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The Time Delay between Nucleosynthesis and Acceleration Based on ACE Measurements of Primary Electron-Capture Nuclides

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Abstract

Supernovae should produce the radioactive nuclide ^{59}Ni, and in the ejecta of the explosions these particles will decay by electron capture with a halflife of 7.6×10^5 yr to produce ^{59}Co. However, if the ^{59}Ni nuclei are accelerated to cosmic-ray energies on a time scale short compared to this halflife, they are stripped of their electrons and decay is prevented. Thus the abundances of ^{59}Ni and ^{59}Co can be used to determine whether the time between nucleosynthesis and cosmic-ray acceleration is short or long compared to the ^{59}Ni halflife (Soutoul, Cassé, & Juliusson 1978). We have used the Cosmic Ray Isotope Spectrometer (CRIS) on the Advanced Composition Explorer (ACE) to measure the abundances of ^{59}Ni and ^{59}Co in galactic cosmic rays, and find that the data are consistent with complete decay of ^{59}Ni indicating a time delay $\gtrsim 10^5$ yr. We present the observations and discuss their significance for models of cosmic ray origin and acceleration.

1. Introduction:

Supernovae are commonly thought to play a central role in the origin of galactic cosmic rays. They are the only candidate sources that are known to have a power output sufficient to maintain the observed energy density of cosmic rays throughout the galaxy. In addition, diffusive shock acceleration by the blast waves that supernovae drive into the interstellar medium appears capable of producing power law energy spectra such as those that are observed. Indeed, many supernova remnants are copious producers of synchrotron radiation, clearly indicating that at least electrons have been accelerated to relativistic energies.

The association between the nucleosynthetic processes that occurred in the supernovae and their progenitor stars and the composition observed in cosmic rays is much less clear. The question of whether there is a direct connection between supernovae ejecta and the seed population from which cosmic rays are derived has been the subject of considerable theoretical interest. Meyer, Drury, & Ellison (1997) proposed that the enhancement of the abundances of refractory elements relative to volatiles in cosmic rays could result from the preferential acceleration of charged grains by interstellar shocks, with subsequent sputtering of the grains acting as the injector for further acceleration. This model offers a possible physical basis for the well-documented correlation between cosmic-ray elemental abundances and first ionization potential (FIP), which is closely correlated with condensation temperature.

Subsequently Lingenfelter, Ramaty, & Kozlovsky (1998) adopted the grain-origin proposal but suggested that the location where it acts is more likely the expanding shells of new supernovae rather than the general interstellar medium. By accelerating grains formed from fresh supernovae ejecta they provided a mechanism by which the spallogenic nuclei such as beryllium and boron in the galaxy could have a “primary” origin, thereby accounting for the observation that the Be/Fe ratio in old, metal-poor stars in the halo of the galaxy is approximately independent of metallicity. A subsequent extension of this model by Higdon, Lingenfelter, & Ramaty (1998) noted that to have a primary source of Be and B it is only necessary that supernovae ejecta not mix significantly with normal interstellar matter before cosmic rays get accelerated. Winds and explosions of massive stars in a large association can blow a low-density "superbubble" in the interstellar medium where ejecta from a supernova can reside unmixed long enough for acceleration to be caused by shocks produced when other supernovae subsequently explode in the association.

The debate continues over the pros and cons of these alternative theories for the origin of cosmic rays, one deriving the cosmic-ray seed population from the general interstellar gas and dust and the other relying on relatively fresh supernovae ejecta.

In this paper we discuss the observational constraint on these models that can be obtained from measurements of radioactive nuclei which should be produced in supernovae explosions and can decay only by orbital electron capture. As first noted by Cassé & Soutoul (1978) and subsequently discussed by Soutoul, Cassé, & Juliusson (1978), such nuclides provide a means for determining the time interval that elapses between nucleosynthesis and cosmic-ray acceleration. In the ejecta of a supernova these nuclides will decay with their laboratory halflife. However, once they are accelerated to cosmic ray energies the nuclei are quickly stripped of their electrons and electron capture decays are prevented. Thus the survival or decay of primary electron capture nuclides in cosmic rays is an indicator of whether the time before acceleration is short or long compared to the halflife.

The most promising nuclides for such a study are ^{59}Ni ($T_{1/2} = 7.6 \times 10^5$ yr) and ^{57}Co ($T_{1/2} = 0.74$ yr) and their daughter products, ^{59}Co and ^{57}Fe. These two time scales can distinguish between prompt acceleration in the initial explosion (neither nuclide decays), acceleration in the remnant (^{57}Co decays, ^{59}Ni does not), and acceleration of ejecta on time scales longer than the time for dissipation of the explosion energy (both nuclides decay) presumably by shocks from other supernovae.

It has previously been suggested that ^{56}Ni, with $T_{1/2} \sim 6$ day, can also be used for such studies. However for this isotope β^+ decay is allowed and may have a branching fraction as large as 1%, which would allow it to decay after acceleration on a time scale short compared to the cosmic ray confinement time in the Galaxy. In addition, cosmic rays contain a variety of pure electron capture nuclides with mass number less than 56 (e.g., ^{55}Fe, ^{53}Mn), but these are dominated by secondaries produced during propagation and are therefore not suitable for addressing the problem of the acceleration time delay.

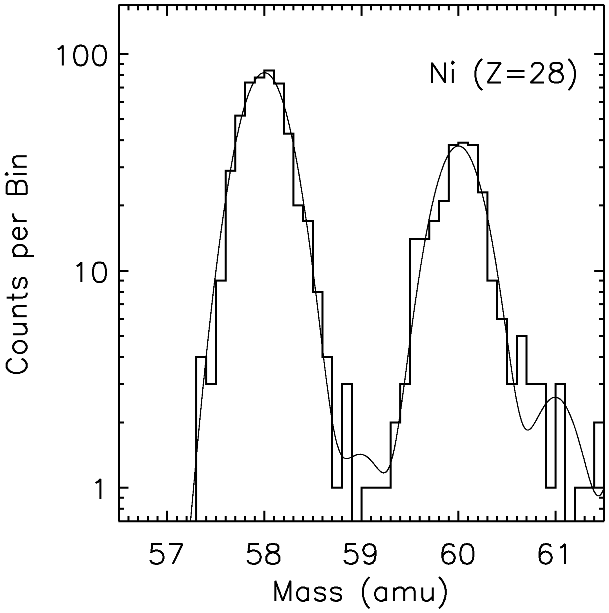

Figure 1. Measured mass histogram for nickel emphasizing the region around the electron capture radionuclide ^{59}Ni. The sooth curve is a fit to the data.

2. Observations and Interpretation:

The ACE Cosmic Ray Isotope Spectrometer (CRIS) uses the dE/dx vs. total energy technique to measure the charge, mass, and energy of cosmic ray nuclides with $3 \leq Z \lesssim 40$ over the energy interval $50 \lesssim E/M \lesssim 500$ MeV/nuc. Results reported here use data collected under solar minimum conditions between August 1997 and December 1998. The CRIS instrument and data analysis techniques are described by Stone et al. (1998). A more detailed report of the CRIS analysis of cosmic ray ^{59}Ni and ^{59}Co has been given by Wiedenbeck et al. (1999a).

CRIS mass histograms for Fe, Co, and Ni are shown by Wiedenbeck et al. (1999b), who report on the source composition of the primary isotopes of these elements. These same data were used in the present work. Figure 1 shows the ^{58}Ni through ^{60}Ni region plotted with a logarithmic vertical scale to emphasize the ^{59}Ni which is of interest for this acceleration time

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delay study. The smooth curve shows the fitted mass distribution. Although a finite abundance of ^{59}Ni is obtained from the fit, we report an upper limit for ^{59}Ni because of possible spill-over from ^{58}Ni and ^{60}Ni.

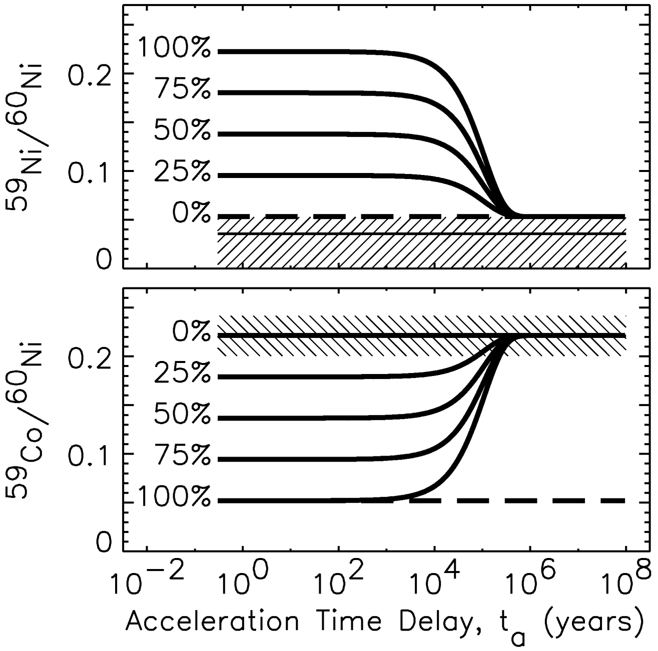

Figure 2. Calculated time evolution of the abundances of the radionuclide ^{59}Ni and its daughter product ^{59}Co. Hatched bands represent the CRIS measurements with 1σ uncertainties. The dashed lines show the secondary contributions to the two isotopes.

A leaky box propagation calculation was performed (Wiedenbeck et al., 1999b) to determine the secondary contributions to ^{59}Ni, ^{59}Co, ^{57}Co, and ^{57}Fe. Subtracting these from the observed abundances yields the composition of the accelerated material, after any electron capture decays have occurred. Since these decays alter the charge but not the mass of the nuclei, the totals $^{59}\mathrm{Co} + {}^{59}\mathrm{Ni}$ and $^{57}\mathrm{Fe} + {}^{57}\mathrm{Co}$ in the accelerated population are unchanged from the values in the synthesized material (barring other fractionation processes). Figure 2 compares the observed abundances (hatched regions) with the values expected for various assumed time delays and synthesized fractions of the isobars with $A = 59$. For example, the curves labeled 100% show how the observed abundances of ^{59}Ni and ^{59}Co depend on the delay time: for times short compared to the 7.6×10^5 yr halflife, the observed ^{59}Co is entirely secondary while the ^{59}Ni contains all of the $A = 59$ primaries plus a small secondary contribution. At delay times close to the halflife the primary composition changes from being dominated by ^{59}Ni to being dominated by ^{59}Co as a result of the decays.

Figure 2 shows that the observed abundances are consistent with essentially complete decay of ^{59}Ni, leading to the conclusion that the time delay between nucleosynthesis and acceleration is $\gtrsim 10^5$ yr. This interpretation depends on the assumption that $\gtrsim 20\%$ of the $A = 59$ material was synthesized in the form of ^{59}Ni. As discussed by Wiedenbeck et al. (1999a), numerical calculations of nuclide yields from core collapse supernovae (SN II) indicate that the ^{59}Ni fraction should be at least this large for supernovae resulting from progenitor stars of all the masses that contribute significantly to iron-group abundances.

We also find that abundances of ^{57}Co and ^{57}Ni are consistent with the complete decay of the primary ^{57}Co (Wiedenbeck et al., 1999a). This is expected since the halflife of ^{57}Co is much shorter than that of the ^{59}Ni. However, the ^{57}Co result does provide a useful cross check on the overall validity of the model.

3. Discussion:

The constraints on the time delay between nucleosynthesis and acceleration that we obtain from the CRIS observations of the mass 57 and mass 59 nuclides can be used to help distinguish between the alternative models for the origin of cosmic rays. In the Meyer, Drury, & Ellison (1997) model the cosmic ray seed population is the general interstellar gas and dust which, on average, was synthesized at least several billion years ago and is easily consistent with the decay of the cosmic ray ^{59}Ni.

In the model of Lingenfelter, Ramaty, & Kozlovsky (1998) the cosmic rays are accelerated from fresh supernovae ejecta, which must occur on a time scale not exceeding the $\sim 10^4$ yr that it takes for the supernova energy to dissipate. This is clearly in conflict with the ^{59}Ni observations. One may be able to get around this constraint by assuming exceptional conditions for the synthesis or acceleration of the cosmic rays. If cosmic rays were produced predominantly by stars in a very restricted mass range that strongly favors production of $A = 59$ nuclides as ^{59}Co rather than ^{59}Ni then a long delay time would not be essential. Such special conditions seem improbable given the strong similarity of cosmic ray source and solar system abundances over a broad range of elements and isotopes (Meyer & Ellison, 1999; Wiedenbeck et al., 1999b). Another possibility is that cosmic rays are initially accelerated out of the fresh supernovae ejecta to an intermediate energy ($\lesssim$150 MeV/nuc) where at least one orbital electron can be retained a significant fraction of the time. If the particles were to spend $\gtrsim 10^5$ yr at this energy before undergoing subsequent additional acceleration to the the energies at which they undergo most of their propagation, the ^{59}Ni decay could still occur. This possibility, for which we know of no direct evidence, is difficult to exclude because the effects on observed spectra and composition (other than electron capture primaries) are likely to be small.

The Higdon, Lingenfelter, & Ramaty (1998) model posits that cosmic rays mostly originate in superbubbles where the ejecta from supernovae can reside unmixed with the general interstellar gas for times long compared to the 10^5 yr delay time required by the ^{59}Ni and ^{59}Co data. This material, accelerated by shocks from subsequent supernovae which occur after the ^{59}Ni has decayed, could have the composition of fresh supernovae ejecta except for the electron capture primaries and the daughters produced by their decays. This picture does not conflict with the results reported here. However, as discussed by Meyer & Ellison (1999) and Wiedenbeck et al. (1999b), the cosmic ray source composition appears to require contributions from Type Ia supernovae (SN Ia) as well as SN II. The SN Ia arise from low mass stars in binary systems which evolve for more than a billion years before exploding. Thus one does not expect SN Ia, or their nucleosynthesis products, to be associated with superbubbles, which disperse on much shorter time scales.

Based on the long time delay between nucleosynthesis and cosmic ray acceleration and on the great similarity of the isotopic composition of cosmic ray source material to that of solar system matter, it appears that one must look to the general interstellar medium for the cosmic ray seed population. Alternatively, the seed material might arise from stellar atmospheres where the abundances would reflect those of the interstellar matter from which the star formed (Meyer, 1985). In either case an additional source appears to be needed to provide the large abundance of ^{22}Ne found in cosmic rays (Meyer, Drury, & Ellison, 1997).

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