First Measurements of the Isotopic Composition of the Ultra-heavy Galactic Cosmic Ray Nuclei $_{31}$Ga and $_{32}$Ge from the CRIS Experiment on ACE

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Abstract: The Cosmic Ray Isotope Spectrometer (CRIS) instrument on the NASA Advanced Composition Explorer (ACE) satellite was launched in August, 1997 and has collected excellent data over this ~14 year period of time. The large geometrical factor of the instrument, combined with the very long exposure time and extended solar minimum, has enabled us to measure the cosmic ray isotopic abundances of $_{31}$Ga, and $_{32}$Ge for the first time, and to greatly improve earlier published measurements for $_{29}$Cu and $_{30}$Zn. We have collected a total of over 700 nuclei heavier than $_{28}$Ni with energies in the range of ~150 to 600 MeV/nucleon. In this paper we report the isotopic composition measurements and compare the observed isotopic fractions with those found in solar system material.

Keywords: Cosmic rays; isotopes; abundances; nucleosynthesis

Introduction

Measurements of the elemental and isotopic abundances of galactic cosmic rays provide one of the keys to understanding the origin of galactic cosmic rays. The ACE-CRIS experiment [1] was designed to measure the elemental and isotopic abundances of nuclei with charge (Z) $4 \leq Z \leq 30$. Isotopic abundances obtained by CRIS over this charge range have previously shown that the abundance patterns are consistent with an OB-association origin of a large fraction of galactic cosmic rays [2-4]. The very long exposure time of ACE (~14 years) has enabled us to accumulate sufficient numbers of events to measure elemental abundances up through $_{38}$Sr [5] with statistical accuracy comparable to that of the TIGER experiment [6]. In addition, we have been able to measure the isotopic composition of $_{31}$Ga and $_{32}$Ge for the first time, and obtain greatly improved measurements of $_{29}$Cu and $_{30}$Zn isotopes, which were reported by George et al. [7] and Wiedenbeck et al. [8]. In this paper we present preliminary results for the isotopic composition analysis of copper through germanium in the large data set covering two solar minima.

Experiment

The CRIS instrument consists of four stacks of silicon detectors to measure dE/dx and total energy (E_{tot}), and a scintillating-fiber hodoscope to measure trajectory. The dE/dx-E_{tot} method is used to determine particle charge and mass and the total vertical thickness of silicon is 4.5 cm. The precision with which angle is measured by the fiber hodoscope is ≤ 0.1°. The instrument is described in detail in [1].

Measurements

In Figure 1 we show a histogram of the “charge estimate” for nuclei from copper through germanium. The identity of the peaks can be confirmed through a mass calculation, but the results are presented most easily in terms of a “charge estimate”. We see that there are clear peaks for the most abundant stable isotopes of each element. The "charge estimate" has been binned into 0.05 charge unit (cu) bins to more clearly show the peaks for the low statistics measurements of Ga and Ge.

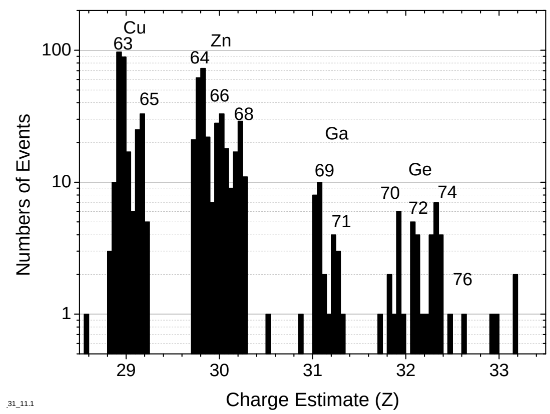

Figure 1—Histogram of the isotope distribution of Cu, Zn, Ga, and Ge.

If the binning size is reduced to 0.01 cu (Figure 2), we see the deep valleys between the copper and zinc isotopes. The statistical sample is nearly a factor of 10 greater than the earlier [7,8] work. For example, in our data set below there are 331 zinc nuclei compared with 35 in [7].

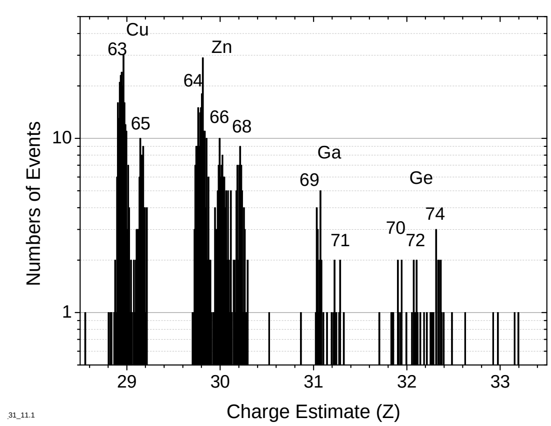

Figure 2—Same data as in Figure 1 but binned more finely to show the deep valleys between the isotopes of copper and zinc.

These data were collected over the period from December 4, 1997 through April 2, 2011, excluding only intervals of high solar activity. Events shown in these plots were selected to have good agreement between the multiple charge estimates made on each particle using different combinations of the silicon signals for dE/dx and residual energy (E_R) [1], a good trajectory indicated by a good fit to a straight line in the three scintillating fiber hodoscope planes, and incidence angle < 45°. Additionally, events that stopped in or near the "dead layers" of the silicon detectors were rejected [1].

Results

To obtain the numbers of nuclei detected for each isotope, simple cuts were taken at the valleys between the peaks of the isotopes shown in Figure 1. For the cases of Cu and Ga, only two stable isotopes exist. For zinc, in addition to those isotopes clearly resolved in Figure 1, ^{67}Zn and ^{70}Zn are low abundance stable isotopes with solar system abundances [9] of 4.1% and 0.6% respectively. To account for ^{67}Zn we have assumed that it has solar system composition and subtracted half of that fraction from the adjacent isotopes (i.e. 2% of the total number of zinc nuclei, which corresponds to 6.6 particles, were subtracted from the number of ^{66}Zn and ^{68}Zn obtained by cutting at the valley in Figure 1). The single particle at ~Z=30.5 was assumed to be ^{70}Zn and was included in the total number of zinc. For germanium, ^{73}Ge and ^{76}Ge are stable isotopes with solar system abundances of 7.7% and 7.4% respectively that are not resolved. In like manner as for the zinc, we assumed that ^{73}Ge had solar system abundance and 1.5 particles were subtracted from its adjacent isotopes of ^{72}Ge and ^{74}Ge.

In Figure 3 we show the elemental abundance fraction for each stable isotope for these nuclei (data points) and compare them with solar system abundances [9]. The error bars on the data points are statistical only. These results are preliminary since the measured abundances have not yet been propagated back to the source to obtain source abundances. In addition, they have not been corrected for interactions in the instrument or energy intervals. However, the combination of these corrections will have a small effect on the abundances, in most cases substantially smaller than the error bars on the data points in Figure 2. Additionally, a careful assessment of systematic error has not yet been performed, although we believe these will be small. We see that there is reasonable agreement with solar system abundances, except for copper.

In more detail, we see that the zinc, gallium, germanium isotopes are in good agreement with solar system abundances within the measurement errors. We note that in [7], there were clear ^{64}Zn and ^{66}Zn peaks, but there was very little ^{68}Zn. The authors stated that this could simply be due to statistical fluctuations since the numbers of events were not large. That appears to be the case since with our higher statistical sample, ^{68}Zn agrees very well with solar system abundances. The ^{63}Cu and ^{65}Cu abundance fractions disagree with solar system abundances by ~3 standard deviations.

Unlike the isotopes of ^{22}Ne and ^{58}Fe, the enhancements due to nucleosynthesis in massive stars of the isotopes measured here are expected to be relatively small, and are also roughly the same magnitude within a single element [10]. Thus, after mixing of massive star outflow with normal interstellar medium (ISM) material in a roughly 20%/80% mix [2,3], these isotope ratios should not differ much from those in normal ISM, and that is, in fact, what we observe, with the possible exception of copper..

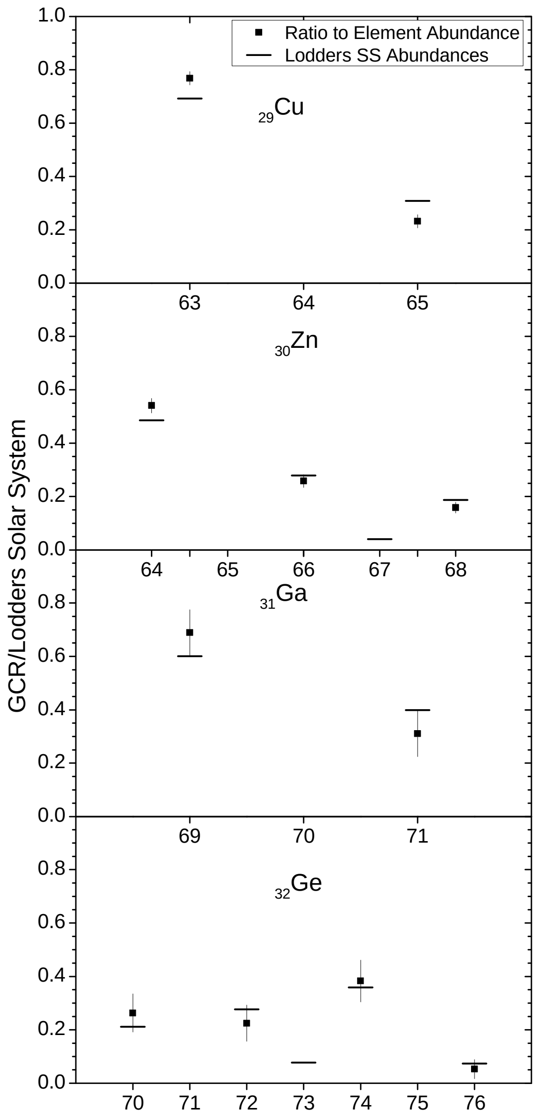

Figure 3—Ratio of GCR abundance relative to solar system abundances [9] for Cu, Zn, Ga, and Ge isotopes.

Conclusions

We have obtained for the first time measurements of the isotopic abundances of $_{31}$Ga and $_{32}$Ge in the galactic cosmic rays. In addition, we have obtained greatly improved abundances of the isotopes of $_{29}$Cu and $_{30}$Zn over those previously measured [7,8]. We find generally good agreement between our measured isotopic abundances and solar system abundances for zinc, gallium, and germanium, but .the copper isotopes differ from solar system abundances by about 3 standard deviations.

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