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Half-life of ^{10}C

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In two separate experiments the half-life of ^{10}C has been measured to be 19.294±0.016 s and 19.300±0.041 s. This has resolved the previous disagreement in the literature and gives a final value of 19.290±0.012 s when combined with the other, concordant determinations. Only the branching ratio now needs to be remeasured to enable the *ft* value of the ^{10}C superallowed positron decay to be calculated with a precision of 0.1%.

INTRODUCTION

It has been emphasized that the decay of ^{10}C to the 1.74 MeV state of ^{10}B is a particularly interesting example of a $0^+ \rightarrow 0^+$, $T=1$ superallowed positron decay, because Coulomb corrections to the calculation of the decay strength should be the least uncertain of any for such nuclear decays.[1] The experimental data needed to calculate this strength, or *ft* value, are the maximum energy release, the total half-life, and the branching ratio, and of these, the first has been measured,[2] and the last is in the process of being measured,[3] both with an accuracy which is sufficient to allow conclusions to be drawn which bear on the assumptions of the standard model.

In their collation of the experimental data relating to superallowed positron decays, Hardy and Towner[4] give the half-life of ^{10}C as 19.255±0.053 s, but show that in reality the confidence level to be assigned to this number is zero, since it is based upon four mutually inconsistent values, 19.282±0.020 s,[5] 19.27±0.08 s,[6] 19.480±0.050 s,[7] and 19.151±0.026 s.[8] The aim of the present work is to resolve this disagreement, and to determine the half-life to an accuracy of 0.1%, which is the level of the uncertainties of the other parameters contributing to the *ft* value, and which would put the *ft* value on a par with those of the most accurate of the other, similar cases.

The simplest way of monitoring the decay of ^{10}C is to detect the 718 keV gamma rays which follow the positron emission. In both the experiments to be described this was done with 20% efficient Ge(Li) detectors connected to ORTEC 572 amplifiers which had been set to a 1 μs time constant. The full width at half maximum (FWHM) of the 718 keV peak was around 2.5 keV.

THE FIRST EXPERIMENT

Targets of approximately 100 μg/cm^2 isotopically enriched boron (99.5% ^{10}B, 0.5% ^{11}B) on tantalum backings were bombarded with beams of protons from the tandem accelerator AURA2. The proton energy was 5.8 MeV, which corresponds to a local minimum in the ratio of cross sections for production of ^{11}C and ^{10}C, and the beam intensities were varied between 80 nA and 500 nA. After a period of 40 s, the beam was interrupted 5 m upstream, the target translated downwards 40 cm to lie on the axis of a Ge(Li) detector, and the time decay of the gamma radiation emitted from the target examined for 512 s. The target was then raised again into the beam line, and the cycle repeated between 6 and 20 times. The distance from the front face of the detector to the target was varied from 7.5 to 21 cm, and in the 37 runs taken, four separate targets were used.

The time dependence of the intensity of the 718 keV gamma rays was studied by placing a single channel analyzer (SCA) window around the full energy peak in the Ge(Li) spectrum. The SCA output went to an ORTEC model 6240 multichannel analyzer (MCA) used in the multiscalar mode in 512 channels, with a stepping time of 1 s. The width of the SCA window was approximately twice as great as the total width of the 720 keV peak in order to try to minimize any effects due to changing gains caused by varying count rates. The stepping time per channel, which was the fundamental time scale for the whole experiment, was provided by stepping down a 1 MHz quartz oscillator, whose frequency was calibrated using several Hewlett Packard frequency counters, all of which were in accord to better than 1 part in 10^6, and showed that the oscillator was stable over weeks to better than 1 part in 10^6. The dead times of the MCA and SCA were measured using a variable frequency oscillator to simulate their input pulses, and were determined to be 0.2±0.02 μs and 1.23±0.02 μs per pulse, respectively.

After initial tests had been completed, it was decided essentially to double the rate of data taking by using a second, similar Ge(Li) detector—572 amplifier—SCA system in parallel with the first, and "OR"ing the two outputs in an ORTEC 418A universal coincidence, before the input to the MCA. In hindsight, this was almost certainly a retrograde step, since, although the dead time of the 418A module in the context of the count rates to be discussed was quite short (later measured to be 1.56±0.02 μs by the source-pulser method[9]), it is difficult to see how to correct for it in the subsequent analysis of the single time spectrum produced from the two quasiindependent inputs.

In principle, the time curves were analyzed in terms of a function

$$Y_i(t) = A_1 \exp(-\lambda_1 t_i) + A_2 \exp(-\lambda_2 t_i) + A_3 \ ,$$

where A_3 represents a constant background, λ_1 the decay constant of ^{10}C, and λ_2 that of a (known) long-lived contaminant. The Y_i were corrected in a straightforward way for the dead time of the MCA.

In practice, there are several effects which could complicate this simple behavior, and among them are the following:

(a) Misidentification of the contaminant, or the presence of more than one contaminant.

(b) Pileup in the electronic systems of a low-energy pulse with a pulse which would have been in the SCA window, thus removing it from the window. This is more likely to happen at the beginning of a count period, and thus leads to extracted lifetimes which are too long.

(c) Pileup in the electronic systems of two low-energy pulses whose sum lies within the SCA window. Since the overwhelming majority of the activity seen by the detectors is from the decay of ^{10}C, this leads to a decaying component of half-life approximately 9.6 s.

(d) Thermal effects in the target caused by the power deposited there by the beam. The decision to use a tantalum substrate for the targets rather than gold, despite the inferior heat conduction, was taken because the evaporated boron adhered much better. However, any tendency of the target to deform under thermomechanical forces during the count periods would obviously affect the count rate seen by the detectors.

It should be emphasized, however, that beam currents were always less than 500 nA, the count rate into the multiscalar was never greater than 550 s^{-1}, and indeed, as will appear in the analysis, all runs with an initial count rate of greater than 250 s^{-1} were excluded. This latter corresponded to a total count rate out of the detectors of 2100 s^{-1}.

A very sensitive test of the possible presence of any of the effects (a)–(d) above is the analysis technique which we refer to as "channel chopping." In this, a decay curve is analyzed in terms of the function above, and the half-life of the ^{10}C determined. The curve is then analyzed again, starting at a point which corresponds to approximately half a half-life later (10 s). This process is repeated for 4 or 5 half-lives. If the extracted half-life varies monotonically with the starting channel of the analysis, and in particular if a group of runs taken under similar circumstances behaves in this way, that is a strong indication that one or more of the above effects is present.

Table I presents the summarized analyses for the data. The experimental conditions of count rate, beam current, and detector distance were varied systematically, and "channel chopping" was practiced on each run individually and on the summed groups of runs as indicated. No trace of the long-lived contaminant ^{11}C from ^{11}B(p,n) was ever seen, but in the very last group of runs, 45–56, ^{13}N from ^{13}C(p,n) was identified by its half-life of 600 s. This was undoubtedly because the last target had been left at pressures of ≈0.001 atmosphere for several days and had accreted a thin deposit of oil from the vacuum pumps. Consequently all runs were treated as if they contained a contaminant of that half-life, but only the last group showed an amplitude for it which was not consistent with zero. The percentage shown in the table refers to the ratio of the initial amplitudes.

As an additional check for each group of runs, they were summed in their groups, and the sum curve analyzed. The results for the extracted half-lives agreed with those presented to within ±0.002 s.

The final values seen in Table I are somewhat worrying. The runs 30–36 were not usable at all. Their channel-chopping behavior was unsatisfactory, but not in any way that was systematic enough to be able to be corrected for. They were, however, done with high count rates and marginally the highest beam currents. The other three groups did not show any suspicious behavior as far as channel chopping is concerned, but the internal agreement, as represented by the reduced χ^2_ν, particularly for runs 21–29, is not reassuring.

An unweighted combination of the three results of Table I leads to a value of 19.284±0.038 s, but this treatment is hardly realistic. Better is to take the weighted mean, which gives 19.290±0.022 s, but with a reduced χ^2_ν of 2.9, which becomes 19.290±0.038 s when the error is inflated by the square root of χ^2_ν, which is a common and reasonable practice. However, perhaps the most defensible procedure is to form the weighted mean, having first multiplied the errors by the square root of χ^2_ν, and then to increase the error on that in the same way. This gives 19.300±0.041 s, which is the final value we present from these data.

Despite the fact that this seemed to have resolved the disagreement discussed in the Introduction, it was felt that considerable improvement could be made. Nearly a third of the runs showed contaminant, which could be avoided. Although dead time in the MCA could be corrected for, the evidence for count-rate pileup effects in the rest of the electronic system could be seen only retrospectively in the channel-chopping behavior, and the only remedy was exclusion of the data. Accordingly, it was decided to carry out a further experiment with revised procedure and apparatus.

TABLE I. Summary of the experimental conditions and results for the runs of the first experiment.

Runs	Count rate (s)	Beam current (nA)	Detector distance (cm)	% ^{13}N	Half-life (s)	χ^2_ν
21–29	<250	≈400	11	≈0	19.271(37)	2.3
30–36	≈500	≈450	7	≈0		
37–44	≈100	≈180	11	≈0	19.356(37)	1.0
45–56	<130	<160	15,21	3–5	19.225(43)	1.3

THE SECOND EXPERIMENT

The changes made for this new measurement were the following. The output from a single Ge(Li) detector was taken through an ORTEC 572 amplifier and SCA as before. The logic pulse from the SCA then passed to a custom-made 100 MHz scalar and latch which was serviced under interrupt by an HP1000 computer. Each time the scalar received a 1 s interval stepping pulse from the timing system, its contents were latched and then cleared, and the contents of the latch were then read by the HP1000. The dead time per pulse of this procedure was measured to be less than 65 ns, and no corrections to the data for it needed subsequently to be made. The dead time between channels was constant at around 20 μs, and did not affect the analysis of the data.

To deal with pulse pileup in the Ge(Li) preamplifier-amplifier system, pulses from a 1 kHz oscillator, suitably shaped, were fed into the test input of the preamplifier and emerged from the amplifier with the same shape as the gamma-ray pulses, but with an amplitude so chosen as to be greater than that of the 720 keV peak and to be in a region of the energy spectrum where there were few other pulses. This pulser peak was then windowed by a second SCA, of the same width as the first, and the SCA output went to a second scalar-latch combination, identical with the first. Thus any count-rate problems which tended to remove pulses from the 720 keV window would also have the same effect on the pulser window, and could be corrected for.

It is emphasized, however, that although such corrections, of up to a few percent at the start of a decay curve, were made, they were not relied upon uncritically, but rather each corrected decay curve was subjected to a full channel-chopping analysis, and had to satisfy the criteria entailed in that before it was accepted.

In all, 29 runs were taken with beam currents ranging from 130 to 750 nA, initial 720 keV SCA count rates of from 300 to 900 s^{-1}, and target-detector distances of 25 and 65 mm. The decay curves were analyzed, in terms of the function cited above, using two different algorithms. The first used matrix inversion of the normal equations, and the second a form of steepest descent, to find the minimum of the χ^2 statistic, and in every case the minima found by the two methods were essentially identical. The errors quoted on the individual half-lives were those derived from the former method as they have been found to be the more reliable in the past. In addition, the weighting factor for the contents of each channel was taken to be not the reciprocal of the channel contents, but rather at each iteration the reciprocal of the fitted estimate of the channel contents. This procedure avoids biases in the analysis which have been shown to occur otherwise.[10]

Figure 1 illustrates channel-chopping behavior for three different cases. MSCAL88 is a run for which the beam current was 250 nA and the initial counting rate 350 s^{-1}. No suspicious features are seen and the extracted half-life of 19.30±0.07 s is therefore to be accepted. On the other hand, MSCAL79, although with a beam current of 270 nA, was in the closer geometry and therefore suffers from an initial count rate of 700 s^{-1}, the effect of which can be clearly seen in the first few points of Fig. 1(b). Finally SUM6 is the analysis of the sum of six decay curves added together channel by channel, each run having been taken under approximately the same conditions as for 1(a). The behavior seems unexceptionable.

Table II presents the analyses of the whole body of

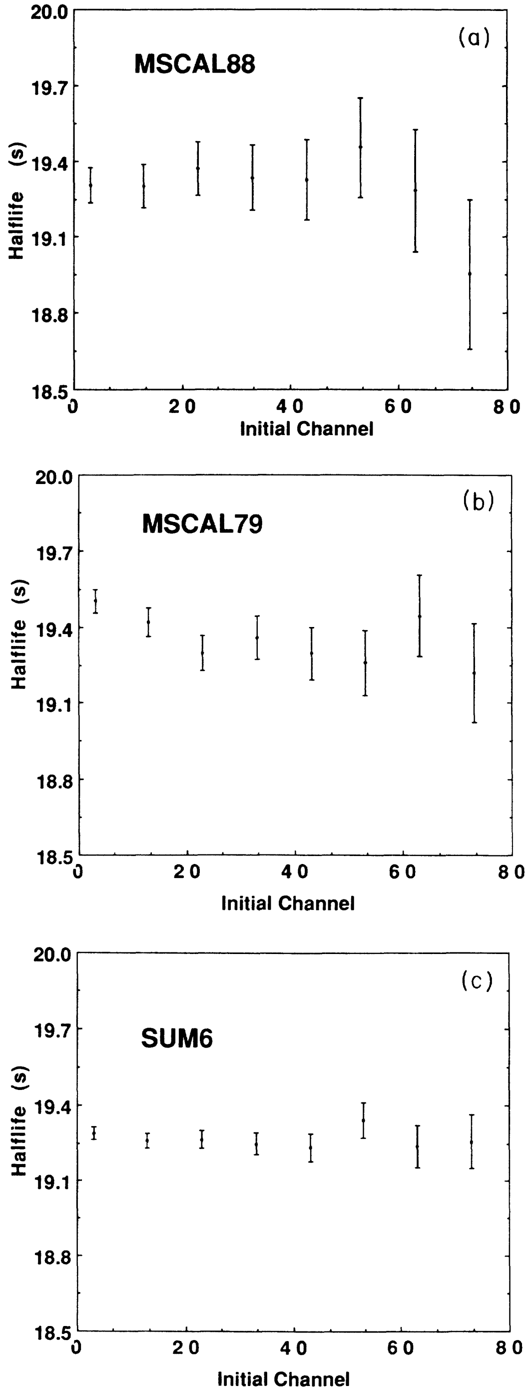

FIG. 1. (a) The "channel chopping" behavior of run MSCAL88. See text. (b) The "channel chopping" behavior of run MSCAL79. See text. (c) The "channel chopping" behavior of the sum of six runs. See text.

TABLE II. Summary of the experimental conditions and results for the runs of the second experiment.

	Number of runs	Beam current (nA)	Initial count rate (s^{-1})	Half-life (ms)	χ_ν^2
1	23	<400	<400	19 294(16)	0.9
2	23	<400	<300	19 288(21)	1.1
3	23	<400	<200	19 268(24)	1.5
4	18	<300	<400	19 310(18)	0.7
5	18	<300	<300	19 311(22)	0.8
6	18	<300	<200	19 292(27)	1.1

data for which the channel-chopping behavior was acceptable. The six runs for which the beam current was either 750 or 550 nA did not satisfy the criteria outlined above in this regard. Since the experience of the first experiment had shown that the initial count rate and the beam current were the most important factors, the results 1–6 are shown in order of increasing restrictiveness in these two aspects, and are the weighted means of the individual values included. It should be pointed out that, for example, all runs with beam current less than 400 nA could be included in the results 1, 2, and 3, because the analysis of each could be started at the point in the decay curve where the count rate fell to below 400, 300, and 200 s^{-1}, respectively, and similarly for results 4–6.

In contrast to the earlier experiment, although the analysis was performed with the inclusion of a 600 s half-life contaminant, no evidence for it was seen in any of the runs. There is no question of any kind of average being taken of the results in Table II, as it all refers to the same data. Since result 1 is obviously a self-consistent set of values, we take the half-life of ^{10}C as determined in this experiment to be 19.294±0.016 s.

CONCLUSION

The two experiments described above lead to a set of values for the ^{10}C half-life of 19 300(41), 19 294(16), 19 282(20),[5] 19 270(80),[6] 19 480(50),[7] and 19 151(26) ms.[8] We believe the disagreement referred to in the Introduction is now resolved, and propose to omit the last two. While the result of Ref. 7 was obtained without that attention to pileup and contamination problems which one now realizes is necessary, and indeed the analysis was in terms of a linear function fit to the logarithm of the data, which is known to produce biased answers, that of Ref. 8 was more carefully considered. One of the present authors was in fact involved in the data taking, although not in the analysis. Nevertheless, in that reference and in the fuller report,[11] there is discussion of some runs which exhibited half-lives which were lower in their earlier channels than in the full decay curves. Among the possible causes of this effect, that of the possibility of pileup of two gamma rays from nonassociated ^{10}C decays is discounted. In our view, this mechanism is not so easily avoided, as, contrary to the assertion in Ref. 11, practically every gamma ray detected has come from a ^{10}C decay, and one must consciously avoid conditions where such pileup occurs.

Finally, therefore, we take the half-life of ^{10}C to be the weighted mean of the first four values given above, 19.290±0.012 s. If some uneasiness is felt about the older result of Ref. 6, or about the result of our first experiment, the remaining values give a mean which is essentially unchanged at 19.289±0.012 s.

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