OG 1.1.05

Secondary Electron-Capture Clock Isotopes as a Probe of Reacceleration

S.E. Mahan[1], W.R. Binns[1], E.R. Christian[4], A.C. Cummings[2], J.S. George[2], P.L. Hink[1], J. Klarmann[1], R.A. Leske[2], M. Lijowski[1], R.A. Mewaldt[2], E.C. Stone[2], T.T. von Rosenvinge[4], M.E. Wiedenbeck[3], and N.E. Yanasak[3],
[1] *Washington University, St. Louis, MO 63130 USA*
[2] *California Institute of Technology, Pasadena, CA 91125 USA*
[3] *Jet Propulsion Laboratory, Pasadena, CA 91109 USA*
[4] *NASA/Goddard Space Flight Center, Greenbelt, MD 20771 USA*

Abstract

Cosmic rays that are produced by nuclear interactions during propagation and decay only by electron capture can be used to determine the level of cosmic ray reacceleration that has occurred. The high resolution, large statistical sample of cosmic rays collected by the Cosmic Ray Isotope Spectrometer (CRIS) aboard the Advanced Composition Explorer (ACE) spacecraft provides a data set that allows precision measurements of these isotopic abundances. We discuss electron capture decay, the signatures of reacceleration, and the sensitivity with which reacceleration models can be tested.

1 Introduction:

Secondary electron-capture isotopes are unique probes of cosmic-ray reacceleration. Electron capture is inhibited at the high energies typical of cosmic rays, since orbital electrons which allow electron capture to occur are stripped from these nuclei; electron-capture isotopes can only decay substantially at lower energies, where they have a significant probability of electron attachment. Electron capture decay of ^{51}Cr, for example, is rare at energies greater than 800 MeV/nucleon (Silberberg *et al.* 1983). A comparison of secondary electron-capture isotopes of a given charge (at energies where they are expected to be fully stripped of electrons) with the abundances expected from fragmentation of primary cosmic rays in the interstellar medium should reveal whether radioactive decay and subsequent reacceleration occurred.

The use of secondary electron-capture isotopes to study cosmic ray propagation and the acceleration process has been discussed, e.g., by Raisbeck *et al.* (1973, 1975), Letaw (1984), Silberberg and Tsao (1990), and recently by Soutoul *et al.* (1998) using Voyager and ISEE-3 data. The CRIS data set, described here, has the mass resolution and number of events necessary to determine whether the measured isotopic abundances differ from abundances predicted by the standard leaky-box model (e.g. Leske 1993) and energy-dependent survival curves (e.g. Raisbeck *et al.* 1975). This paper will discuss one approach to studying possible reacceleration of cosmic rays during propagation through the interstellar medium and show the mass resolution for these isotopes now available in the CRIS data set.

2 Secondary Electron-Capture Decay Isotopes:

The seven electron-capture isotope pairs listed in table 1 may be used to probe the energy history of the cosmic rays. All seven parent isotopes (^{7}Be, ^{37}Ar, ^{44}Ti, ^{49}V, ^{51}Cr, ^{55}Fe, and ^{57}Co) are secondary isotopes, created by fragmentation of heavier cosmic rays as they propagate through the interstellar medium. These seven isotopes decay only by electron capture; they require the presence of orbital electrons to decay. Their half-lives with a single K shell electron (approximately twice the laboratory half-life in the table below, as explained in Wilson, 1978) range from several days to several years, significantly less than the 10^{5} year delay between nucleosynthesis and acceleration indicated by the Co and Ni isotopic ratios (Wiedenbeck *et al.*1999). Since nuclei with such short half-lives as these would have decayed during this 10^{5} year delay, these isotopes in the cosmic rays must have been produced as secondaries during galactic propagation. If these secondary nuclei remained at high energies throughout transport, then only a small fraction would decay (reflecting the small possibility that a nucleus at such an energy would have an orbital electron). If measured abundances of the daughter isotopes are much greater than the abundances expected from primary production in the source and secondary production during propagation, electron capture may have occurred. If large abundances of these daughter isotopes and correspondingly smaller abundances of the parent isotopes are measured in the CRIS data set, we may conclude that the cosmic rays spent some time at lower energies, electron-capture decay occurred, and the nuclei were subsequently reaccelerated. With sufficient mass resolution and updated propagation models, we expect to set limits on the amount of cosmic-ray reacceleration during propagation.

Parent	Laboratory Half-Life	Daughter
^{7}Be	53 days	^{7}Li
^{37}Ar	35 days	^{37}Cl
^{44}Ti	67 years	^{44}Sc → ^{44}Ca
^{49}V	337 days	^{49}Ti
^{51}Cr	27.7 days	^{51}V
^{55}Fe	2.7 years	^{55}Mn
^{57}Co	272 days	^{57}Fe

Table 1. Selected electron-capture isotope decay pairs

3 Reacceleration:

Cosmic-ray nuclei may be accelerated to high energies during ejection from supernovae (Ramaty *et al.* 1997), or by interaction of interstellar dust grains and gas with supernova shock waves (Meyer, Drury, and Ellison 1997), or in other, as yet unknown, processes. These nuclei subsequently encounter interstellar material, where energy loss occurs. It is quite plausible that the converse is also true – that cosmic-ray nuclei can encounter moving magnetic irregularities in the interstellar medium during propagation that boost their energy and cause acceleration. Letaw (1993) and others posit that these cosmic rays encounter supernova remnant shocks and are accelerated to high energies through distributed reacceleration. Heinbach and Simon (1995) propose instead a diffusive reacceleration, whereby particles encounter turbulent magnetic fields and gain large amounts of energy.

Analysis of the abundances of secondary electron-capture isotopes, and the energy dependence of these abundances, can reveal new information about the type and amount of reacceleration that has occurred. The first-order question, whether reacceleration occurred, may be answered by comparing the measured abundances of electron capture decay isotopes with the abundances predicted by a leaky-box model such as Leske (1993), subject to uncertainties in the measurements, nuclear fragmentation cross sections, and electron-capture rates. If electron-capture isotope decays are evident, then we know that the cosmic rays spent time at lower energies at some point during propagation and reacceleration subsequently occurred. If no electron-capture isotope decays are evident, then significant interstellar reacceleration is ruled out.

A second approach may reveal the amount of reacceleration that occurred. The CRIS data set is large enough to be divided into several distinct energy bins, with enough events per energy bin to perform realistic peak-fitting and calculation of isotopic ratios for most isotopes of interest. As CRIS continues to collect data, the data set (adjusted for solar modulation level) may be divided into even finer energy bins without sacrificing statistics. More high-energy bins will be added, as the interplanetary adiabatic energy loss increases during the approach to solar maximum. This greater number of events, over a larger energy range, will better enable us to examine energy dependence of electron capture decays in secondary cosmic rays.

If electron capture decay isotope abundances in different energy regimes vary, they (or their surviving fraction, relative to secondary production) can be plotted as functions of energy in interstellar space. Since survival depends on the energy at which they propagate through the galaxy, we can model expected abundances also as a function of interstellar energy, producing isotope survival curves. Raisbeck *et al.* (1973, 1975) and others (Letaw *et al.* 1985, Silberberg and Tsao 1990) have advocated the use of energy-dependent survival curves to study reacceleration of cosmic rays, the density of the formation medium, relative production probabilities, density variations in the propagation medium, and the duration of cosmic ray containment in the halo. When appropriate values are chosen for the density of the propagation medium and other variables, the survival versus energy curves can be used as another test of reacceleration.

By comparing measured abundances with abundances predicted by various models, we can determine whether electron-capture decay has occurred, whether different energy cosmic rays experienced different amounts of decay, and whether there is agreement with calculated survival curves and their predictions.

4 Instrumentation:

The Cosmic Ray Isotope Spectrometer (CRIS) on the ACE satellite is designed to detect cosmic rays with charge 3 to 30 (lithium to zinc) with a large collecting power (geometrical factor of 250 cm^2 sr) and excellent mass resolution (< 0.25 amu for iron). CRIS consists of a scintillating optical fiber trajectory (SOFT) hodoscope and four silicon solid-state detector telescopes. The SOFT hodoscope, which has three *xy* scintillating fiber planes and a trigger fiber plane, is used to determine trajectories of incident nuclei. The silicon detector telescopes, each a stack of 15 silicon wafers with individual thicknesses 3 mm, are used to determine particle charge and mass, using dE/dx and total energy measurements. The instrument is described more completely in Stone *et al.* (1998).

The nominal energy range of the detector is 50 – 500 MeV/nucleon, depending on charge. The energy range for detection of Ar nuclei, for example, is 95 – 470 MeV/nucleon, which, using the simplest force-field approximation of solar modulation for the first year of CRIS data collection, translates to energies of approximately 315 – 690 MeV/nucleon at heliospheric entry. The large collecting power yields a first-year data set that is already statistically large enough to study even the less-abundant secondary electron capture decay isotopes.

5 Measurements:

Initial analysis of the CRIS data set confirms good peak separation even for previously indistinguishable isotopes of elements such as vanadium and titanium. A preliminary histogram for argon isotopes is shown below. The excellent mass resolution allows very accurate determination of relative abundances.

Soutoul *et al* (1998) have used the vanadium isotopic measurements of Voyager and ISEE-3 to estimate that as much as 25% of the electron capture isotopes ^{51}Cr and ^{49}V decayed during propagation at an energy approximately 100 MeV/nucleon less than their observed energy. This result came from comparisons of the $^{51}\mathrm{V}/^{49}\mathrm{V}$ ratio and the nuclear fragmentation cross sections reported by Webber, Kish, and Schrier in 1980. More recent nuclear cross sections (Webber *et al*, 1998) that incorporate energy dependence will improve estimates of production of secondary isotopes by fragmentation during propagation. The CRIS mass resolution also will allow a more precise calculation of the $^{51}\mathrm{V}/^{49}\mathrm{V}$ ratio, leading to a better estimate of the amount of and energy at which electron capture decay occurred.

We can similarly study the problem using all seven of the electron capture decay pairs, both parent and daughter, for each decay. A thorough examination of the problem requires study of several isotopes with various half-lives, at various energies. It is already possible, however, to begin to set limits on the amount of reacceleration that has occurred. The histogram below shows that ^{37}Ar, an electron capture decay isotope with a laboratory half-life of 35 days, is present in the cosmic rays. Since ^{37}Ar has not completely decayed, the cosmic rays in this energy interval spent a limited amount of time at lower energies. By comparing this abundance to the abundance predicted using the electron stripping and attachment cross sections, as well as results from the leaky-box propagation model, limits can be set on the reacceleration of the cosmic rays.

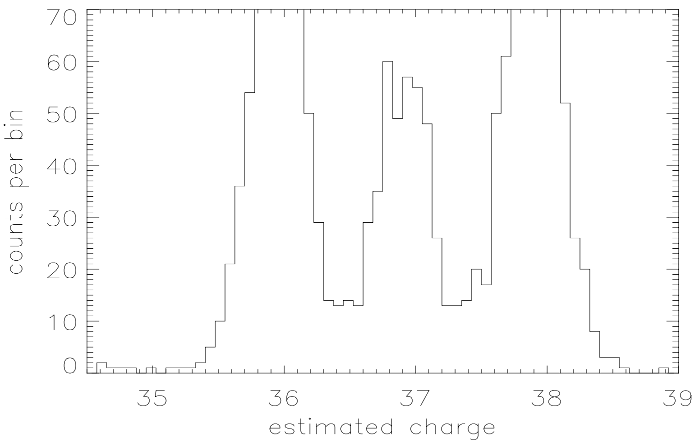

Figure 1. Ar isotopes with angle, trajectory, and dead layer restrictions

6 Conclusions:

The high statistics and good mass resolution of the CRIS data set enable us to study secondary electron-capture decay isotopes and their decay products, use their abundances to probe whether acceleration occurred in the cosmic rays, and set limits on the amount of reacceleration that has occurred. If electron capture decay has occurred, and yet the cosmic rays are measured at high interstellar energies (after accounting for solar modulation), then reacceleration did indeed occur. This problem can be further studied by comparing the energy dependence of the abundance of these isotopes to abundances predicted by energy-dependent model survival curves.

Acknowledgements: This research was supported by NASA at the California Institute of Technology (under grant NAG5-6912), the Jet Propulsion Laboratory, the Goddard Space Flight Center, and Washington University.

References

Heinbach U. and Simon M. (1995) ApJ 441: 209-221.
Leske, R. A. (1993) ApJ 405: 567-583.
Letaw J. R., Adams J.H., Silbeberg R., and Tsao C. H. (1985) Ap&SS 114: 365-379.
Letaw J. R., Silberberg R., and Tsao C. H. (1993) ApJ 414 (2): 601-611.
Letaw J. R., Silberberg R., and Tsao C. H. (1984) ApJ 56: 369-391.
Meyer J. P., Drury L.O'C., and Ellision D. C. (1997) ApJ 487: 182-196.
Raisbeck G., Perron C., Toussaint J., and Yiou F. Proc. 13th ICRC (Denver, 1973) 2:534-539.
Raisbeck G. M., Comstock G., Perron C., and Yiou F. Proc. 14th ICRC (Munich, 1975) 2: 560-563.
Ramaty R., Kozlovsky B., Lingenfelter R. E., and Reeves, H. (1997) ApJ 488: 730-748.
Silberberg R., Tsao C. H., Letaw J. R., and Shapiro M. M. (1983) Phys. Rev. Lett. 51(13): 1217-1220.
Silberberg R. and Tsao C. H. (1990) Phys. Rep. 191 (6): 351-408.
Silberberg R., Tsao C. H., and Barghouty A. F. (1998) ApJ 501: 911-919.
Soutoul A., Legrain R., Lukasiak A., McDonald F. B., and Webber W. R. (1998) A&A 336: L61-L64 .
Stone E. *et al.* (1998) SSRv 86: 285-356.
Tsao C. H., Silberberg R., and Barghouty A. F. (1998) ApJ 501: 920-926.
Webber W. R., Kish J. C., and Schrier D. A. (1990) Phys. Rev. C. 41, 547-565.
Webber W. R., *et al.* (1998) Phys. Rev. C. 58(6): 3539-3552.
Wilson, L. (1978) Ph.D. thesis, University of California at Berkeley.
Wiedenbeck M. E. *et al.* (1999) submitted to ApJ.