Improved measurement of the ^{44}Ti half-life from a 14-year long study

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(Received 12 June 2006; published 18 December 2006)

The half-life of ^{44}Ti was determined by following the decay of ^{44}Ti and ^{60}Co for 14 yr. Mixed sources containing ^{44}Ti and ^{60}Co and pure sources of ^{44}Ti and ^{60}Co were prepared and their γ-ray spectra were measured with a Ge spectrometer once or twice a year. Counts in the 1157.0-keV γ-ray photopeak of ^{44}Ti and the 1173.2- and 1332.5-keV γ-ray photopeaks of ^{60}Co were used for this measurement. From the decay of the ^{44}Ti and ^{60}Co activity ratios, the half-life of ^{44}Ti was determined. Using a value of 5.2711±0.0004 yr for ^{60}Co half-life, we determined the half-life of ^{44}Ti as 58.9±0.3 yr. Special efforts were made to check for systematic errors and these were found to be negligible within the quoted uncertainty.

DOI: 10.1103/PhysRevC.74.065803 PACS number(s): 21.10.Tg, 26.30.+k, 26.40.+r, 27.40.+z

I. INTRODUCTION

One of the radioactive nuclides, suited for the study of cosmic rays and supernova (SN) explosions, is ^{44}Ti, which decays with a half-life of 59 yr. The nuclide ^{44}Ti decays to ^{44}Sc, which in turn decays to ^{44}Ca, producing a 1157.0-keV γ ray. The latest decay scheme of ^{44}Ti [1] is shown in Fig. 1. Live ^{44}Ti has been observed directly by γ-ray astronomy via identification of the 68-, 78- and 1157-keV γ rays from a point source identified as Cassiopeia A (Cas A). Several γ- and x-ray telescopes (CGRO, RXTE, and BeppoSAX) and very recently the INTEGRAL mission [2,3] have been involved in these observations. Cas A is believed to be the remnant of a core-collapse SN [4] whose distance from Earth and age are calculated to be $3.4^{+0.3}_{-0.1}$ kpc (1 kpc = 3,262 light yr) [5] and ∼330 yr [6], respectively; the explosion may have been sighted by the English astronomer J. Flamsteed in 1680 [7]. Using the half-life recently measured (59.2±0.6 yr) [8] and the combined γ flux from all observations [$(2.7 \pm 0.6) \times 10^{-5}$ photons cm^{-2} s^{-1}], an initial ^{44}Ti yield of $(1.6 \pm 0.6) \times 10^{-4}$ $M_\odot$ ($M_\odot$ denotes a solar mass) is implied [3]. Woosley and Weaver [9] and Thielemann *et al*. [10] calculate a range of $\sim 8 \times 10^{-6}$ to 6×10^{-5} $M_\odot$ and $\sim 7 \times 10^{-5}$ to 1.7×10^{-4} $M_\odot$, respectively, for given progenitor masses and composition. Among proposed explanations of the discrepancy between measured and calculated ^{44}Ti mass is the possible ionization of ^{44}Ti, increasing its effective pure EC-decay half-life [11,12] and consequently increasing the ^{44}Ti activity observed several half-lives after production [11]. It is, however, not established that the degree of ionization required is compatible with the temperature and plasma conditions in the SN remnant. An additional open question regarding the ^{44}Ti yield in Type II SNs is the fact that no other source of ^{44}Ti activity in addition to Cas A has been confirmed so far, despite a number of candidates and the sensitivity of the INTEGRAL γ-ray telescope [2]; this improved sensitivity is verified by the detection of γ-ray lines from interstellar ^{60}Fe, recently reported [13].

Measurement of long half-lives by decay method requires that the decay be followed for a long time (at least one-tenth of the half-life) to detect any contaminant in the source. Also, because the decay between the two successive measurements of γ-ray spectra is very small, each peak area should have very small uncertainty. This requires a large number of counts in the peaks. In addition, the detection efficiency of the counting system should remain constant over the duration of the half-life measurement. However, it is difficult to measure the detector efficiency for each data point with the required precision. One way to overcome any possible change in the detector efficiency is to measure the half-life relative to that of another nuclide whose γ-ray energy is close to that of the isotope of interest and whose half-life has been measured with high precision. For the case of ^{44}Ti, the most suitable isotope is ^{60}Co, whose half-life is known to be 5.2711±0.0004 yr [14] and whose γ rays have energies of 1173.2 and 1332.5 keV, very close to 1157.0 keV of ^{44}Ti.

The half-life values [15–18] measured before the observation of ^{44}Ti γ ray from the supernova Cas A are listed in Table I. The disagreement among the values listed required a new measurement. Therefore in 1992 we started a measurement of the half-life of ^{44}Ti . For the ^{44}Ti half-life measurement, we prepared three mixed sources of ^{44}Ti and ^{60}Co, which were distributed to Torino, Jerusalem, and Argonne. Their γ-ray spectra were measured with Ge spectrometers over a period of 5 years and the half-life of ^{44}Ti was determined from the decay of the ratios of the ^{44}Ti and ^{60}Co activities. By combining the half-life values measured at the three laboratories, a value of 59.0±0.6 yr was obtained [8]. In the late 1990s, several other measurements were performed and the half-life values obtained in these studies [19–23] are

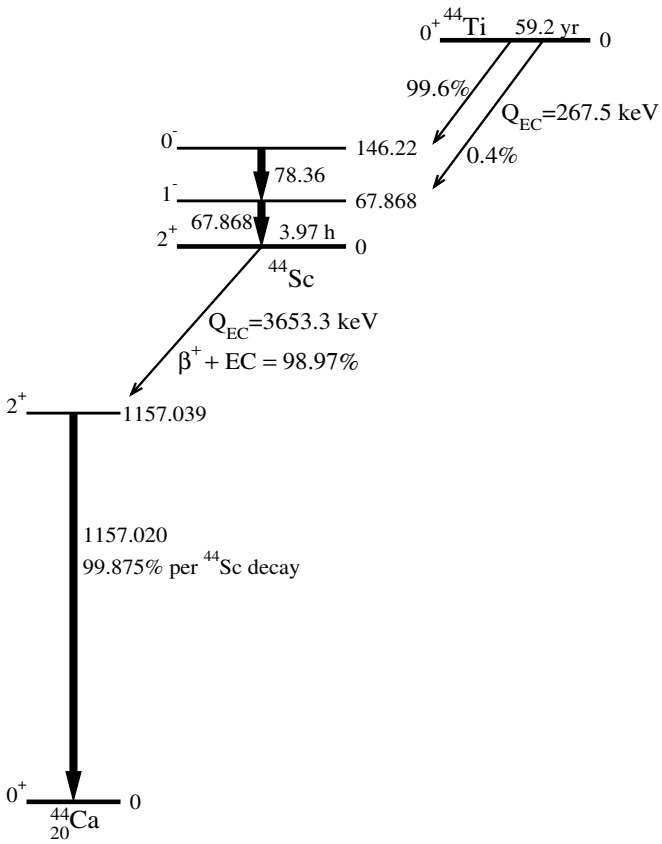

FIG. 1. Partial decay schemes of ^{44}Ti and its daughter ^{44}Sc from Ref. [1].

included in Table I. As can be seen, all these new values are in agreement with each other within the quoted uncertainties.

To improve the statistical uncertainty in the half-life value and to detect any possible systematic error we continued the measurement of γ-ray spectra. Another reason to continue the measurement of ^{44}Ti half-life was that during the 5-year measurements the Ge detector at Argonne underwent annealing that changed the detector efficiency slightly and required correction in the 1332.5-keV peak area for the determination of the half-life. The goal of the continuing measurement was to use data after the detector repair for the half-life measurement, thus avoiding any correction. We were able to follow the decay for 10 years after the Ge detector repair and using these data we have determined a more precise value of the half-life that agrees with our published value [8] within the quoted uncertainty.

In principle, the half-life of ^{44}Ti can be determined from one set of γ-ray spectra measured by placing the mixed source at one distance. However, the history of previous measurements shows that errors in the measurement are often dominated by systematic errors. To check on systematic errors, we made several sets of measurements under different conditions and analyzed the data in several ways.

TABLE I. Summary of previous measurements of ^{44}Ti half-life.

Half-life (years)[a]	Method used for the measurement[b]	Reference
46.4±1.7	Specific activity (MS + γ activity)	[15]
48.2±0.9	Specific activity (MS + γ activity)	[16]
54.2±2.1	Specific activity (AMS + γ activity)	[17]
66.6±1.6	Decay (β activity)	[18]
63±3	Decay (γ activity)	[19]
59.0±0.6	Decay (γ activity relative to ^{60}Co)	[8]
60.3±1.3	Specific activity (HISP + γ activity)	[20]
62±2	Decay (γ activity relative to ^{22}Na)	[21]
60.7±1.2	Decay (γ activity)	[22]
59±2	Specific activity (HISP + γ activity)	[23]

[a] 1σ uncertainties are given except for Ref. [18], where the authors report 2σ uncertainty.

[b] Abbreviations: MS = mass spectrometry; AMS = accelerator mass spectrometry; HISP = heavy-ion spallation reaction with on-line counting of ^{44}Ti ions.

II. EXPERIMENTAL METHODS AND RESULTS

A. Source preparation

The ^{44}Ti source material was produced by the ^{45}Sc(p,2n) reaction using 45-MeV protons from the Jülich Isochronous Cyclotron. The details of the irradiation and isolation of ^{44}Ti have been described previously [17]. Three mixed sources of ^{44}Ti and ^{60}Co, and three pure sources of ^{60}Co were prepared from a solution of ^{44}Ti and a solution of ^{60}Co. Each mixed source was prepared by placing a drop of ^{44}Ti solution and a drop of ^{60}Co solution at the center of a 2.5-cm diameter, 0.5 g/cm^2 thick Pt disk and drying them. The activity was then covered with a piece of scotch tape to fix it to the Pt surface. The Pt disk was placed in the recess of a lucite disk, which was covered by another lucite disk with acetone between them, and then they were pressed together. The acetone caused the two disks to glue together, producing a physically stable air-tight source, 5.1 cm in diameter and 1.27 cm in thickness. Because of the transparency of the lucite, the Pt disk and the activity location were clearly visible and they showed no change over the 14-yr counting period. The three sets of sources had similar activities: ~0.3 μCi ^{44}Ti + ~0.3 μCi ^{60}Co for the mixed source, and ~0.3 μCi for the pure ^{60}Co source. One set of mixed and pure ^{60}Co sources was sent to Jerusalem, one was sent to Torino, and one set was kept at Argonne. In addition, a pure ~0.3 μCi ^{44}Ti source was prepared for Argonne. The spectra of pure ^{44}Ti and pure ^{60}Co sources were measured at Argonne with a Ge detector placed in a very low background shield. No contaminant γ-ray line was observed indicating the purity of the sources.

B. Measurements at Argonne

The half-life measurement described here was started in March 1992 and the last set of spectra was measured in December 2005. Gamma-ray spectra of sources were measured with a 25% Ge spectrometer at regular intervals. The high-purity Ge detector, which had a resolution [full width at half maximum (FWHM)] of 1.8 keV for the 1332.5-keV γ ray of ^{60}Co, was purchased from ORTEC in 1984. It was placed in the center of a room without any shielding. The reason for

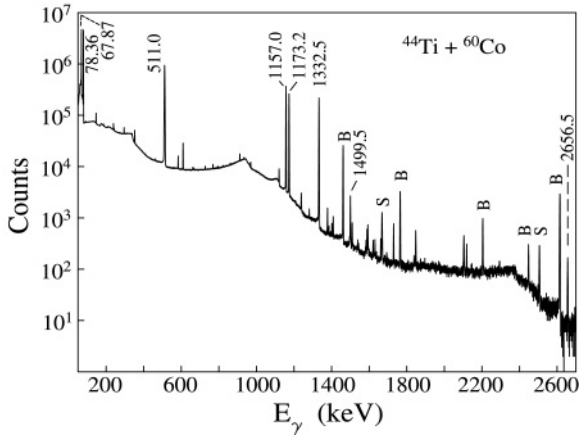

FIG. 2. γ-ray spectrum of a mixed source of ^{44}Ti and ^{60}Co measured with a 25% Ge spectrometer. This spectrum was measured 2 years after the start of the experiment. Energies of ^{44}Ti and ^{60}Co γ rays are given in keV. The source-to-detector distance was 10.2 cm and the counting time was 48 h. B denotes peaks from room background and S denotes sum peaks.

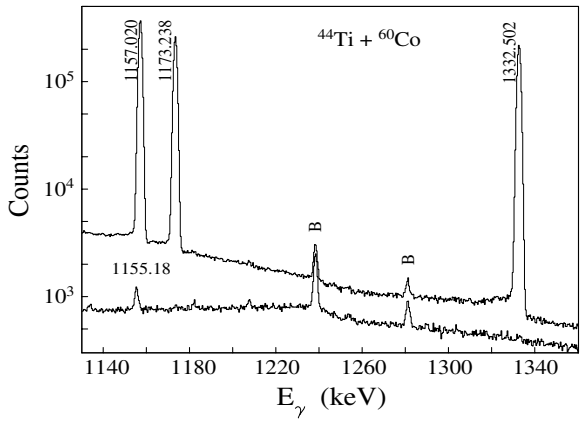

FIG. 3. A portion of the γ-ray spectrum displayed in Fig. 2 showing the ^{44}Ti and ^{60}Co peaks of interest. The lower spectrum represents the room background measured for the same time interval as the source spectrum. The 1155.18-keV peak belongs to ^{214}Bi, decay product of ^{238}U, present in concrete. B denotes peaks from room background.

not using any shield was that ^{44}Ti and ^{60}Co peaks had large number of counts under them because of coincidence summing of the photopeak with the Compton scattered photons from the coincident γ ray. Shielding could have reduced the counts from the room background but not the counts due to coincidence summing. A plastic holder with five slots, equally spaced 1 cm apart, was placed on the detector endcap and was kept at a fixed position with plastic screws. The source in the lucite disk was placed in an aluminum holder and taped, and then the aluminum holder was placed in the last slot of the plastic holder. The source was mounted such that the source activity was facing the Ge crystal. During the first 5 years, each sample was counted for 48 h and for the later spectra the counting time was increased to 96 h to obtain approximately the same number of counts in ^{60}Co peaks as during the first 5 years. An example of the γ-ray spectrum of the mixed source measured for 48 h is displayed in Fig. 2. The region of the spectrum containing peaks of interest is displayed in Fig. 3. Also shown in this figure is the background spectrum measured for 48 h with the source removed from the plastic holder. For each set of data, eight spectra were measured. First, the room background spectrum was measured by placing the source holder at 5.2 cm. The measurement of the background spectrum provided a check that no unwanted radioactive source was present in the room. This spectrum was subtracted from the source spectra to obtain counts due to the source decay only. Then spectra of the mixed source, pure ^{44}Ti, and pure ^{60}Co were measured at a source-to-detector distance of 5.2 cm. Similarly, four spectra were measured at a source-to detector distance of of 10.2 cm. However, because each spectrum took long time, in few cases some of the spectra were not measured.

At the start of the measurement (March 1992), our aim was to determine the half-life by following the decay of the ^{44}Ti γ ray and also from the decay of the ratio of ^{44}Ti and ^{60}Co activities. A tail pulser was used to determine the livetime for each spectrum. This tail pulser, however, distorted the peak shapes because of random summing of the photopeaks with tails of the pulser signals. Although the effect was extremely small, to reduce any uncertainty from peak distortion, we removed the pulser after 9 months during which six sets of spectra were measured at regular intervals.

After about 7 yr of measurement, we placed the Ge detector in a lead shield to decrease the background and measured two sets of spectra. However, we observed an increase in the total γ-ray count rate due to the scattering of the source γ rays from the shielding walls. This effect caused slight deviation in the ratios of peak areas from the value expected from the decay curve determined from ratios measured without shield. We, therefore, returned the detector to the center of the room as before so that all measurements could be made under identical conditions. The two data points obtained with the detector in the shield were excluded from the final analysis.

Another change occurred in October 1994 when the detector preamplifier stopped working and the Ge spectrometer was sent back to ORTEC for repair. The preamplifier was repaired and the Ge crystal was annealed. This changed slightly the relative efficiency of the detector as a function of γ-ray energy. The change in the detector efficiency was clearly visible when we compared the ratios of the counts in the 68- and 1157.0-keV peaks in the pure ^{44}Ti spectra before and after the detector repair. The ratio was 4.3% higher in the spectra measured before the repair compared with the ratio measured after the repair indicating increase in the dead layer of the Ge crystal. Using the ratios of counts in the 1173.2- and 1332.5-keV peaks in spectra of the pure ^{60}Co source before and after the repair, we found that the 1173.2/1332.5 ratio decreased by 0.16% after the repair. From this decrease we extrapolated that the decrease in the 1157.0/1173.2 ratio would be $\sim$0.016% after the repair, which has a negligible effect on the half-life determination. The 1157.0/1332.5 ratios after the detector repair were corrected using the measured change in the relative efficiencies and these were used to obtain the half-life. The half-life values thus measured were combined with the half-life values determined from the ratios of 1157.0-

TABLE II. Summary of ^{44}Ti half-life measurement using data after the Ge detector repair in March 1995. All values except those given in the last line were measured at Argonne.

Source	Distance	Number of data points	Half-life from 1157/1173 ratio[a]	χ^2/DOF[b]	Half-life from 1157/1333 ratio[a]	χ^2/DOF[b]
Measurements at Argonne						
Mixed ^{44}Ti+^{60}Co	5.2 cm	22	58.8±0.4 yr	0.97	59.0±0.3 yr	1.03
Mixed ^{44}Ti+^{60}Co	10.2 cm	19	58.7±0.5 yr	1.5	58.8±0.4 yr	0.95
Pure ^{44}Ti and pure ^{60}Co	5.2 cm	18	59.0±0.5 yr	2.1	59.4±0.6 yr	3.5
Pure ^{44}Ti and pure ^{60}Co	10.2 cm	15	58.5±0.6 yr	1.8	59.2±0.6 yr	2.3
Measurements at HU						
Mixed ^{44}Ti+^{60}Co	6.7 cm	18	58.4±0.5 yr	1.2	59.0±0.7 yr	0.8

[a] 1σ uncertainties are given. The weighted average of all above numbers give a value of 58.9±0.2 yr.
[b] DOF = degree of freedom.

and 1173.2-keV peaks to obtain the final value reported in Ref. [8].

C. Data analysis of the Argonne measurements

We measured a total of 34 data points for the mixed source at 5.2 cm, of which 24 were obtained after the detector repair. Two of the data points were obtained with the detector in the shield that were excluded from the analysis. We analyzed the remaining 22 data points and the half-life values determined from this data set are given in Table II. Whereas there was no peak in the background spectrum at 1173.2 and 1332.5 keV, there was a small peak at 1155.2 keV in the room background spectrum due to ^{214}Bi (decay product of ^{238}U) decay. The counts in the 1155.2-keV peak of the room background spectrum were only 0.066% of the counts in the 1157.0-keV peak of the ^{44}Ti+^{60}Co spectrum at 5.2 cm. The data were analyzed in the following way. First the background spectrum was subtracted from the three spectra of the mixed, pure ^{44}Ti, and pure ^{60}Co sources. Areas of the three peaks (1157.0, 1173.2, and 1332.5 keV) in each spectrum of the mixed source were determined by using the *sb* command of the Gelifit program [24]. In this procedure the background under the peak was defined by marking points on the left and right sides of the peak and drawing a straight line between them. The counts in the peak after subtraction of the background were integrated to obtain the peak area. The ratios of the counts in the 1157.0-keV peak to that of the 1173.2-keV peak were fitted as a function of the time since the beginning of the experiment with an exponential function. The slope of the line gives the difference between the decay constants of ^{60}Co and ^{44}Ti, $\lambda(^{60}\text{Co}) - \lambda(^{44}\text{Ti})$. The half-life of ^{44}Ti was deduced by substituting 5.2711±0.0004 yr for the ^{60}Co half-life. The half-life was also obtained from the ratios of the peak areas of the 1157.0- and 1332.5-keV γ rays. The analysis was carried out for the four sets of data obtained with the mixed source of ^{60}Co+^{44}Ti at the two distances of measurement. The fit of the data to the exponential function was very good, giving a χ^2 per degree of freedom (χ^2/DOF) of ∼1.

Spectra of the pure ^{44}Ti and pure ^{60}Co sources were analyzed in the same way as the spectra of the mixed source to determine peak areas. Whereas no correction was needed for the peak areas of the mixed source, two corrections were applied to peak areas of pure ^{44}Ti and ^{60}Co sources. First, because the ^{44}Ti and ^{60}Co spectra were measured at different times (2–6 days apart), decay correction was applied to the ^{60}Co peak areas to find the peak counts of ^{44}Ti and ^{60}Co at the same time. Second, as the activities decayed, the total count rate decreased and hence the loss of the peak areas due to random summing. The random summing loss depends on the total count rate and the pulse width. Because the amplifier pulses were Gaussian, not flat, we determined the effective pulse width for random summing. This was obtained by measuring the alpha spectrum of a ^{249}Cf source using similar pulse heights and 3 μs amplifier shaping time constant, the same as used with the Ge detector. From the ratio of the random sum counts to the counts in the α peaks we determined the effective pulse width as 7.5 μs. Using this pulse width, we calculated the loss of counts in each peak due to random summing and added it back to the peak areas for the calculation of the half-life. The half-life values were obtained in the same way as from the data on the mixed source.

The half-life values obtained from the eight ratios are given in Table II. The table contains the half-life values, one standard deviation, σ, and χ^2 per degree-of-freedom. The data from the mixed source at 5.2 cm have the smallest uncertainties because of the highest number of counts in the peaks and the identical solid angles for ^{44}Ti and ^{60}Co γ rays. The counts in the peaks when the source was at 5.2 cm were 2.6 times the counts in the peaks for the 10.2 cm spectra. Hence the uncertainties are slightly larger for the 10.2-cm data. The decay curve for the 1157.0/1173.2 ratio measured at 5.2 cm is displayed in Fig. 4. The line in the figure represents the best fit to the data and gives a value of 58.8±0.4 yr for the ^{44}Ti half-life. The uncertainty is one standard deviation, σ, and χ^2 per degree of freedom is 0.97. The lower part of the figure, showing the differences between the data points and values of the fit function, illustrates the dispersion of the data points and uncertainties around the fitted line.

For the measurement of the spectra of pure ^{44}Ti and ^{60}Co sources, the plastic holder was mounted on the Ge detector for each set of spectra and was removed after the measurement. However, once the holder was in place, the solid angle was almost identical for the ^{44}Ti and ^{60}Co sources. Because the ^{44}Ti and ^{60}Co sources were mounted separately, it is likely

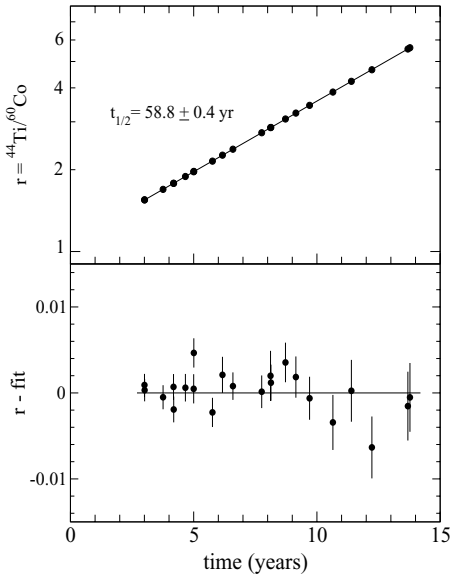

FIG. 4. Semilogarithmic plot of the ratios of the areas of the 1157.0-keV peak and the 1173.2-keV peak against the time of measurement for the Argonne data (top figure). The set contains 22 data points. Data points measured very close in time overlap and hence are indistinguishable in the figure. The line represents the best fit to data points and gives a value of 58.8±0.4 yr. The bottom figure shows the differences between the measured data points and the values calculated by the fit.

that the distance between the source and detector was not exactly the same for the two sources for each data point. One therefore expects larger uncertainties for the half-life values and larger values of (χ^2/DOF) from the separate sources.

D. Half-life from the decay of ^{44}Ti peak

In the above analysis we used the ratio of ^{44}Ti and ^{60}Co activities to determine ^{44}Ti half-life. We can also use the decay of ^{44}Ti activity itself to find its half-life. However, this method will give a half-life with a larger uncertainty. For each data set, we placed the plastic holder on the detector endcap and removed it after the measurement. For the 5.2 cm data, the holder was placed such that it touched the detector endcap and stopped. Thus for the 5.2 cm data, the source-to-detector distance was reproducible to within few micrometers. We therefore fitted the counts in the 1157.0-keV peak of pure ^{44}Ti spectrum to an exponential function and obtained a half-life value of 57.6±1.2 yr. Using the ^{44}Ti peak areas obtained from the spectrum of the mixed source we obtained a value of 58.7±1.5 yr. The weighted average of 58.0±1.0 yr is consistent with the more precise value of 58.9±0.3 yr obtained from the ^{44}Ti and ^{60}Co activities ratios. A similar analysis gave a value of 5.25±0.02 yr for the ^{60}Co half-life which is in good agreement with the literature value of 5.2711±0.0004 yr [14].

E. Measurements at Hebrew University

Measurements were performed over a period of 10 yr at Hebrew University (HU) on a mixed ^{44}Ti+^{60}Co source and a pure ^{60}Co source whose activities at the start of the measurements (March 1992) were ∼0.4 and ∼0.3 μCi, respectively. The sources, sealed in lucite disks identical to those used at Argonne, were directly mounted in a low-mass plastic holder with precision slots, sliding over the detector casing and pushed until contact onto the front window of the γ spectrometer. The distance between the center of the lucite disk (γ source pointing to the detector) and the front window was 6.7 cm with a reproducibility estimated to 0.02 cm. The γ spectrometer, a 100-cm^3 (35%) Ge(Li) detector continuously kept at LN_2 temperature, was unshielded from room background. The location of the detector was kept fixed and the source holder was kept on the detector during the whole duration of the measurements, except for two interruptions at $t = 1.6$ yr (for detector service) and $t = 8.3$ yr (when the detector had to be moved to a different room and was serviced again). No significant change in the ratios of the 1173.2- and 1332.5-keV photopeak areas (1.1149±0.0003) of the pure ^{60}Co source was observed over the duration of the measurements. Sequences of measurements of the mixed ^{44}Ti+^{60}Co source, pure ^{60}Co and room background were performed at irregular time intervals, resulting in 18 data points. Counting times for both sources were increased over the duration of the measurements. The integral counts in the 1157.0-keV ^{44}Ti photopeak were of the order of 5×10^6 and in the 1173.2- and 1332.5-keV peaks between 4×10^6 and 1.5×10^6. Only the activity ratios between the 1157.0-keV line of ^{44}Ti and the 1173.2- and 1332.5-keV lines of ^{60}Co have been analyzed for the ^{44}Ti half-life determination.

To reduce a possible source of errors in the subtraction of backgrounds from the photopeaks of the 1157.0-, 1173.2- and 1332.5-keV lines in the individual spectra, a fully computerized method was used for the data analysis. It is also believed that good agreement obtained between these independent data and analysis method and the Argonne data described in the previous section, further indicates that the systematic error in the half-life determination is insignificant within the quoted uncertainty. A custom-written fitting code was used, taking the empirical shape of the ^{60}Co photopeak at 1173.2 keV in the pure ^{60}Co spectra as a model peak to fit the region between 1130 and 1188 keV in the mixed ^{44}Ti+^{60}Co source. Before the analysis, the spectrum of the room background was subtracted from each mixed ^{44}Ti+^{60}Co and pure ^{60}Co spectrum. We denote the spectrum of the pure ^{60}Co source (model peak) in the fitting interval by the function $f_{\mathrm{mod}}(x_i)$, where x_i represents the energy channel. The fitting function f_{fit} used to represent the experimental spectrum $f_{\mathrm{exp}}(x_i)$ of the mixed ^{44}Ti+^{60}Co source is written as the sum of two scaled and shifted model peaks and an underlying (parabolic) background:

$$f_{\mathrm{fit}}(x_i) = a_1 f_{\mathrm{mod}}(x_i/r - a_2) + a_3 f_{\mathrm{mod}}(x_i - a_4) + a_5 + a_6 x_i + a_7 x_i^2, \quad (1)$$

for $x_{\mathrm{low}} \leqslant x_i \leqslant x_{\mathrm{high}}$. The fitting interval ($x_{\mathrm{low}} = 3300$, $x_{\mathrm{high}} = 3470$, corresponding to 1130 to 1188 keV) was kept fixed for all analyzed spectra. Values of the model peak at noninteger channel values were calculated by linear interpolation between the adjacent channels. In Eq. (1), $a_j (j = 1, 7)$ denotes the fitting parameters and the ratio r, representing the ratio of the

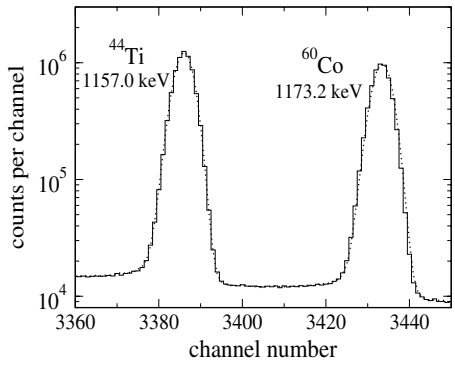

FIG. 5. Semilogarithmic plot of the 1157.0 keV (^{44}Ti) and 1173.2 keV (^{60}Co) photopeaks (solid line) collected at Hebrew University for the mixed ^{44}Ti+^{60}Co source and of the fit to the experimental spectrum (dotted line) obtained to extract the ratio of counts between the two peaks (see text for details). The experimental spectrum was collected close to the start of the measurements ($t = 0.73$ yr).

photopeak energies at 1173.2 and 1157.0 keV, was kept fixed at the value $r = 1157.0/1173.2 = 0.9866$. In the final fits, the parameters a_2, a_4, and a_7 ($a_7 = 0$) were kept fixed, leaving only a_1, a_3, a_5, and a_6 as free parameters to be fitted over the 161 experimental values (channel number and counts). The MINUIT least-squares code [25] was used to fit the function above to the experimental spectrum and was used systematically on all 18 pairs of spectra (mixed ^{44}Ti + ^{60}Co and pure ^{60}Co sources). A weight equal to $1/(f_{\text{mod}} + f_{\text{exp}})$ was given at each channel to represent the statistical errors in the values of the model peak and experimental spectra. Fits of excellent quality were obtained (Fig. 5) and the ratio of the best-fit parameters a_1/a_3 with their 1σ errors was taken as the experimental value and uncertainty of the ratio of the 1157.0 keV to the 1173.2-keV photopeak areas. A similar procedure was used for the ratio of the 1157.0-keV ^{44}Ti and 1332.5-keV ^{60}Co photopeaks. The results for the ^{44}Ti half-life are included in Table II. The half-life value was extracted in the same way as described for the Argonne data and agrees very well with the Argonne results; the slightly larger errors may result from a smaller set of data points and from the different method of data analysis.

III. DISCUSSION

A. Possible sources of systematic errors

In the value of the half-life, determined from the analysis of spectra of the mixed source, most of the uncertainties cancel out because the same corrections apply to counts in the ^{44}Ti and ^{60}Co peaks. These include random summing, coincidence summing, counting system deadtime, and possible changes in the detector efficiency and solid angle. The only source of error that could influence the final result is the subtraction of background counts under the peaks. Because the counts underneath the peaks include counts from ^{44}Ti and ^{60}Co decays, improper setting of the background subtraction could produce counts from ^{60}Co decay in the ^{44}Ti peak and vice versa. We have determined the contribution of this effect to the systematic error in the half-life value in the following way.

For each data set, spectra of pure ^{60}Co, pure ^{44}Ti, and mixed ^{60}Co+^{44}Ti source were measured under identical conditions and for the same duration. We have analyzed one set of data obtained midway during the 14-yr decay. First, all spectra were gain matched and the room background spectrum was subtracted. The spectrum of pure ^{60}Co, normalized to the counts in the 1173.2-keV peak of the mixed source spectrum, is displayed in the top panel of Fig. 6 along with the spectrum of the mixed source (bottom panel). By drawing a linear background between channels 2850 and 2871, which is only 9 keV wide, we determined the counts in the 1157.0-keV ^{44}Ti peak as 3,054,562(1761) and spectrum background (area under the line) as 47,334(220). We also determined the counts in the 1157.0-keV peak from the difference spectrum (mixed source spectrum − ^{60}Co spectrum) as 3,054,355(1753) and spectrum background as 18,017(135). This spectrum does not contain any ^{60}Co counts. The agreement between the two values of the peak area demonstrates that the counts in the 1157.0-keV ^{44}Ti peak determined from the mixed source does not contain any significant number of counts from ^{60}Co.

As the ^{60}Co spectrum shows (Fig. 6), the background from ^{60}Co in the region of the 1157.0-keV peak is quite linear. The sum of the counts in the ^{60}Co spectrum between channels 2850 and 2871 is 29,525(172). We compare this number with the background counts (18,017(135)) due to ^{44}Ti itself, determined from the difference spectrum. In the ^{60}Co spectrum, the difference between the sum of counts between channels 2850 and 2871 and the area under the line is 193(172), which is a small fraction of the statistical error of 1761 in the peak area. This suggests that the background from ^{60}Co is very linear and it contributes very little to the systematic error in the ^{44}Ti half-life. Because the ^{60}Co source is pure, the linearity of the background will not change during the 14-yr decay.

In Fig. 6 (top panel) we have also plotted the spectrum of pure ^{44}Ti normalized to the counts in the 1157.0-keV peak of the mixed source. This spectrum shows that the backgrounds in the vicinity of the 1157.0-keV peak and under the 1173.2-keV peak are also linear. Thus the inclusion of 0.1 yr as the systematic error in the final value of the half-life is a very good estimate. The effect discussed for the mixed source is, however, not present in the peak areas determined from the spectra of pure ^{44}Ti and pure ^{60}Co sources.

In the analysis of the HU data discussed in Sec. II E, the fitting method used for data analysis, which uses empirical spectral shape of the 1173.2-keV peak of the pure ^{60}Co spectrum in the entire region of the ^{60}Co and ^{44}Ti peaks, reduces the ambiguity in background subtraction. The excellent agreement between the values obtained from the ANL and HU data sets is probably fortuitous in view of the random errors associated with both half-life values but these results are consistent with the negligible systematic error discussed above.

The other source of error is the way the peak areas are determined. For the mixed source data at 5.2 cm, we independently determined the areas of peaks by the peak fitting program of the GeLifit code using step function spectrum background. The peak fitting program gave a half-life value of 58.5±0.4 yr and

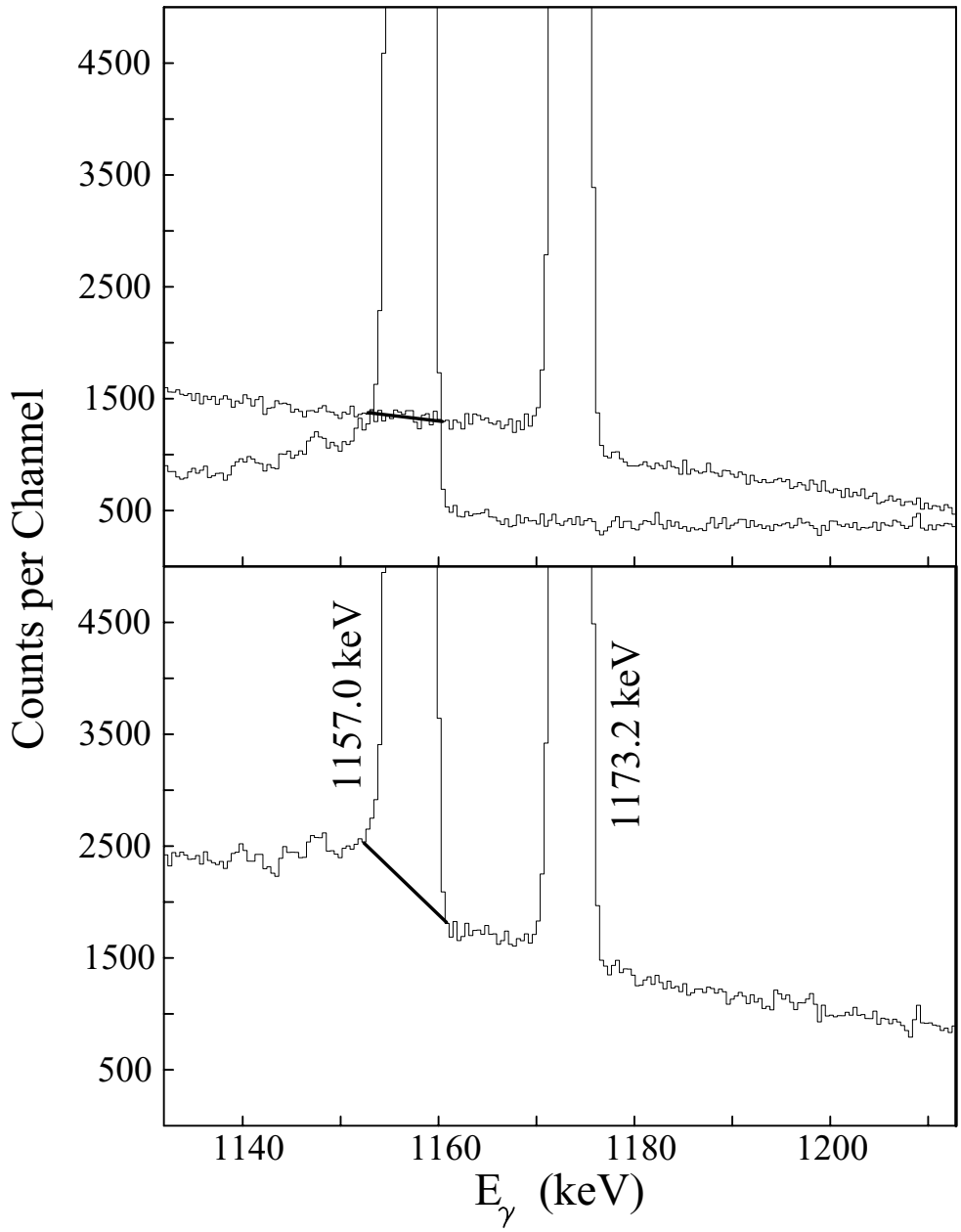

FIG. 6. A portion of the γ-ray spectrum of a mixed ^{60}Co and ^{44}Ti source obtained after subtraction of the room background spectrum (bottom panel). Also shown (top panel) are spectra of a pure ^{60}Co source (normalized to the counts in the 1173.2-keV peak of the mixed source) and a pure ^{44}Ti source (normalized to the counts in the 1157.0-keV peak of the mixed source). All the three spectra were measured at a source-to-detector distance of 10.2 cm and are plotted with the same x and y scales.

58.9±0.4 yr for the 1157.0/1173.2 and 1157.0/1332.5 ratios, respectively, in agreement with the corresponding values of of 58.8±0.4 yr and 59.0±0.3 yr obtained by using the *sb* command. To exclude any personal bias in data analysis, the spectra were analyzed by two collaborators. The values independently determined by different collaborators agreed within the quoted uncertainty.

As Fig. 1 shows, ^{44}Sc, the short-lived daughter of ^{44}Ti, decays by β^+ emission. Positrons stop in the plastic disk containing the source producing annihilation 511.0-keV γ rays. We have used 511.0-keV peak areas to determine the half-life values. We determined the half-life values from the four ratios of 511.0-keV γ ray and ^{60}Co γ rays for the mixed source at two distances and obtain a weighted average of 58.7±0.3 yr, in excellent agreement with the values determined in Table II. Becuase detector efficiencies at 511.0 and 1332.5 keV are quite different, the agreement among the half-life values determined from the ratios of various γ rays indicates that the Ge detector efficiency remained constant after the detector repair. We have not included this value in the final analysis, because, in principle, the 511.0-keV peak could contain small amount of some contaminant.

The overall agreement of half-life values determined by different analysis methods and the detailed analysis of the spectrum background under the peaks discussed above show that the systematic error in the half-life is less than 0.1 yr. A weighted average of the values in Table II gives a half-life of 58.9±0.2 yr for ^{44}Ti decay. Because the values determined from the 1157.0/1173.2 and 1157.0/1332.5 ratios are not independent, we have increased the uncertainty to 0.3 yr, giving a final value of 58.9±0.3 yr.

B. Summary

The half-life of ^{44}Ti has been measured by following the decay of the 1157.0-keV γ ray of ^{44}Ti relative to the decay of ^{60}Co γ rays. Spectra of mixed ^{44}Ti+^{60}Co, pure ^{60}Co, and pure ^{44}Ti sources were measured with Ge spectrometers in two different laboratories and analyzed by different methods. The analysis gave a value of 58.9±0.3 yr for the ^{44}Ti half-life. The systematic error was evaluated by detailed analysis of the spectrum background under the peaks and was found to be less than 0.1 yr.

ACKNOWLEDGMENTS

The authors thank S. Zhu for help in data analysis and Y. Kashiv for useful discussions. This work was supported by the U.S. Department of Energy, Office of Nuclear Physics, under contract W-31-109-ENG-38.

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