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# Cosmic Ray Source Abundances for 29≤Z≤34

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**Abstract**

The Cosmic Ray Isotope Spectrometer (CRIS) instrument on board the Advanced Composition Explorer (ACE) spacecraft is making new measurements of nuclides just beyond the iron-nickel peak in the galactic cosmic rays. Isotopes of copper and zinc have been resolved for the first time. Elemental abundances for nuclei with 29≤Z≤34 are reported with good separation between species. Several of these elements are useful for studying fractionation processes which may depend on the first ionization potential or volatility. Source abundances are estimated using a prior propagation calculation and their potential for distinguishing between source models are discussed.

## 1 Introduction:

The composition of ultra-heavy (Z>28) cosmic rays in the galaxy yields important clues to their origin, acceleration, and transport. The rare elements just beyond nickel are particularly interesting as their abundances do not suffer from significant contamination from spallation of heavier nuclei, hence their composition largely reflects that of the source. The rarity of these elements has made observation in this region difficult. Zinc and copper are each nearly 1500 times less abundant than iron while heavier elements are even more rare. While observations of some elemental abundances have been made (e.g. Byrnak 1983), measurements with both isotopic resolution and good statistical accuracy have only recently become available.

The Cosmic Ray Isotope Spectrometer (CRIS) instrument was launched aboard the Advanced Composition Explorer (ACE) spacecraft in August 1997. Data reported here were collected over a period of 17 months of solar minimum conditions. The instrument consists of four stacks each of nine silicon detectors covered by a scintillating optical fiber (SOFT) hodoscope consisting of three x and y fiber planes (Stone et al. 1998). The charge and mass of cosmic rays that stop in the silicon stacks are identified using multiple measurements of dE/dx versus total energy. CRIS has an average geometry factor of nearly 250 $cm^2$sr and a mass resolution of $\leq$ 0.25 amu for iron, allowing measurements of significant amounts of the very rare ultra-heavy nuclei. The instrument is sensitive to heavy nuclei with energies between about 100 and 500 MeV/nucleon.

## 2 Isotopic Abundances:

CRIS data in the trans-nickel region are limited by statistics, not by resolution. Enough copper and zinc nuclei have been recorded to identify peaks corresponding to specific isotopes. Figure 1 shows a histogram of the estimated nuclear charge for copper and zinc. The elements are clearly separated from each other and from the vastly more abundant nickel peak. Because the energy deposited in the silicon detectors depends on both the nuclear charge and the atomic mass, solving the range-energy relation for an estimated charge will retain a dependence on the isotopic mass. The estimated charge histogram then contains sub-peaks corresponding to distinct isotopes.

A number of consistency cuts are placed on the data to ensure that events are identified correctly. Tracks in SOFT must have clear signatures in all six planes that reconstruct in a straight line. The particle must stop no sooner than the third silicon detector. This ensures at least two measurements of dE/dx and a residual energy.

We also required that stopping trajectories pass more than 1.5 mm inside the edge of the active area of any detector. Dead layer cuts removed events stopping within 500 microns of the top or bottom face of any silicon detector.

The two stable isotopes of copper (A=63,65) and two of zinc (A=64,66) are clearly evident in the data. The identities of the peaks are confirmed with a mass calculation, but are most easily presented in terms of the estimated charge. These isotopes appear at about the same level as the $^{64}$Ni isotope which is also measured for the first time in CRIS (Wiedenbeck, et al. 1999b). The apparent lack of the $^{68}$Zn isotope may easily be due to statistical fluctuations at these low count levels.

The inset box of Figure 1 shows the relative abundances of the zinc and copper isotopes in the solar system (Anders & Grevesse 1989). The overall heights have been roughly scaled to the peak of the $^{63}$Cu distribution for comparison. Within statistical uncertainties, the abundances of the copper isotopes and those of the zinc isotopes as confirmed by the mass calculation are consistent with the corresponding solar system values.

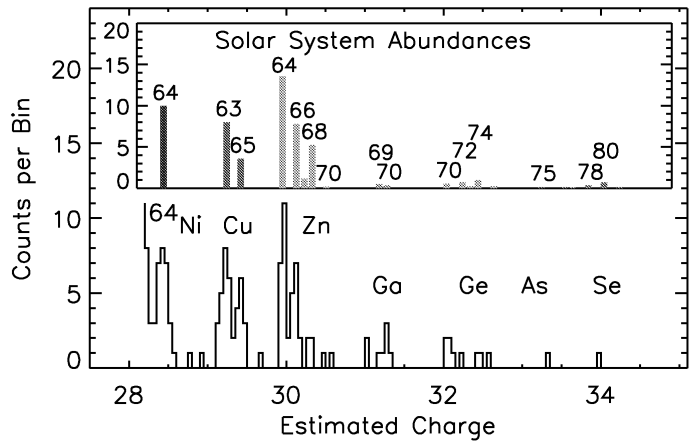


**Figure 1:** Charge histogram of heavy isotopes.

## 3 Elemental Abundances:

Elemental abundances are obtained by summing the counts within specified charge boundaries. Since isotopic resolution is not required, nuclei stopping in the second silicon detector are included to increase the number of counts. The abundances are corrected for differences in the SOFT efficiency, losses from spallation inside the detector, and the energy response of the instrument.

Figure 2 shows the relative abundances of the heavy elements as measured in CRIS. Error bars indicate statistical uncertainties. The dotted histogram gives the relative abundances of these elements in the solar system (Anders & Grevesse 1989). The dashed histogram is the result of propagating solar system abundances (with no FIP adjustment) through a standard galactic propagation model (Byrnak et al. 1983). Data from HEAO-3 C2 (Byrnak et al. 1983), HEAO-HNE (Binns et al. 1983), and Ariel 6 (Fowler et al. 1987) are included for comparison.

The abundances of the heavy elements are of particular interest as indicators of the origin of cosmic rays. Deviations in the fluxes of certain elements in the galactic cosmic rays as compared to solar system abundances can help to identify the GCRs as having come from a particular type of seed population or environment.

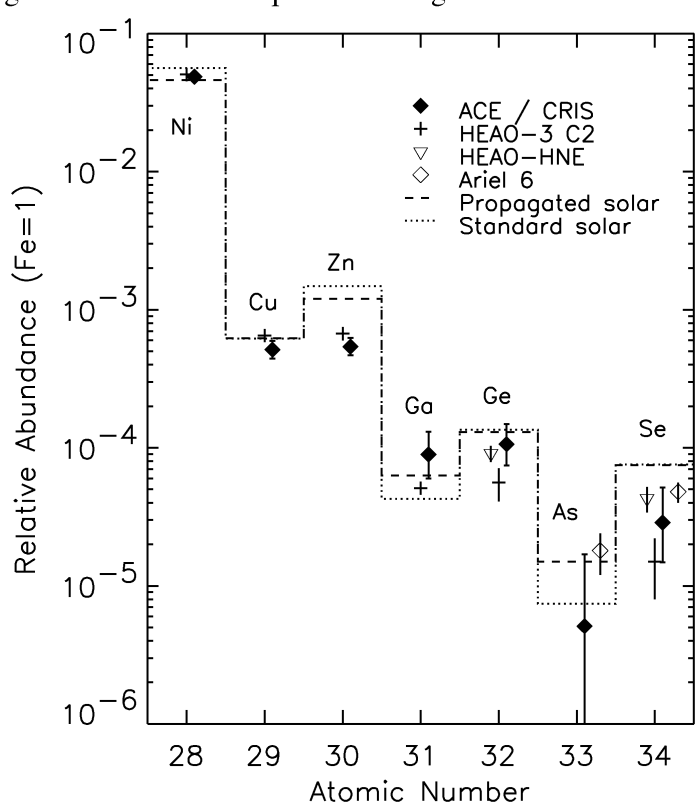


**Figure 2:** CRIS relative elemental abundances.

Cassé and Goret (1978) noted the now well-known apparent fractionation by first ionization potential (FIP)

in the galactic cosmic rays. This effect amounts to the observation that elements with first ionization potential higher than ∼10 eV are depleted relative to those with lower FIP when compared to solar system abundances. A similar fractionation is observed in the composition of the solar corona, solar wind, and solar energetic particles. This resemblance has led to the suggestion that the cosmic rays originate from stellar material.

It has also been realized for some time that the commonly known FIP effect might actually reflect a dependence on volatility (Epstein 1980; Bibring & Cesarsky 1981). An element's volatility is defined by its condensation temperature and is generally correlated with the first ionization potential. A volatility dependence might indicate that cosmic rays come from interstellar dust grains which are themselves depleted in the more volatile (generally high-FIP) elements because of difficulty in condensing them into the grain (Meyer, Drury & Ellison 1997).

Either model might account for the striking difference between the observed zinc to copper ratio compared to the solar system value. The 7.7 eV FIP of copper places that element with the undepleted species, while that of zinc is an intermediate 9.4 eV. In the condensation model, copper is known as a "semi-volatile" while zinc is a full-fledged volatile element and so a greater depletion would be predicted.

There are a few elements which break the general correlation of FIP and volatility. These are useful as discriminators between the two models and include many of the heavy elements whose abundances are becoming accessible with CRIS. Copper and gallium are both low-FIP but moderately volatile. Germanium and iron have nearly identical FIP values but germanium is volatile while iron condenses easily. Significant depletions of the volatile elements with respect to solar system abundances could indicate that volatility, not FIP, governs the observed fractionation. Zinc and selenium are volatile elements with FIP values in the intermediate region. Some depletion in these elements is consistent with the FIP model.

# 4 Source Abundances:

The source fraction for each element can be estimated from the ratio of the the solar system elemental abundances to the propagated solar abundances in Figure 2. Abundances measured locally by CRIS are multiplied by these ratios to estimate the abundances at the cosmic ray source. Figure 3 shows the ratio of these estimated source abundances to the solar system values as a function of the FIP value for each element. The error bars on the CRIS data points (in bold) represent Poisson statistical uncertainties for 84% confidence limits (Gehrels, 1986; Israel, 1968). The overlaid line represents one possible parameterization of the FIP step. Source abundances from the HEAO experiments (Ferrando, 1993), based on their own propagation calculation, are added with the lighter crosses for context. The CRIS cobalt source abundance used here is based on a detailed study of the nickel and cobalt isotopes reported elsewhere (Wiedenbeck et al., 1999a).

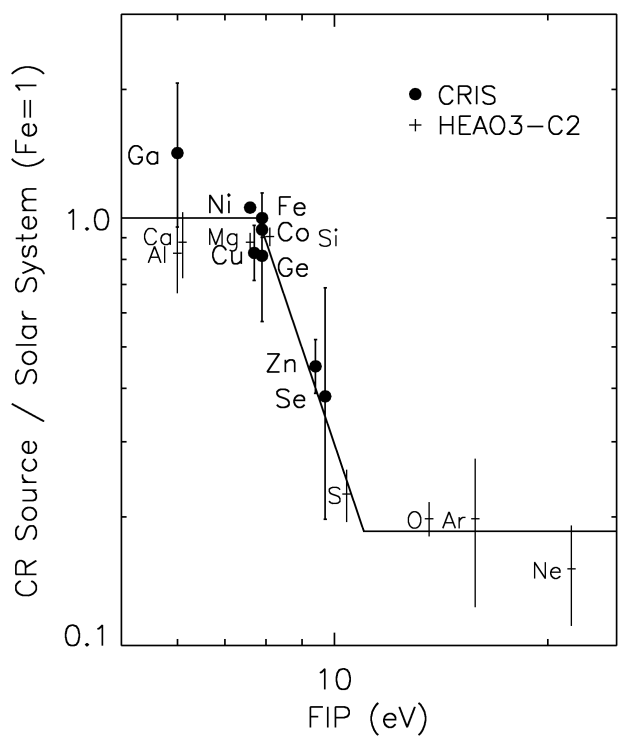


**Figure 3:** Source abundances relative to solar system.

The Cu/Fe and Ge/Fe ratios in Figure 3 are of particular interest. At this point both are consistent with FIP as the relevant parameter. Both ratios should be good indicators of the nature of the source fractionation and will bear watching as additional data accumulates. Copper and germanium have small secondary contributions to the observed fluxes

so the source abundances can be fairly reliably determined.

Zinc and selenium are in the intermediate FIP region. With only a few counts, selenium is consistent with either model at this point. Zinc has good statistical accuracy, but the possibility of a deficit depends a great deal on how one parameterizes the transition between the high and low-FIP steps. For this reason zinc by itself does not have much discriminating power despite the amount of data recorded. The gallium abundance is consistent with the solar system value.

## 5 Summary:

Heavy element abundances are measured in the CRIS instrument with very good charge and mass resolution at rates of a few per month for Cu and Zn to a few per year for Ga and heavier nuclei. Isotopes of copper and zinc have been resolved in the cosmic rays for the first time. Additional isotopes, including those of heavier elements, are expected to be resolvable as data accumulates.

Source elemental abundances of the heavy elements have been estimated from a prior propagation calculation and have been compared to solar system values. Within the limits of statistical accuracy, the data are consistent with either the FIP or the volatility model. In spite of the large collecting power of the CRIS instrument, the number of events remains limited.

Both CRIS and the ACE spacecraft are in excellent health and enough fuel remains on board for a five year or longer mission. It is possible that the CRIS heavy element data set can be increased by a factor of two to three depending on the increase of solar activity. This kind of improvement in statistics along with continuing improvement in propagation models and understanding of possible systematic effects could give CRIS the potential to make an important contribution to the question of source fractionation in the coming years.

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