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The isotopic composition of cosmic-ray calcium

M. E. Wiedenbeck[1], J. S. George[2], W. R. Binns[3], E. R. Christian[4], A. C. Cummings[2], A. J. Davis[2], M. H. Israel[3], R. A. Leske[2], R. A. Mewaldt[2], E. C. Stone[2], T. T. von Rosenvinge[4], and N. E. Yanasak[2]

[1]Jet Propulsion Laboratory, California Institute of Technology Pasadena, CA 91109 USA
[2]California Institute of Technology, Pasadena, CA 91125 USA
[3]Washington University, St. Louis, MO 63130 USA
[4]NASA/Goddard Space Flight Center, Greenbelt, MD 20771 USA

Abstract.
The isotopic composition of galactic cosmic-ray Ca has been measured over the energy range ~ 150 to 400 MeV/nuc on the Advanced Composition Explorer (ACE) mission. Using the measured abundances of the dominantly-secondary Ca isotopes with $A = 41$–46 as constraints, in combination with measured cross sections for the production of Ca isotopes by fragmentation of ^{56}Fe on hydrogen, we show that the two doubly-magic isotopes ^{40}Ca and ^{48}Ca consist mainly of primary material. We find that their relative abundances in the cosmic-ray source are very similar to those found in solar-system material, in spite of the fact that different types of stars are thought to be responsible for producing these two isotopes. This observation is consistent with the view that cosmic rays are derived from a mixed sample of interstellar matter.

1 Introduction

Most cosmic-ray nuclides in the mass range $33 \leq Z < 56$ are dominated by secondary nuclei produced by fragmentation of ^{56}Fe or of secondary species produced from ^{56}Fe. Thus, while this intermediate mass region of the periodic table is very important for studies of cosmic-ray propagation, its usefulness for investigating the nucleosynthetic origin of cosmic-ray source material is limited.

However, in this mass region there are a small number of isotopes for which secondary production does not dominate. Since cosmic-ray instruments are now capable of resolving essentially all isotopes up through the iron group, one can investigate the source abundances of these specific nuclides while using nearby secondary nuclides to constrain the calculation of secondary corrections. This approach has previously been used (Krombel and Wiedenbeck, 1985) for deriving the source abundance of ^{40}Ca, since this nuclide is mostly primary while the other major isotopes of Ca are almost completely secondary.

2 Cosmic-ray observations

For this study we used data collected by the Cosmic-Ray Isotope Spectrometer (CRIS) instrument (Stone et al., 1998) on ACE from December 1997 through April 2000. Figure 1 shows the Ca mass histograms that were obtained. The histogram on the left is restricted to particles incident with angles $\theta < 25°$ from the normal to the silicon detectors used in this dE/dx vs. total energy spectrometer. The mass resolution is particularly good in this subset of the data. To obtain additional statistics for rare isotopes separated by 2 amu such as ^{46}Ca and ^{48}Ca we also analyzed the larger data set with $\theta < 65°$, as shown on the right.

In previous studies of Ca isotopic composition (Krombel and Wiedenbeck, 1985; Lukasiak, McDonald, and Webber, 1997), ^{40}Ca was well measured because it has a significantly larger abundance than the adjacent electron-capture radioisotope ^{41}Ca. However, the major secondary isotopes ^{42}Ca, ^{43}Ca, and ^{44}Ca were only poorly resolved, and the rare, heavy isotopes ^{46}Ca, and ^{48}Ca were not identified due to limited resolution and statistics. With the ACE data it is now possible to distinguish all seven of the Ca isotopes expected in cosmic rays.

3 Fragmentation cross sections

As we have previously discussed (Wiedenbeck et al., 2001), calculations of the secondary production of Ca isotopes using semi-empirical estimates of fragmentation cross sections (Silberberg, Tsao, and Barghouty, 1998) indicate that ^{48}Ca should be predominantly primary, in spite of its very low abundance. The small cross section for production of ^{48}Ca is presumably a result of the large difference of mass-to-charge ratio (A/Z) between this nuclide and ^{56}Fe, the main contributor to its secondary production. There is concern, however,

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Correspondence to: M. E. Wiedenbeck
(mark.e.wiedenbeck@jpl.nasa.gov)

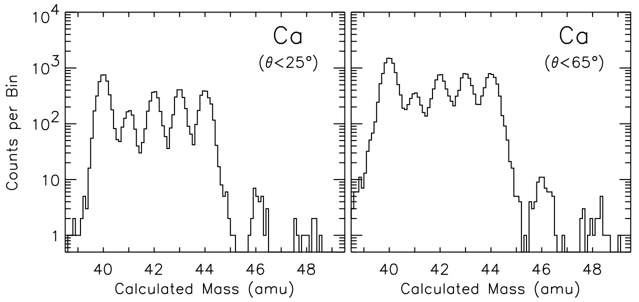

Fig. 1. Ca mass histogram from ACE/CRIS using two different cuts on particle angle of incidence. Note the logarithmic scale used for the ordinate.

about a possible large error in the calculated cross-section value since the measured cross sections on which the formulas were based were mainly for production of nuclides with significantly lower A/Z.

New measurements of cross sections for the production of the isotopes of a wide range of elements from fragmentation of 500 MeV/nuc ^{56}Fe on ^{1}H were made at the GSI heavy-ion synchrotron in 2000 by a multi-disciplinary international team. Preliminary results from the analysis of these data (George et al., 2001) include relative cross sections for producing the Ca isotopes, including ^{46}Ca and ^{48}Ca. In order to convert these relative values into absolute cross sections that can be used for evaluating secondary contributions to our measured Ca isotopic abundances, we normalized the sum of the production cross sections for the Ca isotopes found in cosmic-rays (40–44, 46, 48) to the corresponding sum of cross sections reported by Webber, Kish, and Schrier (1990) from measurements at 600 MeV/nuc, after making a small correction ($\sim 18\%$) for the energy difference.

The resulting normalized cross sections are shown as the filled circles in the left panel of Fig. 2. These values are compared with cross sections obtained from the same GSI experiment at 1000 MeV/nuc and from several previous experiments at energies intermediate between 500 and 1000 MeV/nuc. Also shown are calculated values obtained from the semi-empirical formulas of Silberberg, Tsao, and Barghouty (1998) (solid line) and Webber, Kish, and D. A. Schrier (1990) (dotted line). The right panel shows "decayed" cross sections corresponding to expected production of the cosmic-ray Ca isotopes after $\beta^{\pm}$-decays of isobars have had time to occur. The decay contributions are important for ^{42}Ca, ^{43}Ca, and ^{44}Ca, but not for the other Ca isotopes. The new cross-section data suggest that the secondary production of ^{40}Ca is higher than previously reported, but still small in comparison with the production of the major secondary Ca isotopes. The cross section for production of ^{48}Ca is significantly less than calculated from the formula of Silberberg, Tsao, and Barghouty (1998), and minor differences are evident in the relative productions of the various Ca secondaries.

Although ^{56}Fe fragmentation is the dominant source of secondary Ca in cosmic rays, there are also contributions from fragmentation of other cosmic-ray species (mostly secondaries from ^{56}Fe themselves). The upper panel of Fig. 3 compares the relative "secondary production" of Ca isotopes from ^{56}Fe (filled circles) with production from all cosmic-rays (open circles). This quantity is calculated as a sum of the products of measured cosmic-ray nuclidic abundances times the cross sections for nuclides to fragment in the various Ca isotopes. The lower panel shows that $\sim$ 40–60% of the total is attributable to ^{56}Fe fragmentation. The remaining production generally comes from a sizeable group of other nuclides. Aside from ^{56}Fe, we find that the largest individual contributions are $\sim 14\%$ of secondary ^{48}Ca from ^{52}Cr and $\sim 10\%$ of secondary ^{40}Ca from ^{41}Ca. More typically, contributions from individual parent nuclides are $\lesssim$ 5%.

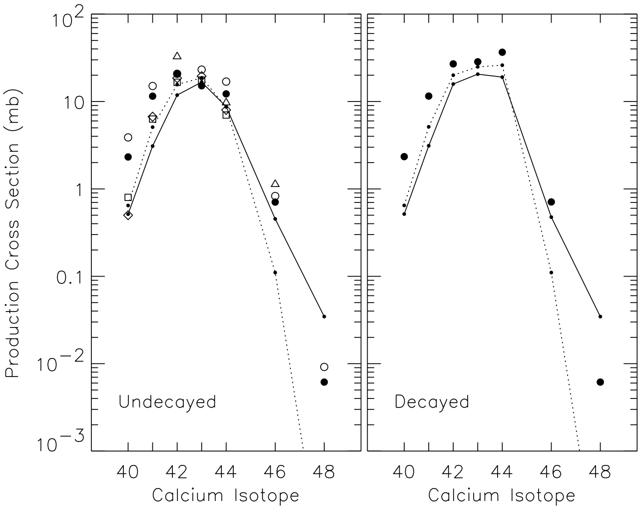

Fig. 2. Left panel: preliminary normalized cross sections for production of Ca isotopes by the reaction ^{56}Fe+^{1}H at 500 MeV/nuc and 1000 MeV/nuc from George et al. (2001) (filled and open circles, respectively) compared with previous measurements: open square—576 MeV/nuc (Webber et al., 1996); open diamond—600 MeV/nuc (Webber, Kish, and Schrier, 1990); open triangle—800 MeV/nuc (Vonach et al., 1997). Solid and dotted curves show cross sections calculated with the formulas of Silberberg, Tsao, and Barghouty (1998) and Webber, Kish, and D. A. Schrier (1990), respectively. Right panel: decayed cross sections. Symbol and line style definitions are the same as in the left panel.

4 Origin of cosmic-ray Ca isotopes

Figure 4 shows measured abundances of cosmic-ray Ca isotopes arriving near Earth, normalized to $^{56}\mathrm{Fe} \equiv 1$, as filled circles. The statistical uncertainty (not plotted) is $\sim$ 22% for the ^{48}Ca abundance and significantly less for the more abundant isotopes. For comparison, the $\times$ symbols show abundances found in solar-system material (Anders and Grevesse, 1989). For other refractory nuclides, cosmic-ray source abundances have been found to closely resemble solar-system values (Wiedenbeck et al., 2001). The large excesses of observed cosmic-ray abundances over solar-system values for the isotopes ^{42}Ca through ^{44}Ca suggest that these isotopes

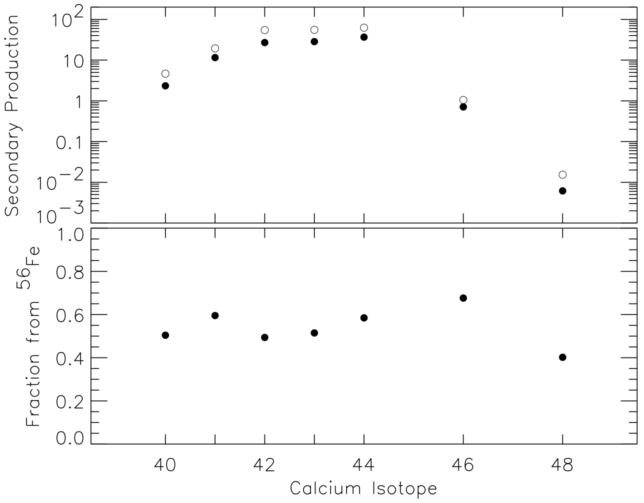

Fig. 3. Upper panel: comparison of the relative production of Ca isotopes by direct fragmentation of ^{56}Fe (filled circles) and by fragmentation of all cosmic ray nuclides (open circles). Lower panel: fraction of the total production attributable to ^{56}Fe.

are all dominated by secondaries. (The radioactive isotope ^{41}Ca should be entirely secondary). In contrast, the cosmic-ray and solar abundances are very similar for ^{40}Ca and ^{48}Ca.

To better understand the origin of ^{40}Ca and ^{48}Ca we have carried out a leaky-box propagation calculation using model parameters described by Davis et al. (2000). Solar-like source abundances were assumed for the isotopes of Ca and heavier elements. The measured cross sections for producing Ca isotopes from ^{56}Fe at 500 MeV/nuc (right panel in Fig. 2) were used, together with the energy dependence predicted by the formula of Silberberg, Tsao, and Barghouty (1998). In the present calculations the solar modulation level was adjusted to a value of $\phi = 460$ MV to correspond to the time interval used in our data analysis.

We have previously found (Wiedenbeck et al., 2001) that this model can, on average, account for the observed abundances of a number of sub-Fe secondaries within $\sim 5\%$. The propagated solar abundances of the Ca isotopes are shown as the unfilled circles in Fig. 4. Although the model overpredicts the abundances of ^{42}Ca, ^{43}Ca, and ^{44}Ca by $\sim 20\%$, the abundance pattern for ^{41}Ca through ^{46}Ca rather closely follows trends seen in the mass-dependence of the cross sections. George et al. (2001) has pointed out that the preliminary cross sections from the 2000 GSI run will require some adjustment downward to correct for production in the windows of the liquid hydrogen target, but estimate that this correction will be $< 15\%$ (and possibly much less). In addition, the absolute normalizations of the GSI results will be independently derived. This will remove uncertainties associated with the present procedure of normalizing to previously reported cross section measurements (Webber, Kish, and Schrier, 1990), which is of particular concern since the two experiments appear to have some significant differences in the reported dependences of cross sections on Ca isotope mass (Fig. 2, left panel).

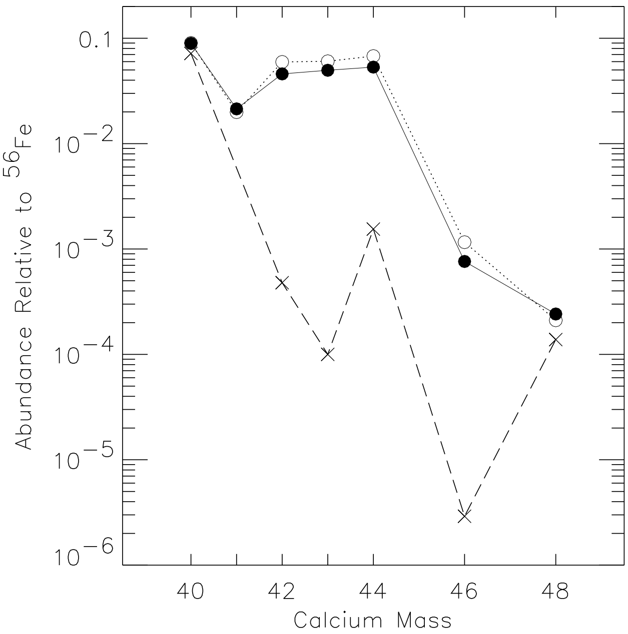

Fig. 4. Abundance comparison including cosmic-rays arriving near Earth (filled circles), solar-system abundances (×'s), and propagated solar abundances (open circles). The radioactive isotope ^{41}Ca is not present in solar-system material but is produced as a cosmic-ray secondary.

5 Discussion

From the comparison in Fig. 4 we conclude that cosmic-ray ^{40}Ca and ^{48}Ca are mainly of primary origin. Furthermore, the source abundances of these nuclides, relative to ^{56}Fe, are equal to solar-system values to within better than a factor of 2. As discussed by Woosley and Weaver (1995), solar-system ^{40}Ca is thought to have been synthesized mainly by oxygen burning (explosive and quiescent) in massive stars that evolve to produce core-collapse supernovae (Type II). However, these authors find that models of this kind are unable to produce ^{48}Ca in its solar abundance and they suggest that this isotope is "made in Type Ia supernova of a special variety, namely those that ignite a carbon deflagration very near the Chandrasekhar mass". Given the very different objects thought to produce ^{40}Ca and ^{48}Ca, it seems reasonable to suggest that the close similarity of the abundances of these isotopes in cosmic-ray and solar-system matter is unlikely to be accidental. More probably, both populations of matter are samples of the same pool of material—presumably the interstellar medium.

Figure 5 shows the results of our earlier comparison of abundances of refractory nuclides in the cosmic-ray source with solar-system values (Wiedenbeck et al., 2001). The derivation of these source abundances was carried out prior to the GSI cross-section measurements. Thus, the calculation of the secondary correction for ^{48}Ca was based entirely

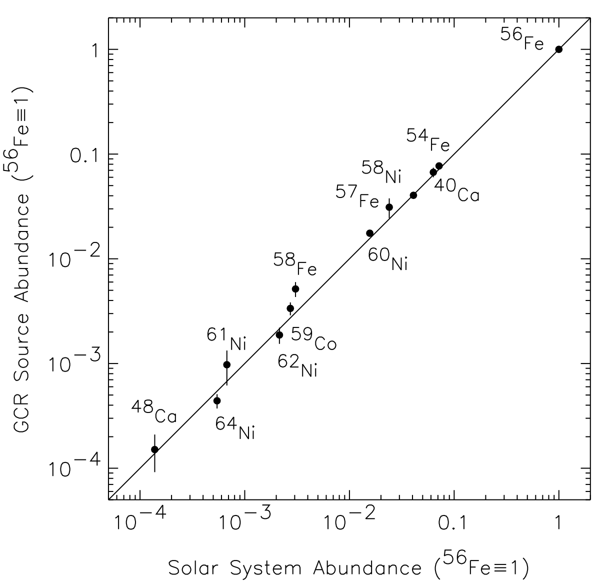

Fig. 5. Correlation between abundances of refractory nuclides in the cosmic-ray source (ordinate) and the solar system (abscissa), from Wiedenbeck et al. (2001).

on calculated cross sections. While an update of the source abundances taking into account the GSI cross-section results will certainly result in minor modification of some of the values shown in Fig. 5, the analysis presented above supports the conclusion that the source abundances for ^{40}Ca and ^{48}Ca are close to solar values, as are the source abundances for the Fe, Co, and Ni isotopes.

Questions remain about the whether spatial and temporal variations of interstellar composition are likely to be small enough to account for the observed small differences between cosmic-ray source and solar abundances. In addition, it is not clear whether cosmic-rays derived from the interstellar medium can so closely track solar system abundances for refractory species and still exhibit some large differences for volatiles. A particularly acute problem is the well-established excess (by a factor ~ 5) of the ratio ^{22}Ne/^{20}Ne in the cosmic-ray source over values measured in the solar wind and in the very local interstellar medium, as inferred from anomalous cosmic rays. It is hoped that the resolution of these questions will both lead to a better understanding of the origin of cosmic rays and and provide a new window on the chemical evolution of interstellar matter.

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