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Measurement of the Relative Abundances of the Ultra-Heavy Galactic Cosmic Rays (30 ≤ Z ≤ 40) with TIGER

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Abstract: Observations of ultra-heavy (Z≥30) galactic cosmic rays (GCR) help to distinguish possible origins of GCR. The Trans-Iron Galactic Element Recorder (TIGER) measures the charge (Z) and energy of GCR using a combination of scintillators, Cherenkov detectors, and a scintillating fiber hodoscope. The two Cherenkov radiators, one acrylic and one aerogel, provide TIGER with an energy sensitivity between 0.3 and 10 GeV/nucleon in the instrument. The threshold at the top of the atmosphere is close to 0.8 GeV/nucleon for Fe. TIGER has accumulated data on two successful flights from McMurdo, Antarctica launched in December 2001 and December 2003 with a total flight duration of 50 days. The combined dataset resolves ~140 nuclei with Z > 30, and provides the best measurements to date for $_{30}$Zn, $_{31}$Ga, $_{32}$Ge, and $_{34}$Se. The results for Ga and Ge taken together are inconsistent with a GCR source with Solar-System abundances modified either by preferential acceleration of elements of low first ionization potential or by preferential acceleration of refractory elements, suggesting that elemental composition of the GCR source is different from that of the Solar System.

Introduction

The principal objective of the Trans-Iron Galactic Element Recorder (TIGER) is the measurement of relative abundances of the lighter ultra-heavy (UH) elements in the charge (Z) interval 30 ≤ Z ≤ 40. Comparing the observed abundances with those expected from various cosmic-ray source models will constrain these models.

In this paper we compare our observations with two possible source compositions. Both models start with the Solar-System abundances of elements [1]. In one model we assume that these Solar-System abundances are fractionated with preferential acceleration for elements with low First Ionization Potential (FIP) [2], and in the other we assume fractionation with preferential acceleration for refractory (non-volatile) elements [3]. Fractionation according to FIP would be expected if the first step of acceleration takes place when atoms are thermally ionized at a temperature of the order of 10^4 K, as is found in stellar photospheres. Such a FIP-dependant composition is observed in solar energetic particles. Fractionation according to volatility would be expected if the elements that are likely to be found in interstellar grains (primarily refractory elements) are preferentially accelerated.

The cosmic-ray abundances for elements with Z < 30 are consistent with volatility-dependent acceleration; but since most refractory elements have low FIP, a FIP-dependent acceleration is not firmly ruled out by those abundances. In the UH charge interval addressed by TIGER, the elements $_{31}$Ga, $_{32}$Ge, and $_{37}$Rb break this FIP/volatility degeneracy, being relatively volatile elements with low FIP. Our TIGER results have good enough statistics and resolution to resolve element abundances of Ga and Ge with sufficient precision to test these two models.

The TIGER instrument

The TIGER instrument is composed of four PVT scintillators, two Cherenkov detectors (one aerogel of index 1.04, and one acrylic of index 1.5), and a scintillating optical fiber hodoscope. The scintillators are squares 1.16 m on a side. The acrylic radiator is 1.14 m on a side. The aerogel radiator is composed of four squares, each 51 cm on a side. The total geometry factor of the TIGER instrument is approximately 1.3 m^2sr. The instrument has been described in more detail at the previous ICRC [4] and in [5].

For nuclei with energy at the detector between the acrylic threshold of 0.32 GeV/nucleon and the aerogel threshold of 2.5 GeV/nucleon, the charge and energy are determined by the dE/dx – C method, with dE/dx (energy loss) determined from the signals in the two scintillators above the Cherenkov detector, and C determined by the signal in the acrylic Cherenkov. Since saturation effects in the scintillator lead to a signal that is not directly proportional to dE/dx, the non-linearity must be corrected. The variation of signal with Z and energy has been determined empirically by fitting data for Z < 30 and extrapolating into the higher-Z region of interest. This process is described in detail in [5]. Work is in progress to test and possibly improve this correction for saturation; however the charge resolution that we have achieved, at least for Z < 35, is evidence that our correction for this range of Z is appropriate. (For Z > 34, our statistics are inadequate to make any firm comment on the quality of the saturation correction.) For nuclei with energy above the 2.5 GeV/nucleon aerogel threshold, the charge and energy are determined primarily from the two Cherenkov signals, the acrylic signal being the main determinant of Z and the aerogel signal being the main determinant of energy. Some additional information for the Z determination comes from the scintillator signal. The hodoscope is used to determine the trajectory of incident particles, thus locating the position in each of the scintillation and Cherenkov detectors and the angle of the particle path with respect to the detector normal. The abundant Fe nuclei were used to map the areal response of each of the scintillators and the Cherenkov detectors and to determine temporal drifts of the detector gains.Crossplots of signals from scintillator vs acrylic Cherenkov detector, and from acrylic vs aerogel Cherenkov detectors were included in the previous ICRC [4], demonstrating the excellent charge determination using these detectors.

Balloon flights

We report results from two long-duration balloon flights over Antarctica. The first flight, launched December 21, 2001, lasted 32 days at an average residual atmosphere of 5.5 mbar. After successful recovery of the instrument and refurbishment, TIGER was flown again, on a larger balloon, thus reaching higher altitude. The second flight, launched December 17, 2003 lasted 18 days at an average residual atmosphere of 4.1 mbar. The on-board data recorder, and some of the electronics were successfully recovered after this second flight; but because the flight was terminated about 2800 km from the McMurdo Antarctic base, recovery of the detectors has not been possible. Thus there will be no further flights of TIGER.

Elemental abundances

The charge histogram combining data from the two flights is shown in Figure 1. Note the factor of 1000 change of scale at Z=29. The charge resolution is good, with clear peaks at Z = 30, 31, 32, and 34.

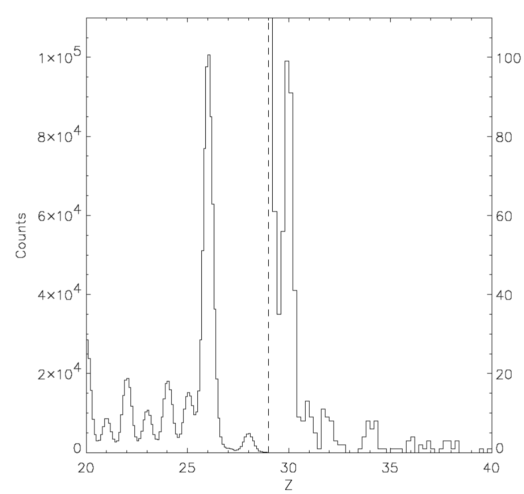

Figure 1: Charge histogram of combined dataset from 2001 and 2003 flights

In Figure 2, we replot these data for $Z > 29.5$, using narrower bins (0.1 instead of 0.2 charge units). Superposed on the histogram is the curve resulting from a maximum-likelihood fit to our full data set over the entire range of $12 \leq Z \leq 40$. The entire set is well fit by Gaussian peaks at each integer Z with $\sigma = 0.23$ charge units.

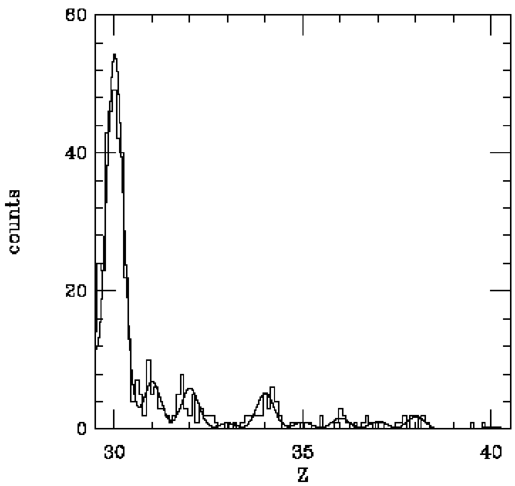

Figure 2: Charge histogram with superposed result of maximum-likelihood fit

As we discuss in the following section, our result of nearly equal abundances of $_{31}$Ga and $_{32}$Ge is inconsistent with a GCR source that has Solar-System abundances. One might be concerned that some of the events that we count as Ga could be spillover of a non-Gaussian tail from the more abundant $_{30}$Zn. However, if there were such a spillover, we would expect a similar spillover of $_{26}$Fe into $_{27}$Co, and Figure 1 shows no hint of such a non-Gaussian tail. Our maximum likelihood fit gives an abundance ratio of Co/Fe = 0.013, an order of magnitude lower than the ratio of Ga/Zn = 0.13 derived from the same fit. (The abundance ratio of Co/Fe outside the atmosphere [6] is 0.005, but it is not surprising that we find a higher ratio at TIGER under several mbar of atmosphere. The important point for this discussion is that our observed Co/Fe ratio is much lower than Ga/Zn.) The elemental abundances derived from our maximum-likelihood fit are shown as data points in Figure 3. Here we see directly our nearly equal abundances of $_{31}$Ga and $_{32}$Ge. TIGER is not the first instrument to see this result. A similar result was reported from the HEAO-C2 instrument [7]. The TIGER and HEAO-C2 results are not strictly comparable, because these TIGER results are at the detector, under a few mbar of residual atmosphere, while the HEAO-C2 observations were made on a spacecraft above the atmosphere. However, we do not expect the atmospheric propagation to change the Ga or Ge abundances relative to Ni or each other by a large amount, so we compare the results of these two instruments in Table 1. There we see that our TIGER results are consistent with those of HEAO-C2. (Calculations are underway to correct the observed TIGER results to the top of the atmosphere.)

Table 1. Relative abundances (Ni = 1000)

	TIGER	HEAO-C2
Ga	1.44 ± 0.25	1.01 ± 0.30
Ge	1.25 ± 0.23	1.11 ± 0.32

Implications for the cosmic-ray source

Figure 3 compares the relative abundances observed at the TIGER instrument with the abundances that would be expected for two possible models of cosmic-ray source abundances. In both of these models the source abundances are propagated through the Galaxy and through the mean residual atmosphere above the TIGER balloon.

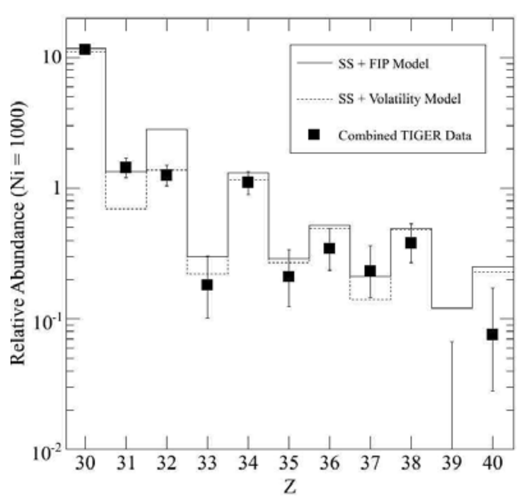

Figure 3: Relative abundances observed at the TIGER instrument, compared with results of propagating two possible source models to the balloon's atmospheric depth.

Both of these models start with Solar System abundances [1] modified with either preferential acceleration for elements with low FIP [8] or with preferential acceleration for refractory (non-volatile) elements. For all the elements with Z > 32 our results are consistent with both models; indeed the differences between the two models are small for these elements, because for them FIP and volatility are closely correlated. In the interval $30 \leq Z \leq 40$, only $_{31}$Ga, $_{32}$Ge, and $_{37}$Rb significantly break the degeneracy between FIP and volatility; for Ga and Ge the numbers of events we observe are sufficient to be able to distinguish between the two model predictions.

The result is that neither of these two models fits the data. While our Ga results are consistent with the FIP model and inconsistent with the volatility model, the Ge results are consistent with volatility and not with FIP. The problem is that the Solar System abundance of Ge is about three times that of Ga. Fragmentation of Ge into Ga during propagation leads to an expectation of observing Ge as roughly twice as abundant as Ga. But we observe these two elements to have nearly the same abundance.

Neither a preferential acceleration model based on FIP nor one based on volatility accounts for the observed near equality of abundance of Ga and Ge. The FIP model that best fits other elements does not distinguish among elements with FIP below about 8.5 eV, and both Ga (FIP = 6.0 eV) and Ge (FIP = 7.9 eV) fall into this low-FIP region. Similarly both Ga and Ge have nearly the same volatility; the condensation temperatures [1] of Ga and Ge are 971 K and 885 K respectively; so any volatility model must treat these two elements the same.

It remains to find a cosmic-ray source in which these two elements would be produced with approximately equal abundances. We have unsuccessfully looked for a process that would do so. For example, the explosive nucleosynthesis of massive stars [9] [10] produces two to three times as much Ge as Ga, similar to the relative abundance found in the solar system.

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