Half-life of the superallowed positron emitter $^{14}\text{O}$

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The nucleus $^{14}\text{O}$ has been produced via the $^{14}\text{N}(p,n)^{14}\text{O}$ and $^{12}\text{C}(^{4}\text{He},n)^{14}\text{O}$ reactions, and its half-life measured by using fast scintillators to detect the 2.3 MeV gamma ray which follows its positron decay. Possible systematic effects due to pileup or dead time in the electronics or data acquisition systems were investigated. Results from data obtained with a germanium semiconductor detector were rejected. A half-life of 70.641(20) s was obtained.

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I. INTRODUCTION

The positron decay of $^{14}\text{O}$ to $^{14}\text{N}$ is shown in Fig. 1. Its $0^+\to 0^+$ branch is one of the nine superallowed decays whose $F_t$ values may, at present, be determined accurately enough to provide a test of the conserved vector current (CVC) theory, and a check on the unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) matrix. A compilation, with its implications, can be seen in Ref. [1].

Briefly, although the CVC theory, applied to the nine decays, seems to be substantiated, there has for several years seemed to be a problem with the unitarity requirement for the first row of the CKM matrix, in that the sum of the squared elements lay below unity by close to three standard deviations. Although some light may have been shed on this situation by a recent study of $K^+$ decay, Ref. [2], the authors themselves advocate caution in assuming this. In any case, the data base from which the nine $F_t$ values are calculated should be improved, both by decreasing the uncertainties in the measured decay parameters and by examining their robustness.

To calculate the $F_t$ value of each one of the nine superallowed decays, three parameters must be measured: the decay energy, the half-life, and the branching ratio. For $^{14}\text{O}$, the first has recently been substantially revised, Ref. [3], and the last has only been measured once, in an experiment which did not set out to measure the branching ratio at all, Ref. [4]. In Ref. [1] the accepted value of the half-life is seen to be determined essentially on the basis of two measurements, Refs. [5,6], neither one of which provides much of the kind of detail one would like to see for a high precision measurement. But they are in mutual agreement. Perhaps the essence of high precision measurements lies in opening the imagination as widely as possible to the many different kinds of systematic error which may arise, and then searching for their effects. This process is heightened if conflicting results are obtained, but can be dulled if a result seems to agree with the accepted value. Half-life measurements are notorious for systematic errors, with, for instance, the quoted half-life of the superallowed positron decay $^{34}\text{Cl}$ having decreased monotonically with time, over 25 years, to its presently accepted value. For this reason, and, as will appear, because one of the earlier results was obtained using a germanium semiconductor detector, we have undertaken a remeasurement of the $^{14}\text{O}$ half-life.

II. EXPERIMENTAL METHOD

In earlier work, Ref. [7], we have determined the half-life of the superallowed positron emitter $^{38}\text{Km}$ by creating it using the $^{38}\text{Ar}(p,n)^{38}\text{Km}$ reaction with a solid target of $^{38}\text{Ar}$, and detecting the positrons in an $E-\Delta E$ telescope. But the positrons from $^{14}\text{O}$ are too low in energy for this technique, and so it was modified to detect the 2.3 MeV gamma rays, which are distinctive.

Accordingly, $^{14}\text{O}$ was produced using the $^{14}\text{N}(p,n)$ reaction with a beam of 7.1 MeV protons and a target of solid $^{14}\text{N}$ at 10 K, isotopically enriched to 99.94%, roughly 8 keV thick to the beam, and frozen on to a thick backing of 99.995% pure gold. The beam intensity was restricted to 50 nA, so as not to overload the refrigerator, and a typical “run” was to bombard the target for 200 s, interrupt the beam, wait for 5 s, and then detect the 2.3 MeV gamma rays emitted from the $^{14}\text{O}$ for the next 1200 s. Data were taken in a two-parameter (time after beam interruption and energy) event mode.

A. The germanium detector measurements

Initially, the 2.3 MeV gamma rays were detected with a 40% or a 20% Ge detector, or occasionally with both. The
signals were processed in standard preamplifiers and then shaped in 0.25 $\mu$s shaping time, pole-zeroed main amplifiers, and finally, after passing through a biased amplifier, were digitized in a 30 ns flash analog-to-digital converter (ADC). A 16-mm thick lead absorber was placed between the target and the detector to improve the ratio of 2.3–0.51 MeV gammas detected. The overall organization was controlled by a CAMAC system, whose time behavior was well understood.

Because it was anticipated that the long time constants associated with the pulses from Ge detectors might lead to problems, pulses, random in time but identical in shape to the real ones, were introduced in parallel at the input to the preamplifier, and their amplitude adjusted so that, in the final spectrum, they produced a peak just above the 2.3 MeV peak from the $^{14}$O. The aim was, at best, to apply to the pulser peak the same analysis process as was used for the 2.3 MeV peak and to confirm that it produced a rate which was constant in time (and independent of the total count rate). An inferior, but perhaps still acceptable procedure would be to find a logical treatment which rendered the pulser rate constant, and then apply it to the 2.3 MeV peak rate.

Roughly 100 runs were taken as described, with initial total Ge detector count rates up to 3000 s$^{-1}$, using 7.1 MeV protons from the Auckland tandem accelerator AURA2. But it seemed very difficult to obtain data which could be analyzed robustly and successfully. Indeed, by choosing a variety of seemingly sensible widths to define the 2.3 MeV and the pulser peaks, it was possible to obtain final values for the $^{14}$O half-life over a range many times larger than the ascribed statistical uncertainty. So a simple test was devised.

A $^{207}$Bi source, emitting gamma rays of 1064 keV at a constant rate, was placed in a fixed position on the axis of the 20% Ge detector, and the total count rate into the detector was varied by altering the distance from it of a $^{137}$Cs source which gave gamma rays of 662 keV. A variety of combinations of pole-zero adjustments, base line restoration and use of a pulser as earlier was employed to try obtain a constant 1064 keV rate, independent of the total count rate, at the 0.1% level, but without success. The fundamental problem is illustrated in Fig. 2, where it can be seen that, as the total count rate increases, pulses from the 1064 keV peak are increasingly spilled out into the surrounding background, an effect attributed to pileup associated with the slow response of the Ge detector. It might be thought that the rates quoted in Fig. 2 are greater than would be used in a measurement of a half-life using a Ge detector, but it should be remembered that the yield is in the full energy peak only, whereas the total count rate into the detector is made up of the whole spectrum, plus that of the two 511 keV gamma rays which accompany the original gamma ray. So, for a peak/total ratio of, say, 0.1 for a 2.3 MeV gamma ray, and an improvement in the 511–2312 keV ratio of a factor 7 by using a 2 cm lead absorber, the ratio of total count rate to yield rate is perhaps 12:1.

As a consequence of our inability to find a justifiable and trustworthy method of analyzing the half-life data, and of the results of the subsequent tests, the use of a germanium detector was abandoned.

B. The $(p,n)$ reaction measurements

Following this, the gamma ray detector was changed to be a $102 \times 102 \times 51$ mm$^3$ NE102 plastic scintillator mounted on a fast photomultiplier. The signals were processed in an electronic system similar to that described in Ref. [7], in which analog pulses were typically a few nanoseconds long, and logic pulses 10 ns. At this stage a 6 $\mu$s, nonextendable veto pulse was applied so that the dead time per pulse involved in the subsequent CAMAC processing, roughly 5.1 $\mu$s, was not involved in final dead time corrections. The length of the veto pulse was monitored using a time-calibrated digital oscilloscope, and was typically 6.03(3) $\mu$s, but the dead time of the system was also measured empirically using a double pulser technique and found to be 5.96(4) $\mu$s. In the subsequent analysis, application of a total dead time correction of, for example 6.0 $\mu$s, led to a half-life shift of typically 0.23 s.

One of the advantages of the production of $^{14}$O from the $^{14}$N$(p,n)$ reaction is that one can check for other activities by taking the proton energy below the 6.35 MeV threshold energy. In Fig. 3 we contrast the gamma spectra from two consecutive runs, one at 6.3 MeV and one at 7.1 MeV, obtained by projecting the event-mode data for the whole 1200 s on to the energy axis. Both spectra show quite a poor energy resolution, as a result of the performance being de-
graded by inappropriately lengthy connecting cables, a situation which was realized only later, but it is evident that there is no contaminant produced above a nominal 1.5 MeV. The activity below threshold is from $^{11}\text{C}$ from the $^{14}\text{N}(p,\alpha)$ reaction, with a half-life of 1223 s. This conclusion was checked by projecting all data above a nominal 1.5 MeV from the below-threshold run on to the time axis, and there was no discernible decay. 58 runs were then taken at a proton energy of 7.1 MeV, using the particle beam from the ANU 14UD accelerator.

C. The $^{3}\text{He},n$ reaction measurements

The experiment then turned to producing the $^{14}\text{O}$ via the $^{12}\text{C}(^{3}\text{He},n)$ reaction using 2.7 MeV $^{3}\text{He}$ ions from the ANU RBS tandem accelerator. The $^{12}\text{C}$ target was around 80 keV thick to the 2.7 MeV beam. The backing was 99.995% pure gold, with less than 2 ppm of anything other than silver. A run with the backing alone produced nothing at all in the energy regions which were subsequently time projected. The obvious advantage of the changed setup was that the target was at room temperature and so the beam intensity was not limited by the refrigerator performance. But, most importantly, it was felt that, in this changed situation, at least some of the potential, unforeseen sources of systematic error would be different. Detection and data acquisition were with the plastic scintillator and CAMAC system, as earlier. With the $(^{3}\text{He},n)$ reaction it is not possible to look below threshold for other activities, but a similar test may be accomplished by comparing the energy projection of events with times from 1 to 500 s with that from 700 to 1199 s. A typical case is shown in Fig. 4, with background subtracted from each projection, and it is immediately obvious that there is much less $^{11}\text{C}$ [$^{12}\text{C}(^{3}\text{He},\alpha)$] than with the $(p,n)$ reaction, and that the detector response at low energies has been improved. Two series of experiments, separated by several months, were performed with this arrangement, with 64 and 89 runs, respectively.

III. ANALYSIS

For each of the experimental arrangements described earlier, the data were in event-mode form. Energy was from the output of a 256-channel, 30 ns flash ADC and time was in either 1200 or 1400 one second steps from a precision oscillator. For each spectrum, the data were first projected onto the energy axis, producing plots resembling Figs. 3 or 4, and
from these, decisions were made as to what sections of the energy spectrum should be projected onto the time axis for half-life analysis. In this, the choices were always conservative, and for those spectra, for example, of Figs. 3 and 4, only events above nominally 1.5 and 1.0 MeV were taken. This was well above the maximum sum pulse limit from the annihilation radiation from 1223 s $^{11}$C made by $^{14}$N($p, \alpha$) or $^{13}$C($^3$He, $\alpha$).

At first glance it might seem that a selection from a lower energy region could have been made, with the resulting data then being analyzed in terms of two exponential decays, one with a 1223 s half-life, but it was not possible to be certain that there was no annihilation radiation present from the decay of 122 s $^{15}$O, possibly made in $^{15}$N($p, n$) or $^{13}$C($^3$He, $n$), although no trace of it had been detected.

Accordingly, the projected time spectra were analyzed in terms of a single exponential with a constant background, using maximum likelihood techniques. A typical data set, with fit, of the projection of nominal positron energies between 1.30 and 1.75 MeV for one $^{12}$C($^3$He, $n$) run, is shown in Fig. 5. Each such time spectrum was corrected for the constant deadtime per pulse, determined as described earlier, of the total count rate. The results were tested for a possible correlation of the extracted half-life with initial total count rate, and for the existence of any contaminant activity, by starting the data analyses successively at times 2, 72, and 142 s. The results of one such test, which is for the projection of nominally 1.75–2.75 MeV positrons from 64 runs of the ($^3$He, $n$) generated $^{14}$O are shown in Fig. 6. They are typical and seem quite satisfactory. Of course, it is possible to imagine a pathological situation in which the effects of, say, a rate-dependent detector gain are just balanced by the presence of an undetected contaminant activity. But, as reported earlier, the ability to look for the latter in the situations illustrated by Figs. 3 and 4 is an advantage of the present method. The former was tested in a variety of circumstances by computing, for several runs, the centroid of the energy spectrum between nominal positron energies of 1.3 and 2.5 MeV, as a function of the reducing count rate. No rate-dependent effects were seen, at a level considerably lower than that illustrated in Fig. 6. For the three series of runs, with 58, 64, and 89 passes, respectively, differing energy projection criteria were used for each, leading to 428 individual decay curves being analyzed in six different groups, each typically with an initial amplitude of 500 s$^{-1}$, initial total count rate of 2000 s$^{-1}$, and constant background of 0.4 s$^{-1}$.

The results from each group, for instance from one of the projections of the 64 pass series, derive from data taken un-
der close to identical conditions, and so the extracted half-lives are expected to be normally distributed. The histogram corresponding to the results shown in Fig. 6 for the 2–1200 s analysis is shown in Fig. 7, together with the fitted normal distribution. The fit is satisfactory, and the center of the distribution, with its attributed uncertainty, is taken to be the best estimate of the half-life for this group.

IV. RESULTS AND DISCUSSION

The six groups of spectra, analyzed as earlier, gave half-life values of 70.59(7), 70.67(25), 70.58(5), 70.65(3), 70.70(5), and 70.71(11) s. These form a self-consistent set, with a weighted mean of 70.641 s. There is a recent germanium detector measurement which finds 70.560(49) s, Ref. [8], but in which the authors do not seem to have addressed the problems discussed earlier. In a yield curve from Ref. [8], of typical data with an associated fit, in 10 s blocks, the maximum rate slightly exceeds 2000 s⁻¹ and in the experimental arrangement described, the ratio of total count rate to yield seems to be much as we discuss in Sec. II A, of order 12:1. It is hard, in these circumstances, to guarantee that pileup effects, probably leading to too low a final half-life value, are not present, and so we do not include the result from Ref. [8] in a recommended value. For similar reasons, we exclude the result from Ref. [6], which was also a germanium detector measurement. On the other hand, the result from Ref. [5], 70.613(25) s, was obtained using a plastic scintillator specifically to avoid pileup problems, and so we combine it with our result and obtain a weighted mean of 70.630(16) s.

The Ft value for the ¹⁴O superallowed decay then becomes 3074.3(9) s, which fits well with the mean of the nine cases reported in Ref. [1] and so supports conserved vector current theory. The ascribed uncertainty in the ¹⁴O Ft value derives almost totally from difficulties in calculating the 1–2% radiative effects, and therefore does not seem to be improvable by experimental means. But one’s confidence in the result would nevertheless be increased if the branching ratio, 99.336(10)%, measured only once, could be confirmed. It should be remeasured, preferably several times.

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