LiBeB, Cosmic Rays and Related X- and Gamma-Rays
ASP Conference Series, Vol. 171, 1999
R. Ramaty, E. Vangioni-Flam, M. Cassé and K. Olive, eds.

Measurements of the Isotopic Abundances of Galactic Cosmic Rays and their Implications for Cosmic Ray Origin

W. R. Binns, P. L. Hink, J. Klarmann, and M. L. Lijowski

Washington University, St. Louis, MO 63130

E. R. Christian and T. T. von Rosenvinge

NASA/Goddard Space Flight Center, Greenbelt, MD 20771

A. C. Cummings, R. A. Leske, R. A. Mewaldt, E. C. Stone, and J. S. George

California Institute of Technology, Pasadena, CA 91125

M. E. Wiedenbeck and N. E. Yanasak

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109

Abstract. We present measurements of the nickel and cobalt isotopes from the Cosmic Ray Isotope Spectrometer (CRIS) which was launched in August, 1997 aboard the NASA Advanced Composition Explorer (ACE). The objectives of CRIS are to measure the isotopic abundances and energy spectra of galactic cosmic rays (GCRs) with $3 \leq Z \leq 30$. We find that for these nuclei the measured ^{59}Ni/^{60}Ni and ^{59}Co/^{60}Ni ratios imply a time delay between nucleosynthesis and acceleration to cosmic ray energies of $> 10^5$ y.

1. Introduction

The Cosmic Ray Isotope Spectrometer (CRIS) was launched in August, 1997 aboard NASA's Advanced Composition Explorer (ACE) into a halo orbit about the L1 libration point, a point of unstable equilibrium located along the Earth-Sun line roughly 1.5 million kilometers toward the Sun, well outside the Earth's magnetosphere. The objectives of the CRIS experiment are to measure the isotopic abundances of galactic cosmic rays (GCRs) with $3 \leq Z \leq 30$ and to determine their energy spectra over the energy range of ~50–500 MeV/nuc. The geometrical factor of CRIS (~250 cm^{2}sr) is considerably larger than previous isotope spectrometers in space and has resulted in improved statistical samples of rare nuclei such as ^{59}Ni and ^{59}Co presented in this paper.

There are three principal models that have recently been discussed as possibilities for the origin of cosmic rays. It has been known for many years that the abundances of cosmic ray nuclei that have a low first ionization potential (FIP) are preferentially enhanced over those of high-FIP elements (Casse & Goret

1978). A similar pattern is also observed in the solar corona, solar energetic particles, and solar wind. This led to models in which it was postulated that nuclei were injected and preaccelerated into the cosmic radiation from stellar atmospheres, and then later accelerated to cosmic ray energies by supernovae shocks (Ferrando 1993; Meyer 1985).

It was also noticed that the chemical volatility of elements exhibits a very similar pattern to that of FIP, such that most elements with a low-FIP are refractory (low volatility) and most with a high-FIP have high volatility. Cesarsky and Bibring (1980) suggested that the cosmic ray elemental abundances are not controlled by FIP, but instead are controlled by volatility. This model has recently been developed in more detail by Meyer et al. (1997) who have pointed out that in addition to a general enhancement of refractory over volatile elements, for the volatile elements there appears to be an enhancement of high mass over that of low mass cosmic ray nuclei. In this model then, the source of cosmic rays is gas and dust of the interstellar medium (ISM) accelerated by supernova shocks. The enhancement of refractory elements is attributed to acceleration of those nuclei to cosmic ray energies after they sputter off of grains that have already been accelerated by the shock.

On the other hand, evidence for the direct acceleration of supernova material has recently been developed (Higdon et al. 1998; Lingenfelter et al. 1998). They note the observed constancy of the Be/Fe ratio over a wide range of metallicities. Be is believed to have a spallogenic origin, being produced almost entirely by interactions of primary C, N, and O cosmic rays (Reeves 1994; Ramaty et al. 1998). The constancy of Be/Fe with time is interpreted as requiring "cosmic ray acceleration of freshly synthesized matter in supernovae and not from the interstellar medium" (Higdon et al. 1998).

Measurements of ^{59}Ni which decays only by electron capture, and its daughter product ^{59}Co, can constrain these models of cosmic ray origin since these abundances provide a measure of the time lapse between nucleosynthesis and acceleration (Soutoul et al. 1978). In this paper we present high resolution measurements of the nickel and cobalt isotopes and discuss the implications for the origin of galactic cosmic rays.

2. Instrument Description

The method of mass identification used in CRIS is the multiple-dE/dx+ total-energy method. In Figure 1 we show the CRIS instrument schematic. CRIS consists of silicon detectors that measure dE/dx and total energy and also provide guard counters (not shown in Figure 1) to help reject interacted, penetrating, or side exiting particles, and a scintillating fiber hodoscope to measure trajectory. The silicon detectors are composed of four identical stacks of fifteen 3 mm thick silicon wafers with diameter 10 cm. The hodoscope is composed of three x, y planes of scintillating fibers with active area 26 cm × 26 cm and fiber size 200 microns square. In addition, there is a fourth fiber plane on top that is used as a trigger signal for the CRIS event logic. The hodoscope fibers are proximity focused onto the face of an image intensifier, the output of which is coupled onto a CCD array. The fiber images projected onto the CCD are read out with each event and are used for deriving the path of each particle through

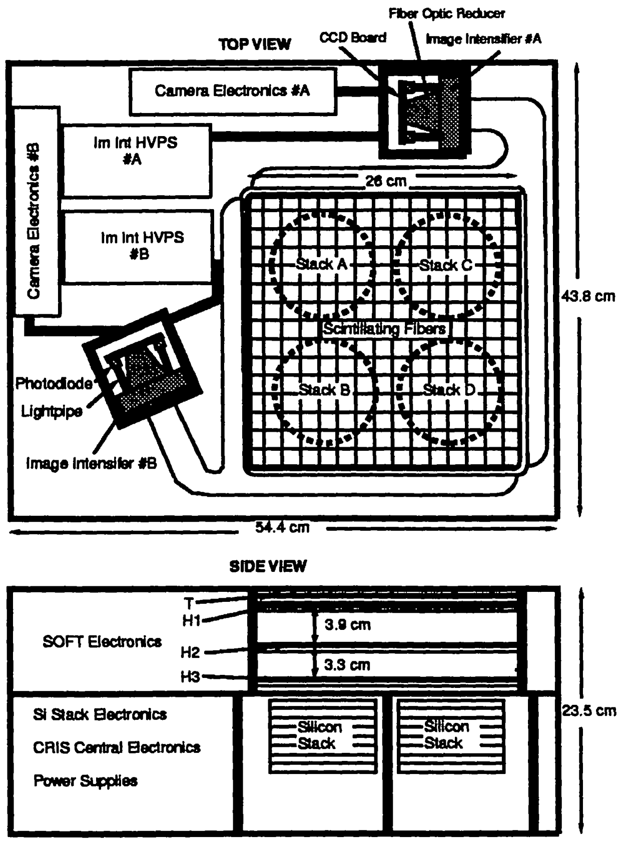

Figure 1. CRIS instrument schematic.

the instrument. The trigger fibers are proximity focused onto two regions of the image intensifer input that are not used by the hodoscope fibers, and the corresponding outputs are coupled onto two silicon photodiodes from which the trigger signals are obtained. A second image-intensified CCD system shown in Fig. 1 is a redundant system that will be used only if the first system fails. For a detailed description of the instrument see Stone et al. (1998).

3. CRIS Science Objectives

For the charge range that is accessible to the CRIS instrument $3 \leq Z \leq 40$ the isotopes can be divided into six separate groups, each of which provides a specific type of information (Figure 2). Galactic cosmic rays are divided broadly into primary and secondary components. The primary cosmic rays are those with measured abundances at Earth composed mostly of nuclei that have not interacted during propagation through the ISM. Secondary cosmic rays are those which have a substantial fraction that are products of interactions of heavier cosmic rays during propagation. These two classes can each be subdivided into three additional classes: nuclei that are stable, radioactive nuclei decaying by β-decay, and radioactive nuclei decaying only by electron-capture. The stable primary cosmic rays are useful for studying nucleosynthesis of GCRs and making

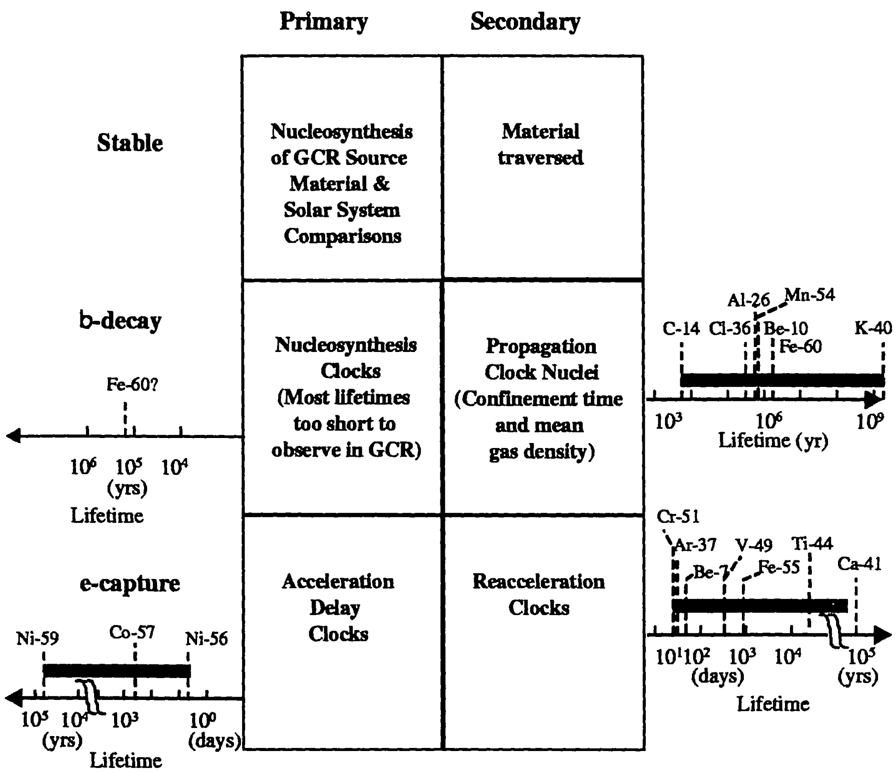

Figure 2. Isotope groups.

comparisons with possible source compositions (e.g., solar-system abundances). Stable secondaries can be used to study the amount of material traversed by the cosmic rays as they propagate through the galaxy. Primary nuclei decaying by β-decay could be used, in principle, as clocks that measure the time between nucleosynthesis and detection at Earth. However, in this charge range the lifetimes are too short to be useful. A variety of secondary radioactive isotopes that decay by β-decay with lifetimes ranging from 5.7×10^3 to 1.3×10^9 y can be studied to determine the mean gas density and confinement time of cosmic rays in the galaxy. Primary isotopes that decay only by electron-capture are useful for studying the time delay between nucleosynthesis and acceleration to cosmic ray energies. The principal isotope of interest is ^{59}Ni, which has a lifetime 7.6×10^4 y, although shorter lifetime isotopes shown in Figure 2 are also of interest. Secondary nuclei that decay only by electron capture are useful for studying possible reacceleration by successive supernova shocks of nuclei as they travel through the galaxy (Letaw, 1985). A number of such nuclei are available for study with lifetimes spanning a range from a few tens of days up to 10^5 y.

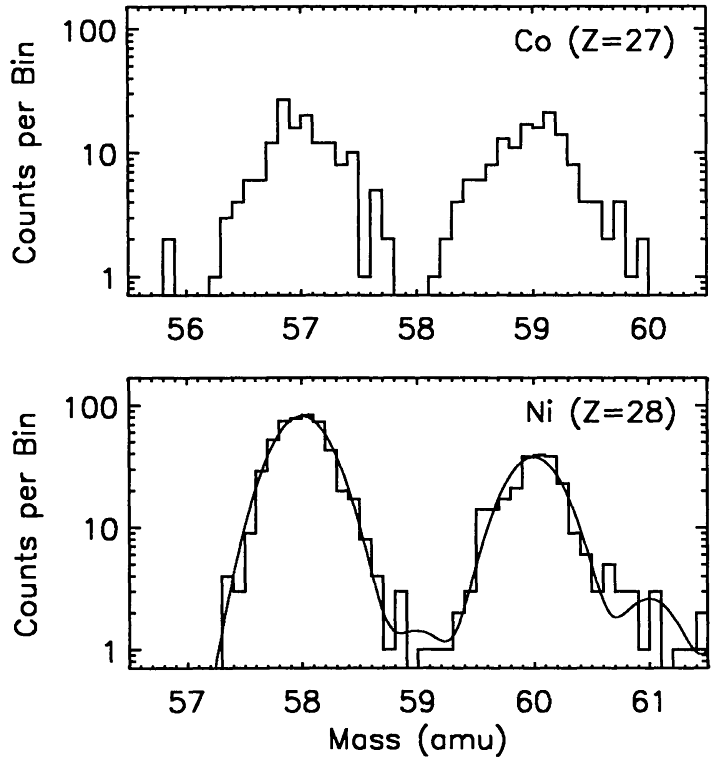

Figure 3. Distribution of measured masses of cobalt (top panel) and nickel (bottom panel) nuclei measured by CRIS from 28 August 1997 through 18 December 1998. Cobalt data are selected for trajectory angle $\leq 62°$, and nickel data are selected for angles $\leq 20°$.

4. Observations

Figure 3 shows histograms of the cobalt and nickel isotopic abundances (Wiedenbeck et al. 1999) observed from 28 August 1997 through 18 December 1998. The mass resolution of CRIS is best at narrow angles. Nickel is relatively abundant so we could confine the analysis of this element to angles $\leq 20°$, thus minimizing particles that might be misidentified as ^{59}Ni, and still have a sufficient statistical sample. The cobalt isotopes are considerably more rare, and the two isotopes are separated by 2 mass units, so a broader range of trajectory angles $\leq 62°$ (nearly the full instrument aperture) was used in the analysis.

We observe clearly resolved peaks for ^{58}Ni and ^{60}Ni with very few particles in the ^{59}Ni region. Likewise we see clearly resolved peaks for ^{59}Co, which is the daughter product of ^{59}Ni electron capture decay, and for ^{57}Co which also decays only by electron capture but has a half-life of 272 days and so is expected to be present in the cosmic rays primarily as a fragmentation product of ^{58}Ni and ^{60}Ni nuclear interactions. It is clear from Figure 3 that if a significant amount of ^{59}Ni was present at the source, all or nearly all of it has decayed.

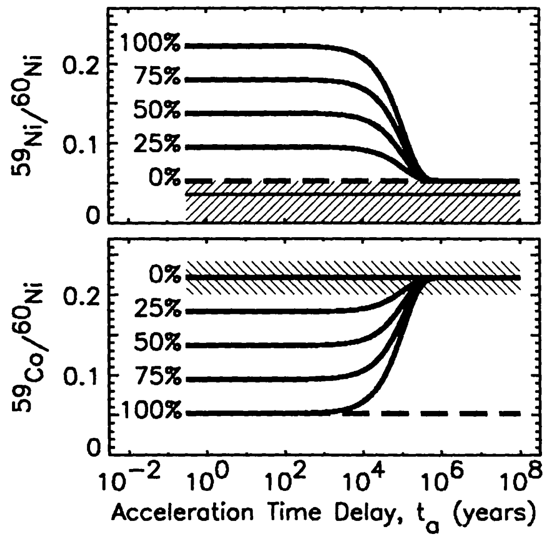

Figure 4. The calculated ratios of ^{59}Ni/^{60}Ni (top panel) and ^{59}Co/^{60}Ni (bottom panel) are plotted vs. the time delay between nucleosynthesis and acceleration. The contours are labeled according to the fraction of mass-59 nuclei synthesized as ^{59}Ni. The ratios derived from the CRIS data are shown as a hatched area that represents one standard deviation uncertainties.

In Figure 4 we plot the calculated ^{59}Ni/^{60}Ni and ^{59}Co/^{60}Ni ratios (^{60}Ni is the only important contributor of mass-59 secondaries) as a function of the time delay between nucleosynthesis and acceleration to energies sufficient to fully strip the nuclei so that decay by electron capture is no longer possible (Wiedenbeck et al. 1999). The contours plotted in both the top and bottom panel are labeled according to the fraction of mass-59 nuclei originally synthesized as ^{59}Ni (*i.e.*, $f_0 = {}^{59}\text{Ni}/({}^{59}\text{Ni}+{}^{59}\text{Co})$). The calculated abundances are a combination of this originally synthesized fraction as a function of time (assuming that ^{59}Ni decays into ^{59}Co with its electron capture halflife of 7.6×10^4 y) and secondary contributions from spallation of ^{60}Ni. If there is no ^{59}Ni at the source, we still expect the ^{59}Ni/^{60}Ni to be ~5%. Likewise if there is no ^{59}Co at the source, we expect ^{59}Co/^{60}Ni to be ~ 5% from secondary contributions alone, and this ratio increases as ^{59}Ni decays. The ratios derived from the CRIS data are shown as a hatched area that represents one standard deviation uncertainties. The ^{59}Ni/^{60}Ni ratio is presented as an upper limit since there is no observable peak. Our calculation of the secondary contributions to ^{59}Ni and ^{59}Co in Figure 4 are preliminary, but future refinement of these values is not expected to change our conclusion that essentially all of the primary ^{59}Ni has decayed.

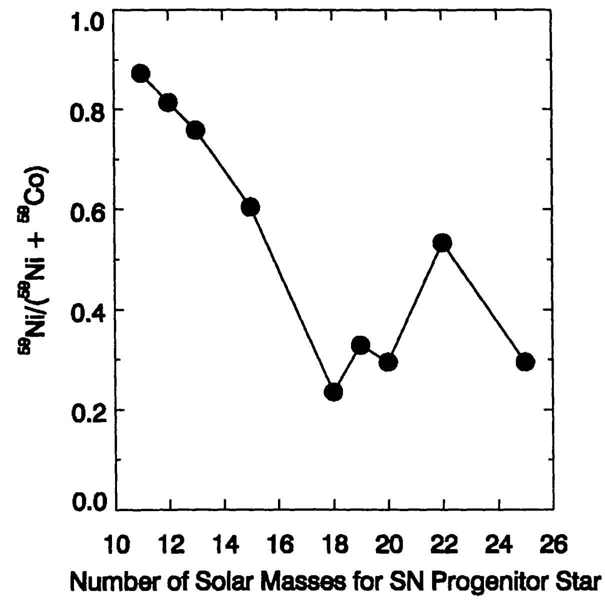

Figure 5. The ratio $f_0 = {}^{59}\mathrm{Ni}/({}^{59}\mathrm{Ni}+{}^{59}\mathrm{Co})$ of ejected mass from type II supernovae is plotted as a function of mass of the SN progenitor star (Woosley et al. 1995).

5. Discussion and Conclusions

The crucial question then is what fraction of mass-59 nuclei do we expect to be synthesized as ^{59}Ni. Using the modeling results of Woosley and Weaver (1995), we have calculated the ratio $f_0 = {}^{59}\mathrm{Ni}/({}^{59}\mathrm{Ni}+{}^{59}\mathrm{Co})$ of ejected mass from type II supernovae as a function of mass of the SN progenitor star (Figure 5). We see that the range of values goes from about 23% to 87%. Assuming that the cosmic ray seed material comes from a mix of sources similar to the general population of stars in our galaxy, a mean of the SN progenitor star masses weighted by an appropriate mass distribution gives an estimate of a best value for f_0. Using a Salpeter initial mass function (proportional to $m^{-2.35}$ where m is the mass of the star when it forms) and integrating over mass, results in an average $f_0 \sim 60\%$ (Wiedenbeck, et al. 1999). To be consistent with the CRIS measurements, if $t_a < 10^5$ y, f_0 would have to be near zero which is inconsistent with the Woosley and Weaver calculated mass fraction f_0. Thus we see from Figure 4 that our data imply that ^{59}Ni has decayed, *i.e.*, they require a time delay between nucleosynthesis and acceleration significantly greater than the ^{59}Ni halflife of 7.6×10^4 y, provided that a significant fraction of the mass 59 nuclei are synthesized as ^{59}Ni.

We conclude that the measured ^{59}Ni/^{60}Ni and ^{59}Co/^{60}Ni ratios show that the seed material from which these cosmic rays were accelerated has spent $\geq 10^5$ y in an environment where electron capture decay can occur. This conclusion depends on the assumption that a significant fraction of the mass-59 material was synthesized as ^{59}Ni, as indicated by supernova model calculations (e.g., Woosley & Weaver 1995). For these nuclei, prompt supernova shock acceleration of freshly synthesized individual nuclei is ruled out, as is acceleration of particles from freshly synthesized grains in times much less than 10^5 y. Our data are consistent with models in which the cosmic ray seed material originates in ISM dust and gas, material from stellar atmospheres, or "nearly fresh" SN material in the form of grains sputtered and accelerated on time scales of 10^5 y.

Acknowledgments. We are grateful to the large number of individuals that contributed significantly to the development of the CRIS instrument (listed in Stone et al. 1998). This research has been supported by NASA at the California Institute of Technology (grant NAG5-6912), the Goddard Space Flight Center, the Jet Propulsion Laboratory, Washington University in St. Louis.

References

Casse, M., and Goret, P. 1978, ApJ 221, 703

Cesarsky, C. J. and Bibring, J. P. 1980, IAU Symp. 94 "Origin of Cosmic Rays", Dordrecht: Reidel, 393

Ferrando, P. in 1993 Proceedings of the XXIII International Cosmic Ray Conference, Invited, Rapporteur, and Highlights volume, Ed. Leahy, Hicks, and Venkatesan, World Scientific, 279

Higdon, J. C., Lingenfelter, R. E., Ramaty, R. 1998, ApJ, 509, L33

Letaw, J. R., 1985, Astrophys. and Space Sci., 114, 365

Lingenfelter, R. E., Ramaty, R., and Kozlovsky, B. 1998, ApJ, 500, L153

Meyer, J. P. 1985, ApJS, 57, 173

Meyer, J. P., Drury, L. O'C., and Ellison, D. C. 1997, ApJ, 487, 182

Ramaty, R., Kozlovsky, B., and Lingenfelter, R. 1998, Phys. Today, 51:4, 30

Reeves, H. 1994, Rev. Mod. Phys. 66, 193

Soutoul, A., Casse, M., and Juliusson, E., 1978, ApJ. 219, 753

Stone, E. C., Cohen, C. M. S., Cook, W. R., Cummings, A. C., Gauld, B., Kecman, B., Leske, R. A., Mewaldt, R. A., Thayer, M. R., Dougherty, B. L., Grumm, R. L., Milliken, B. D., Radocinski, R. G., Wiedenbeck, M. E., Christian, E. C., Shuman, S., von Rosenvinge, T. T. Binns, W. R., Dowkontt, P., Epstein, J. W., Hink, P. L., Klarmann, J., Lijowski, M., and Olevitch, M. A. 1998, Space Sci. Rev., 86, 283

Wiedenbeck, M. E., Binns, W. R., Christian, E. R., Cummings, A. C., Dougherty, B. L., Hink, P. L., Klarmann, J., Leske, R. A., Lijowski, M., Mewaldt, R. A., Stone, E. C., Thayer, M. R., von Rosenvinge, T. T., and Yanasak, N. E. 1999, ApJL, Submitted for publication

Woosley, S. E. and Weaver, T. A. 1995, ApJS, 101, 181