BRIEF REPORTS

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Half-life of ^{56}Ni

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The half-life of ^{56}Ni was reinvestigated by measuring the time-dependent yields of several nuclear γ-ray lines over a period of 38 days. These yields were added and normalized to that of one internal standard, and a value of 6.075±0.010 d was deduced.

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The wealth of 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 [1–3] and the optical light curve of SN1987A [4–6] support the idea that large amounts of radioactive ^{56}Ni and ^{56}Co were produced in the core of the supernova.

In a previous work on ^{56}Ni decay, Sur *et al.* [7] found a half-life of 5.9±0.1 d, which is in disagreement with some of the previous data [8, 9], particularly with the very precise value of Ref. [9], 6.10±0.02 d . The internal standard used by Sur *et al.* for normalization was ^{51}Cr, a source impurity, with its 320-keV transition. The adopted half-life of ^{51}Cr was 27.702±0.002 d. The ^{56}Ni transitions used were 269- and 480-keV, in a total measuring time of 5.5 days. The source of this discrepancy was not found, and to address it we have undertaken a remeasurement of the half-life of ^{56}Ni.

We produced ^{56}Ni by bombarding a stack of two 80 mg/cm^2 Fe metal foils of natural isotopic abundance with a 50-MeV ^{3}He beam for 12 hours. A 4 μA ^{3}He beam was produced by LBL's 88-Inch Cyclotron. The beam energy was chosen to optimize ^{56}Ni production in the foil stack via the $(^3\mathrm{He}, 3n)$ reaction. The foils were allowed to cool for 14 days, permitting the shorter-lived activities to die away. After this time we identified γ-ray lines of ^{56,57}Ni, ^{56,57}Co, and ^{52,54}Mn coming from the foils were then dissolved in a mixture of concentrated HCl and HNO_3. This was then sorbed onto a column of DOWEX1-X8 anion-exchange resin which had been treated with 10M HCl. The cobalt and part of the manganese fractions remained on the column, while the nickel passed through. The nickel fraction was subsequently precipitated as nickel-dimethylglyoxime (Ni-DMG). The red Ni-DMG precipitate was separated from the liquid phase and again dissolved in concentrated HCl. This chemical purification of the nickel resulted in a supression of other radioactivities by a few orders of magnitude. For the cobalt, in particular, the supression factor was approximately 400.

To prepare a sample of ^{56}Ni for counting we combined ~5 μCi of the nickel fraction with 1 μCi of ^{207}Bi. The ^{207}Bi was of commercial origin and was kept in an acid suspension. The sources were added to a bottle, to a final volume of ~10 cm^3. The bottle was closed with its plastic cap, inserted in a plastic bag in order to secure the source against leaks and spills, and 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, the source and a 1 μCi ^{137}Cs calibration source were anchored to prevent accidental movement. The ^{137}Cs source was also placed in the setup to permit a comparison between the reliabilities of the internal and external standards. The sources were placed 15 cm from the detector to reduce the effects of γ-ray summing in the detector.

The ^{207}Bi and ^{137}Cs provided intense γ-ray lines between 570- and 1063-keV and have half-lives very long compared to that of ^{56}Ni.

Singles spectra were accumulated on a PC-based acquisition system which was configured to collect data for 86 400 seconds in 16 384 channels. At the end of this period the spectrum was recorded onto disk along with various run parameters. The gain of the electronics was set to observe up to ~1.8 MeV in the γ-ray spectrum. 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 662- (^{137}Cs), 569-, 1063-, 1442- (^{207}Bi), 158-, 269-, 480-, 750-, 812-, 1562- (^{56}Ni), 744-, 936-, 1434- (^{52}Mn), 1238-, 1360-, 1772- (^{56}Co), 1378-, and 1757-keV (^{57}Ni) lines. The primary lines of the three

sources (158-, 662- and 1063-keV) each contained on the order of five million counts per day. In order to accurately extract the peak areas for these lines, care was taken to use a peak-fitting routine which treated the backgrounds in a sophisticated manner [10]. In particular, a second-order polynomial was fitted 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. Some of the largest photopeaks needed a skewed Gaussian to be fitted to their low-energy part. We present a typical γ-ray spectrum in Fig. 1. The resolution of the detector was 1.63 keV full width at half maximum (FWHM) at 812 keV during the experiment. It was monitored during the 38-day period and did not vary during the measurements.

The yields for all the ^{56}Ni lines were separately normalized to the ^{207}Bi lines only. We disregard the ^{137}Cs normalization because of observed shifts in its yield, which we attribute to changes in the relative geometry for this source.

The ^{207}Bi half-life was measured by a number of authors, the value quoted in Ref. [11] being the one recommended by Schmorak [12], with a standard deviation increased to 1.3 yr. There is a recent work by Alburger and Harbottle [13], where the authors find a value of 34.9±0.4 yr, as resulting from a very careful work. We used this value.

The ratio of the yields from ^{56}Ni to those of ^{207}Bi 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. The decay of the normalization lines was taken into account when fitting the relative yields versus time. This was done 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

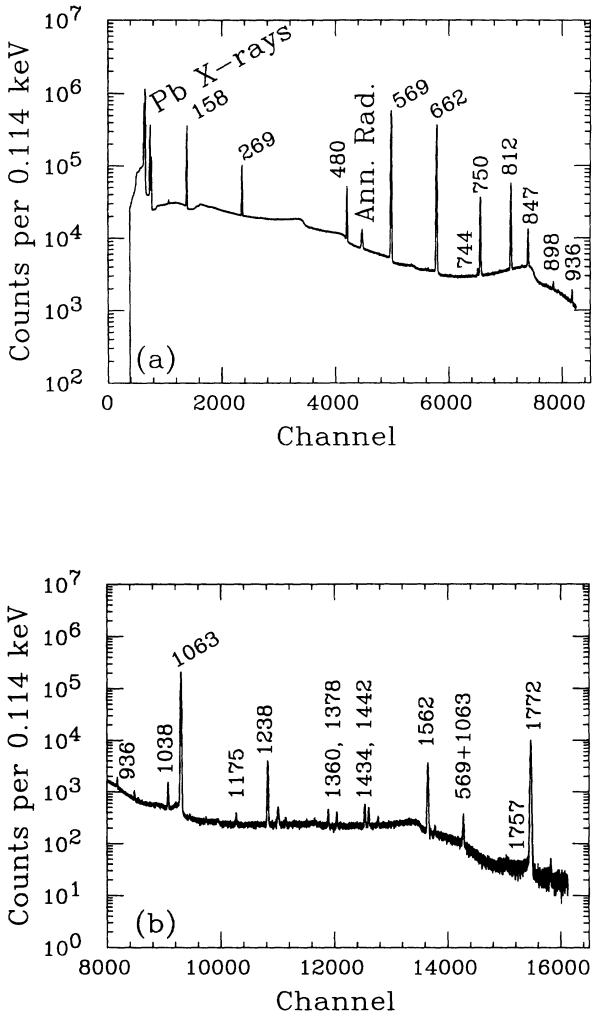

FIG. 1. A typical γ-ray spectrum observed in 86 400 seconds of counting. The main peaks are labeled by energy (in keV). (a) shows the spectrum from channel 0 to 8000, (b) shows the spectrum from channel 8000 to 16 000.

TABLE I. Half-life determinations for the four ^{56}Ni (and their sum), three ^{52}Mn, and one ^{57}Ni γ-ray lines. The third and fourth columns refer to data normalized to the 569-keV γ-ray line, while the fifth and sixth were normalized to the 1063-keV, both of ^{207}Bi. The χ^2_ν per degree of freedom listed are for fitting the degrees of freedom indicated as subscripts. The errors listed are 1σ estimates of statistical accuracy, multiplied by χ_ν.

Isotope	Energy (keV)	$t_{1/2}$ (569) (d)	χ^2_ν (569)	$t_{1/2}$ (1063) (d)	χ^2_ν (1063)
^{56}Ni	158	6.080(5)	1.51_{26}	6.082(5)	1.31_{26}
^{56}Ni	269	6.077(10)	1.08_{26}	6.077(10)	1.05_{26}
^{56}Ni	480	6.043(12)	1.29_{26}	6.043(12)	1.25_{26}
^{56}Ni	1562	6.101(20)	1.79_{26}	6.100(20)	1.74_{26}
^{56}Ni	comb. yield	6.074(5)	1.49_{26}	6.076(5)	1.31_{26}
^{52}Mn	744	5.54(11)	0.84_{15}	5.54(11)	0.83_{15}
^{52}Mn	936	5.60(11)	1.19_{14}	5.60(11)	1.16_{14}
^{52}Mn	1434	5.68(7)	0.89_{26}	5.68(7)	0.91_{26}
^{52}Mn	comb. yield	5.64(8)	1.28_{14}	5.64(8)	1.25_{14}
^{57}Ni	1378	1.522(16)	0.75_{10}	1.525(16)	0.71_{10}

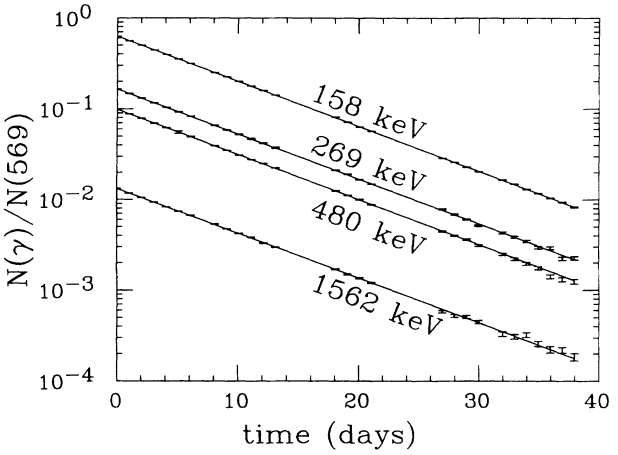

FIG. 2. The data for the time-dependent yields of four γ-ray lines are presented along with the fit calculated using the least-squares fitting routine. These data were normalized to the 569-keV line from the ^{207}Bi source. Similar results are obtained when normalizing to the 1063-keV line.

PC. The data for four 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 I. The data for the ^{52}Mn and ^{57}Ni lines were treated in a similar manner and we deduced half-lives of 5.64±0.09 d, and 1.524±0.021 d, respectively, in good agreement with the accepted values of 5.591±0.003 d and 1.503±0.004 d, [11], respectively. The 812-keV line of ^{56}Ni was found to be contaminated by a small yield of ^{58}Co, identified by remeasuring the source 22 days after the end of the counting period, and calculating the ratio between the yields of 158- and 812-keV lines. The ^{58}Co amount was small enough for its 811-keV line not to be revealed below the low-energy tail of the intense 812-keV photopeak, but sufficiently intense to distort the half-life value obtained for that line. Also, its amount was consistent with the yield of the (^{3}He, p) reaction on the target, under our conditions of activation [14]. The 750-keV line of ^{56}Ni was also found to be contaminated by the double-escape peak of the 1772-keV line of ^{56}Co, which was building up with time due to the decay of ^{56}Ni. The remaining four lines at 158-, 269-, 480-, and 1562-keV, each in turn normalized to the 569- and 1063-keV lines from ^{207}Bi, produced eight values listed in Table I, for the half-life of ^{56}Ni. From the sum of these γ-ray yields we obtain a value of 6.075±0.005 d for the half-life of ^{56}Ni, now in agreement with Wells' result [9]. Our 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 dead time 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 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 5 minutes.

TABLE II. Determinations of ^{56}Ni half-life.

Half-life (days)	Author
6.4±0.1	R.K. Sheline and R.W. Stoughton [8]
6.0±0.5	W.J. Worthington, Jr. [15]
5.8±0.6	S. Monaro *et al.* [16]
6.10±0.02	D.O. Wells *et al.* [9]
5.9±0.1	B. Sur *et al.* [7]
6.075±0.010	This work

The long-term stability of the internal clock on the PC would affect our measurement in an analogous manner. The acquisition board clock was found out to be systematically fast, taking ~40 s less per 86 400 seconds of counting time, uniformly. Due to this, the starting and elapsed times of our runs were controlled by verifying a local time-standard.

The final systematic uncertainty that can affect our measurement is that from the half-life of the calibration source, ^{207}Bi. Propagating the quoted uncertainty for ^{207}Bi through our fitting routine produced an uncertainty of <0.0002 days. A conservative estimate of the total systematic uncertainty would be ±0.005 days, which we add linearly to our statistical error. In Table II we present half-life values of ^{56}Ni from previous determinations as well as our present result of 6.075±0.010 d.

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