885.72 \pm 0.09$ keV.

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