PHYSICAL REVIEW C VOLUME 40, NUMBER 1 JULY 1989

BRIEF REPORTS

Brief Reports are short papers which report on completed research or are addenda to papers previously published in the **Physical Review**. *A Brief Report may be no longer than $3\frac{1}{2}$ printed pages and must be accompanied by an abstract.*

Half-life of ^{56}Co

K. T. Lesko, E. B. Norman, B. Sur, and R-M. Larimer
Nuclear Science Division, Lawrence Berkeley Laboratory, Berkeley, California 94720
(Received 10 April 1989)

The half-life of ^{56}Co was reinvestigated by measuring the time-dependent yields of several nuclear γ-ray lines over a period of 280 days. The ^{56}Co γ-ray yields were normalized to those observed from internal standards. A value of 77.08±0.08 days was deduced by averaging the results obtained from different γ-ray lines and source calibrations.

The wealth of new data provided by observations of SN1987A has done much to suggest that our understanding of the final stages of stellar evolution and nucleosynthesis are basically correct. In particular, the observation of nuclear γ-ray lines from SN1987A (Refs. 1-3) and the optical light curve of SN1987A (Refs. 4-6) support the idea that large amounts of radioactive ^{56}Co and ^{56}Ni were produced in the core of the supernova.[7] In fact, using the observed light curve of SN1987A and assuming that the origin of the photons is due to Comptonized tails of the nuclear γ rays, one can obtain the half-life of ^{56}Co. Specifically, Pinto and Woosley[8] find a value of 77.1±(1%) day, whereas the two compilations give values of 78.75±0.12 days[9] and 77.7±0.5 days.[10] The measurements which make up these average values, presented in Table I, cluster into two groups, the first centering around 78.5 days and the other centering around 77.2 days. To address this discrepancy we have undertaken a remeasurement of the half-life of ^{56}Co.

We produced a sample of ^{56}Co by bombarding a stack of four 20 mg/cm^2 Fe metal foils of natural isotopic abundance with a beam of 13-MeV deuterons. A 5-μA deuteron beam was produced by LBL's 88-Inch Cyclotron. The beam energy was chosen to optimize ^{56}Co production in the foil stack via the $(d,2n)$ reaction. The foils were allowed to *cool* for 24 days, permitting the shorter-lived activities to die away. After this time we identified γ-ray lines of ^{59}Fe, ^{54}Mn, and ^{56,57,58}Co coming from the foils. The foils were then dissolved in a mixture of concentrated HCl and HNO_3. This was then sorbed on a column of AG1-X8 anion-exchange resin which had been treated with 10M HCl. The cobalt and iron fractions remained on the column, while manganese passed through. The cobalt fraction was then eluted with 4M HCl. This chemical purification of the cobalt resulted in a suppression of other radioactivities by several orders of magnitude.

To prepare a sample of ^{56}Co for counting we combined ~1.4 μCi of the cobalt fraction with 0.89 μCi of ^{137}Cs and 0.91 μCi of ^{207}Bi. The ^{137}Cs and ^{207}Bi were of commercial origin and both were in an acid suspension. The three sources were added successively to a well-shaped thin plastic source holder and heated to dryness. The holder was machined to constrain the source liquids to a few mm diameter area. The well, which contained the dried source materials, was capped with epoxy and the entire cell was wrapped in several layers of plastic tape.

This mixed source was counted with a 110 cm^3 intrinsic Ge detector which was shielded by at least 5 cm of lead on all sides. The detector and source were anchored to guard against accidental movement. The source was placed 22 cm from the detector to reduce the effects of γ-ray summing in the detector and to permit additional shielding to be introduced between the source and the detector so that the detector could be used in other experiments when not observing the ^{56}Co source.

The ^{207}Bi and ^{137}Cs provided γ-ray lines which bracket the energy region of the strongest lines of ^{56}Co and have half-lives which are very long compared to that of ^{56}Co. The half-life of ^{207}Bi is 38±3 y and that of ^{137}Cs is 30.174±0.034 y (Ref. 9). The electronic gain of the Ge detector was set to observe up to ~1.5 MeV in the γ-ray spectrum. Several runs collected data up to ~3 MeV to fully identify all the prominent γ-ray lines in the spectrum as coming from ^{56,57,58,60}Co, ^{207}Bi, or ^{137}Cs.

Singles spectra were accumulated on a PC-based acquisition system which was configured to collect data for 86 400 seconds in either 2000 or 4000 channels. At the end of this period the spectrum was automatically recorded onto disk along with various run parameters. The system was automatically cycled every 24 hours during data-taking periods.

The γ-ray spectra were analyzed off-line, extracting the peak areas for the 811- (^{58}Co), 847-, 1038-, 1238-, 1360- (^{56}Co), 662- (^{137}Cs), and 1063-keV (^{207}Bi) lines. The primary lines of the three sources (662-, 847-, 1063-keV) each contained on the order of one million counts per day. In order to accurately extract the peak areas for

TABLE I. Determinations of ^{56}Co half-life.

Half-life (days)	Author
72	Livington and Seaborg[11]
80±5	Cook and McDaniel[12]
77.2±0.80	Burgus *et al.*[13]
77.3±0.3	Wright *et al.*[14]
78.76±0.12	Emery, Reynolds, and Wyatt[15]
78.4±0.5	Cresy, Jr.[16]
77.12±0.10	Anderson[17]
77.12±0.20	Lagoutine, Legrand and Bac[18]
77.32±0.09	Alburger, Warburton, and Tao[19]
77.08±0.08	This work

these lines, care was taken to use a peak-fitting routine which treated the backgrounds in a sophisticated manner.[20] In particular, a second-order polynomial was fit to the background and was folded into an error function which reproduced the observed "step" in counts below a large peak. This "step" is caused by γ rays which are scattered into the detector. The peaks were fitted with a Gaussian function. The detector resolution was such that a skewed Gaussian shape as is often observed with damaged or older detectors was not needed. We present a typical γ-ray spectrum in Fig. 1. The principal energy-labelled peaks are from the decay of ^{56}Co and the other strong transitions are also labelled with the parent nucleus. The inset in the figure illustrates a typical background in the vicinity of a large peak. There exists a significant increase in the background below the large peak due to Compton scattering into the detector. The resolution of the detector was 2.24 keV full width at half maximum (FWHM) at 847 keV during the experiment. It was monitored throughout the 280-day period and did not vary during the measurements.

The yields for all the ^{56}Co lines were separately normalized to both the ^{137}Cs and ^{207}Bi lines. The ratio of yields from ^{56}Co γ-ray lines to those of ^{207}Bi and ^{137}Cs cancelled out the geometric and detector-dependent factors which usually complicate the long counting periods needed for this type of measurement. The use of several different calibration lines over a range of energies reduces the sensitivity to energy-dependent effects. These yields were corrected for the decay of the normalization lines.

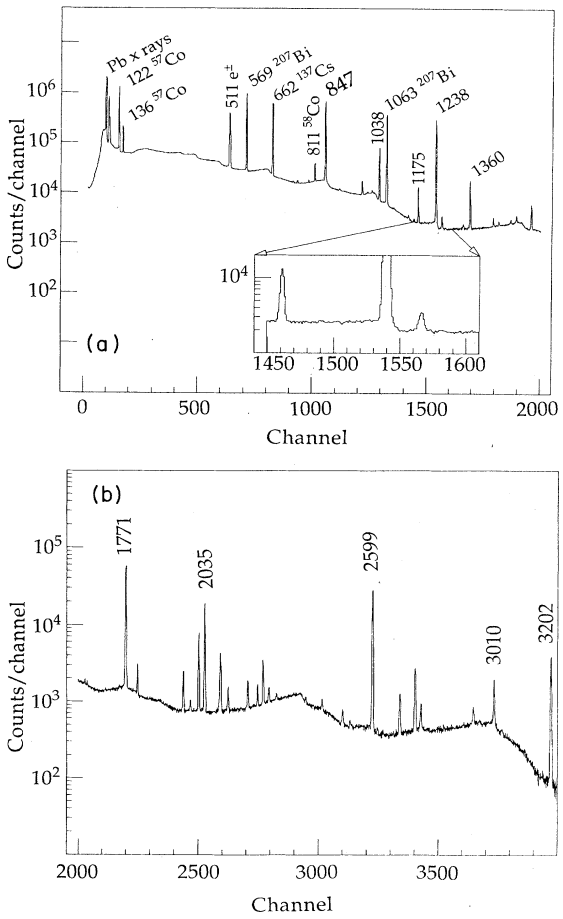

FIG. 1. A typical γ-ray spectrum observed in 86 400 seconds of counting. The peaks labelled only by energy (in keV) are from the decay of ^{56}Co. The other transitions are labelled by the parent nucleus. (a) shows the spectrum from 0 to 2000 channels, (b) shows the spectrum from 2000 to 4000 channels. The inset in (a) shows the detail of the background in the vicinity of a large peak. The "step"-like nature of the background below the large peak is clearly evident.

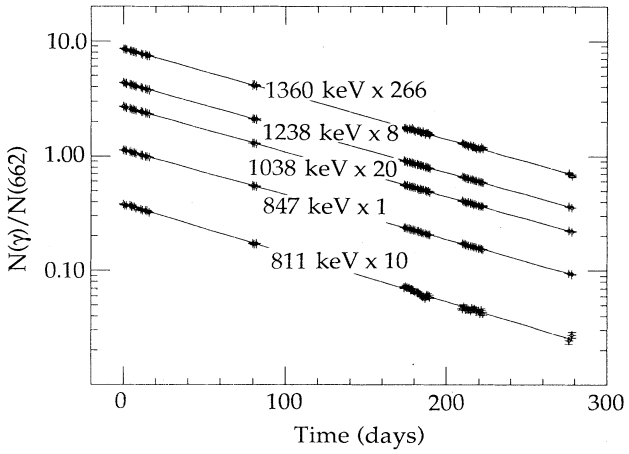

FIG. 2. The data for the time-dependent yields of five γ-ray lines are presented along with the fit calculated using the least-squares-fitting routine. These data were normalized to the 662-keV line from the ^{137}Cs source. Similar results are obtained when normalizing to the ^{207}Bi source. The error bars for the data are smaller than the plotting symbols.

TABLE II. This table presents the half-life determinations for the four ^{56}Co and the single ^{58}Co γ-ray lines. The second and third column are for data normalized to the 662-keV γ-ray line from ^{137}Cs, while the fourth and fifth columns are normalized to the 1063-keV γ-ray line of ^{207}Bi. The χ^2 per degree of freedom listed are for fitting the 50 degrees of freedom with a single exponential function. The errors listed are 1σ estimates of statistical accuracy.

Energy (keV)	$t_{1/2}$ days (662)	χ^2_ν(662)	$t_{1/2}$ days (1063)	χ^2_ν(1063)
810.8 (^{58}Co)	70.87±0.15	1.105	70.85±0.15	1.076
846.8	77.14±0.03	0.755	77.11±0.03	0.951
1037.8	76.95±0.05	0.551	76.93±0.05	0.561
1238.3	77.11±0.03	1.168	77.09±0.03	0.988
1360.2	77.02±0.10	0.670	76.99±0.10	0.656

The resulting ratios were fit to an exponential function with a least squares fitting routine to deduce the half-lives of the various lines. The time for each measurement was determined by the internal clock on the data-acquisition PC. The clock's nominal accuracy was better than ~26 seconds per month. The data for five of the lines and the calculated fits to these data are shown in Fig. 2. The calculated half-lives and their corresponding statistical uncertainties associated with the fits are presented in Table II. The data for the 811-keV γ-ray line ^{58}Co were treated in a similar manner and we deduced a half-life of 70.86±0.15 d, in excellent agreement with the accepted value of 70.78±0.07 d (Ref. 9). We also analyzed data from the 122- and 136-keV lines of ^{57}Co. However, they were found to be contaminated with a small yield of ^{229}Th lines, identified by the presence of other weak lines characteristic of ^{229}Th in the γ-ray spectra. A thorium source was located in the vicinity of our experimental setup and removed midway through our measurements. The lead shielding also may have contained a small thorium impurity. By fitting the yields of these γ-ray lines with the functional form of an exponential added to a constant background (the decay constant for the 7340 y half-life of ^{229}Th is essentially a constant for our measurements) we were able to significantly reduce χ^2_ν for the fit and deduced a value of the half-life which was much closer to the accepted value for ^{57}Co. The 1175-keV line of ^{56}Co was similarly found to contain 1173.5-keV γ rays from ^{60}Co which could not be resolved. ^{60}Co was produced in our bombardment and obviously survived our chemical separation. The remaining four lines at 847, 1038, 1238, and 1360 keV each in turn normalized to the 662- and 1063-keV lines from ^{137}Cs and ^{207}Bi gave eight values, listed in Table II, for the half-life of ^{56}Co. From these we obtain a value of 77.08±0.02 days for the half-life of ^{56}Co. The quoted uncertainty represents the statistical accuracy of the measurement and does not include any estimate of a systematic component.

The effects of small ($<1\%$), but varying, dead times for these measurements were investigated and found to produce a negligible result on our half-life determination. The deadtime of our measurements closely tracked the total activity of the sample and decreased with the decay of the shorter-lived components of our sample. The effects of the varying dead times would be to shift the centroid of each counting period, since the dead time decreases as an exponential function, this can introduce a monotonically varying change of the centroid. However, the change in the centroid from the beginning of the counting to the end was less than a few seconds.

The long-term stability of the internal clock on the PC would affect our measurement in an analogous manner. If the clock were systematically too fast (or too slow), this would result in a determination of the half-life which was too long (short). Conservatively estimating the effects of long-term inaccuracies of the internal PC clock and of the deadtime variations on the centroid to produce a systematic uncertainty of <15 seconds per day would result in a systematic error of <0.02 days.

The final systematic uncertainty which can affect our measurement is that from the half-lives of the calibration sources. Propagating the quoted uncertainties for the ^{137}Cs and ^{207}Bi sources through our fitting routine produced an uncertainty of <0.01 days. A conservative estimate of the total systematic uncertainty would be ±0.06 days which we add linearly to our statistical error.

In Table I we present half-life values of ^{56}Co from previous determinations as well as our present result of 77.08±0.08 days. We find good agreement between our result and several of the more recent values. This half-life of 77.08 days is consistent with the observed light curve of SN1987A and further supports the idea that large amounts of ^{56}Co are produced in supernovae.

This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Nuclear Physics Division of the U.S. Department of Energy under Contract DE-AC03-76SF00098.

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