Cosmic-ray half-life of ^{56}Ni

K. Zaerpoor,[1] Y. D. Chan,[2] M. R. Dragowsky,[1] M. C. P. Isaac,[2] K. S. Krane,[1] R.-M. Larimer,[2] A. O. Macchiavelli,[2] R. W. Macleod,[2] and E. B. Norman[2]

[1]*Physics Department, Oregon State University, Corvallis, Oregon 97331*

[2]*Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720*

(Received 14 December 1998)

The positron decay partial half-life of ^{56}Ni is needed to employ this isotope as a cosmic-ray chronometer. We conducted an experiment by counting a purified 2.8-μCi source of ^{56}Ni in GAMMASPHERE in order to search for the β^+-decay branch of this isotope. A plastic scintillator was used to measure the energy of positrons in coincidence with the positron-annihilation γ rays and the characteristic 158-keV γ ray line. A careful analysis of 96 h of source counting shows no net signal and results in an upper limit of 77 counts of 511-511-158 keV plus scintillator coincident events. From this result we establish a 1σ upper limit on the branch for this decay mode to be $(6.3\times10^{-5})\%$. The discrepancy between the outcome of this experiment and previous measurements of this branch and the implications of this result for the ^{56}Ni cosmic-ray chronometer problem are discussed. [S0556-2813(99)01306-0]

PACS number(s): 21.10.Tg, 26.40.+r, 27.40.+z, 98.70.Sa

The doubly magic nucleus ^{56}Ni is the most abundant isotope produced during the silicon burning stage in massive stars. After this stage the energy from fusion is not available. The core of the star undergoes a gravitational collapse resulting in a shock wave and supernova explosion. The observation of the 77.1-day exponential decay of the light curve from supernova 1987A [1] provides strong evidence that the light output from the supernova remnant is largely due to the energy from the decay of ^{56}Ni and its daughter ^{56}Co [2]. If supernovas are sites for acceleration of relativistic nuclei found in cosmic rays, it is almost certain that ^{56}Ni is one of the species which is accelerated into relativistic energies and therefore completely ionized.

In the laboratory, ^{56}Ni decays via electron capture (EC) transition to the 1720-keV level in ^{56}Co with an almost 100% branch and a half-life of about 6.1 days [3,4]. As a cosmic-ray nucleus, however, ^{56}Ni lacks atomic electrons and is therefore unable to decay by EC. But as shown in Fig. 1, it is energetically possible for ^{56}Ni to β^+ decay to 0-, 158-, and 970-keV levels in ^{56}Co with $J^\pi=4^+$, 3^+, and 2^+, respectively. Since the decay to the ground state of ^{56}Co is a fourth-forbidden transition and decay to the 970-keV level has only 144 keV of available energy, it has been suggested that the second-forbidden unique transition to the 158-keV level is the most likely mode of decay [5]. From studies of the decay of ^{10}Be, ^{22}Na, and ^{26}Al, the log ft values of such transitions have been found to be between 13.9 and 15.7. This means that the range of β^+-decay partial half-life of ^{56}Ni is expected to be approximately $8.5\times10^4<t_{1/2}<5.4\times10^6$ yr. If the β^+-decay partial half-life of ^{56}Ni is long enough, it is possible for ^{56}Ni to survive in cosmic rays, and cosmic-ray abundance measurements of nickel could thus be used to determine the time interval between production and acceleration of cosmic rays [6].

We searched for the positron decay branch of ^{56}Ni by attempting to measure the energy spectrum of emitted positrons in coincidence with back-to-back 511-keV annihilation γ rays and deexcitation γ rays from the ^{56}Co daughter nucleus. In a previous experiment performed at Lawrence Berkeley National Laboratory, Sur *et al.* [7] placed a nickel source between two 1000-μm-thick silicon surface barrier detectors to detect the emitted positrons. Behind the silicon detectors, they placed two 110-cm^{3}germanium detectors surrounded by a 4π sodium iodide annular detector. In this configuration they searched for the back-to-back 511-keV γ rays in the two halves of the NaI detectors and used the germanium detectors to register the coincident deexcitation γ rays. While this experiment did not succeed in observing this decay, Sur *et al.* [7] claimed to establish a lower limit of 2.9×10^4 yr for the partial half-life of ^{56}Ni due to β^+ decay.

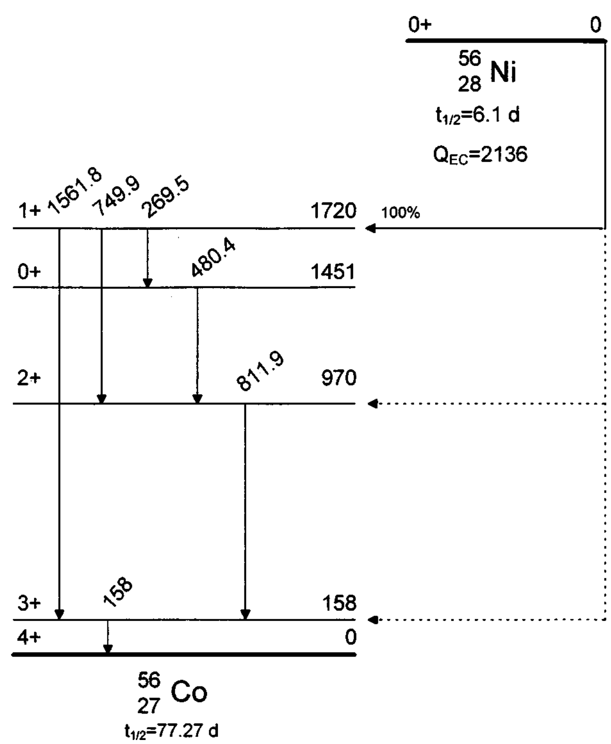

FIG. 1. Decay scheme of ^{56}Ni. Level and transition energies are given in keV. Dashed lines represent the branches studied in the present work.

In order to maximize their detection efficiency, these experimenters had to sandwich the source between the two silicon detectors. Because of this close geometry, a major limitation in these experiments was background and pileup produced by Compton scattering and conversion electron contamination of positron spectra in silicon detectors.

We attempted to improve upon the previous search by preparing a stronger source of ^{56}Ni in a plastic scintillator mounted on a phototube and placing the whole assembly into GAMMASPHERE, an array of Compton-suppressed germanium detectors. We searched for 511-511-158-keV events in coincidence with the light produced by positrons in the scintillator.

The ^{56}Ni source for this experiment was produced by the ^{56}Fe(^{3}He,3n) reaction at the Lawrence Berkeley National Laboratory's 88-Inch Cyclotron. A single 99.99% pure natural iron foil of thickness 78 mg/cm^2 was irradiated with a 2-μA beam of 40-MeV ^{3}He particles (in the $+2$ state) for about 21 h. The irradiated foils were stored for approximately 4 days, allowing the short-lived activities to decay away, as well as reducing the strength of the simultaneously produced ^{57}Ni. The extraction and chemical purification of the ^{56}Ni source was performed according to the procedure explained in [7]. Two cylindrical pieces of plastic scintillators 16 mm in diameter were prepared. A well for the source was bored in one of the scintillators in such a way that once the source was placed in the well and the two pieces of scintillators were attached to each other, the produced positrons had at least 4 mm of scintillator material to travel through before they could escape the scintillator. This arrangement was to make sure all positrons produced due to decay of ^{56}Ni were stopped in the scintillator, and the 158-keV gammas suffered the least amount of attenuation. The source was measured to contain 2.8 μCi of ^{56}Ni, 2.4 μCi of ^{57}Ni, and a minute amount of ^{52}Mn just before being mounted into GAMMASPHERE. The residual ^{57}Ni proved to be invaluable as an *in situ* source for efficiency calibration.

The GAMMASPHERE array consists of 98 Compton-suppressed germanium (Ge) detectors that surround and point inward toward a central source or target position [8]. In order to reduce the ambient background as much as possible, the normal GAMMASPHERE target chamber and beam line were removed for this experiment. Each Ge detector is approximately 275 cm^3 in volume and is surrounded by a hexagonally shaped bismuth germanate (BGO) scintillator that is normally used to reject events in which a γ ray Compton scatters in the Ge crystal. Almost all of the Ge detectors are in pairs that are located diametrically opposite to one another. These pairs are ideally suited to search for the back-to-back 511-511-keV γ rays produced by positron annihilation.

The scintillator with the ^{56}Ni source sandwiched in the middle was mounted on a phototube and was positioned in the normal target position of GAMMASPHERE. The output of the phototube was read into the standard GAMMASPHERE data acquisition electronics as an external detector. Our search consisted of 96 h of counting the source with 42 pairs of live Ge detectors. For all of these measurements, if three or more of the GAMMASPHERE Ge detectors fired within a time window of 1 μs and their immediately surrounding BGO shields did not fire, then the status of the entire array including the output of the scintillator was read out and written to magnetic tape for subsequent off-line analysis. The information recorded for each event contains the energy signal of the auxiliary detector (scintillator), each Ge and each BGO element, the identification number of each element fired, as well as the time when each element fired. The efficiency of this system for detecting back-to-back 511-511-158-keV γ-ray coincidences in Ge detectors was determined to be 4.8×10^{-3} by counting a calibrated 5.35-μCi source of ^{152}Eu and using 511-511-127-keV and 511-511-1377-keV events due to decay of ^{57}Ni. Figure 2 shows the scintillator spectrum in coincidence with 511-511-1377-keV γ rays. The same events in addition to 511-511-1757-keV and 511-511-1919-keV events were used to establish the energy calibration and efficiency of the scintillator. The overall efficiency of our system for detecting 511-511-158-keV events in Ge detectors, in coincidence with the light signal in the scintillator, was determined to be 4.2×10^{-3}. The same type of events was used to establish the peak width of the 511-keV gamma rays and the time distribution of the true coincidence events.

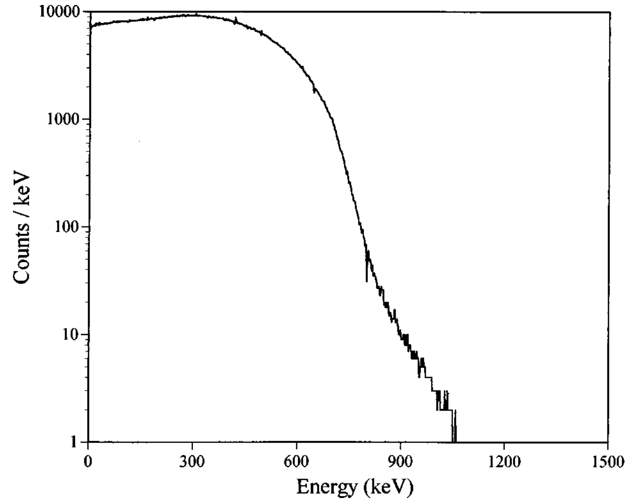

FIG. 2. Spectrum of coincident events seen in the scintillator when a pair of back-to-back 511-keV γ rays in coincidence with a 1377-keV γ ray is observed in germanium detectors.

Since we were ultimately interested in 511-511-158-keV events, we initially searched for events in which three or more Ge detectors fired. Among those, we selected the events which included back-to-back γ rays. Using energy and time information obtained from true positron annihilation events of ^{57}Ni, four 2-dimensional (2D) energy vs energy matrices of four different types of events were formed. In each 2D matrix, excluding the energy information of the back-to-back γ rays, the energy information of all other Ge detectors for each event was stored along the second (y) axis, while the energy signal of the scintillator for that event was stored along the first (x) axis. The first 2D spectrum consisted of those events where the energy of the back-to-back γ rays was in the range of 505–517 keV (on-energy peak events), while the second 2D matrix, which was used for background subtraction, was obtained by setting gates with the same energy width on both sides of the 511-keV line (off-energy peak events). Similarly, third and fourth matrices were formed for time coincidences where events were at

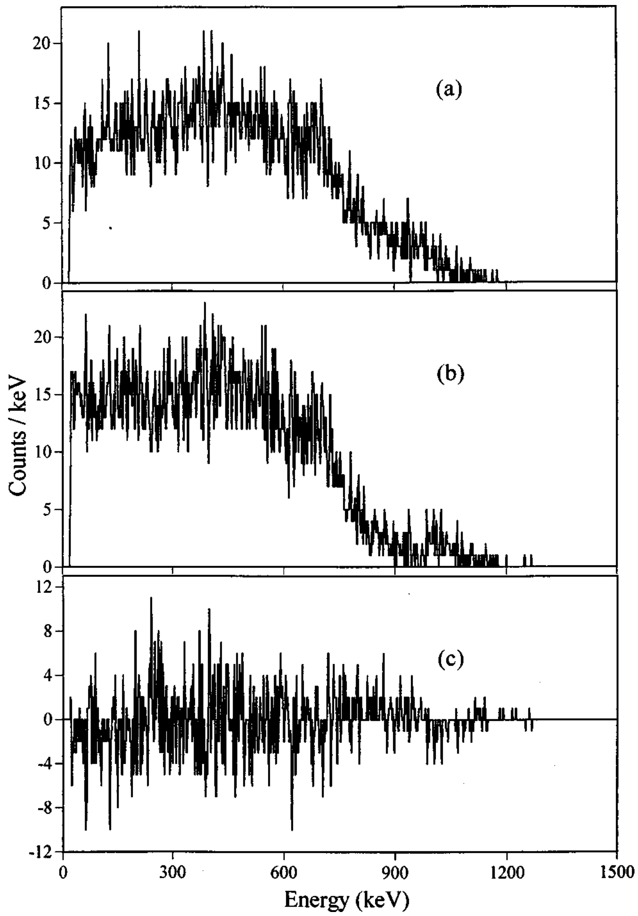

FIG. 3. Spectra of coincident events seen in the scintillator when a pair of back-to-back 511-keV γ rays is observed in germanium detectors (a) gated on the 158-keV peak, (b) gated off the 158-keV peak, and (c) net 511-511-158-keV signal.

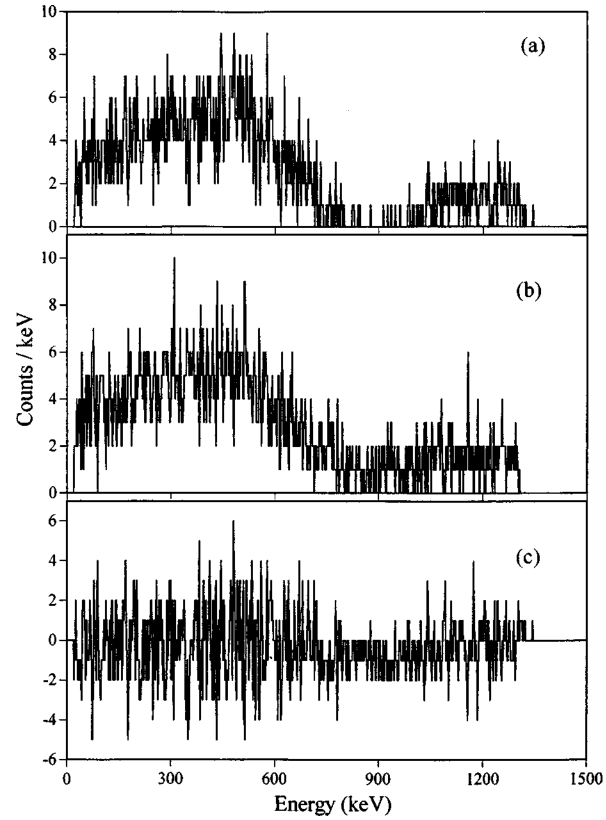

FIG. 4. Spectra of coincident events seen in the scintillator when a pair of back-to-back 511-keV γ rays is observed in germanium detectors (a) gated on the 811-keV peak, (b) gated off the 811-keV peak, and (c) net 511-511-811-keV signal.

most 25 ns apart (on-time peak events) and random events where time gates of the same width were set off of the coincidence time peak (off-time peak events).

In each matrix, on the y axis, gates of 4-keV width were set around the 158-keV mark and the scintillator spectrum was generated. The spectra generated from off-energy peak and off-time peak matrices were used for background and random subtractions. Figure 3(a) illustrates the total scintillator spectrum in coincidence with 511-511-158-keV events. The total number of events in the range of 0–956 keV in this spectrum is 2925 ± 54. Again, in each matrix, gates of 4-keV width were set on both sides of the 158-keV mark, and the corresponding off-energy peak and off-time peak counts were subtracted. This off-158-keV peak spectrum is shown in Fig. 3(b). In this spectrum, the total number of events below 956 keV amounts to 2951 ± 54 counts. The resulting net signal, which was generated by subtracting the off-158-keV events from the on-158-keV events, is shown in Fig. 3(c). The number of events in this spectrum, in the range of 0–956 keV, is -26 ± 77. To be conservative, we take the uncertainty to be equal to the 1σ upper limit on the number of counts, which is 77.

Based on the obtained upper limit on the number of counts and taking into account the efficiency of the system and the duration of the count, we find that the branch for the β^+ transition to the 158-keV level is less than $(6.3 \times 10^{-5})\%$. This would imply that the lower limit on the cosmic ray half-life of a bare ^{56}Ni nucleus due to this decay is 2.7×10^4 yr. This limit on the half-life is somewhat lower than that claimed by Sur *et al.* [7]. The relatively high limit for the partial half-life obtained in that experiment was due to their lower number of 511-511-158-keV events which were in coincidence with an event in their silicon detector. However, it now appears that there was an error with the efficiency calibration that Sur *et al.* applied to their data. Because of the contamination of the silicon spectra in the lower energy range, they focused on the upper third of the ^{56}Ni β^+ spectrum (635–956 keV) and from there inferred the total number of counts in the β^+ spectrum. The efficiency for detecting positrons in this limited energy range was reported to be deduced from an *in situ* measurement of a similar energy interval in the ^{57}Ni β^+ spectrum in coincidence with 511-511-1377-keV gammas. However, a recent review of that data analysis indicates that the true detection efficiency in the Sur *et al.* experiment was much smaller than originally believed [9]. Thus the actual limit on the β^+ decay branch of ^{56}Ni to the 158-keV level in ^{56}Co that can be derived from that experiment is significantly higher than that claimed by Sur *et al.* [7].

In order to set a limit on the β^+ decay branch to the 970-keV level, we set a gate on and off the 811-keV peak in the 2D matrices and generated the corresponding scintillator spectra. Figures 4(a), 4(b), and 4(c) show these spectra and the net results. The on-peak scintillator spectrum below the 145-keV mark, which is the end point energy of the positrons in the β^+ decay of ^{56}Ni to the 970-keV level, contains 1400 ± 37 counts. The off-peak spectrum contains 1438 ±38 counts. The net number of scintillator counts in coincidence with a 511-511-811-keV event is therefore -38 ± 53. Choosing the upper limit of 53 counts and taking into account the efficiency of our system for observing such events and the duration of the count, we calculate a 1σ upper limit for this branch to be $(7.9\times10^{-5})\%$. This result is almost a factor of 20 improvement in sensitivity over that obtained by Sur *et al.* [7].

The present results suggest that ^{56}Ni could survive and reach us in the cosmic rays produced by a nearby supernova. In such a case, ^{56}Ni abundance measurements could be used to determine the time interval between the production and acceleration of ^{56}Ni in cosmic rays. However, from studies of other long-lived isotopes, it is known that the average flight time of cosmic rays in our galaxy is on the order of 10^7 yr. If fully ionized ^{56}Ni actually has a half-life comparable to this value, it could be observed in the cosmic rays independent of the acceleration site, provided that the time span between production and acceleration is not too long. Unfortunately, with the present limit on the half-life, a null measurement of the abundance of ^{56}Ni in the cosmic rays would be difficult to interpret. To overcome this problem, higher sensitivity measurements of the β^+ decay branch of ^{56}Ni are necessary.

This work was supported at Lawrence Berkeley National Laboratory by the U.S. Department of Energy under Contract No. DE-AC03-76SF00098 and at Oregon State University by Contract No. DE-FG03-98ER41060.

[1] P. A. Pinto and S. E. Woosley, Nature (London) **333**, 534 (1988).
[2] K. T. Lesko, E. B. Norman, B. Sur, and R.-M. Larimer, Phys. Rev. C **40**, 445 (1989).
[3] R. B. Firestone, *Table of Isotopes*, 8th ed. (Wiley, New York, 1996).
[4] M. T. F. daCruz *et al.*, Phys. Rev. C **46**, 1132 (1992).
[5] L. W. Wilson, Ph.D. thesis, University of California, 1978, Lawrence Berkeley National Laboratory Report No. LBL-7723, 1978.
[6] M. Cassé, in *Proceedings of the 13th International Cosmic Ray Conference*, 1973, Vol. 1, p. 546.
[7] B. Sur *et al.*, Phys. Rev. C **42**, 573 (1990).
[8] I. Y. Lee, in *Proceedings of the Workshop on GAMMASPHERE Physics*, edited by M. A. Deleplanque, I. Y. Lee, and A. O. Macchiavelli (World Scientific, Singapore, 1996), p. 50.
[9] B. Sur (private communication).