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COSMIC-RAY ABUNDANCES OF Sn, Te, Xe, AND Ba NUCLEI MEASURED ON *HEAO 3*

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ABSTRACT

Elements with even atomic number (Z) in the interval $50 \leq Z \leq 56$ have been resolved in the cosmic radiation using the Heavy Nuclei Experiment on the *HEAO 3* satellite. The observation that $_{50}$Sn and $_{56}$Ba are more abundant than $_{52}$Te and $_{54}$Xe is inconsistent with a pure *r*-process cosmic-ray source. Adjustment of source abundances for an enhancement of those elements with a low first ionization potential does not change this conclusion.

Subject headings: cosmic rays: abundances — nucleosynthesis

I. INTRODUCTION

Since the early work of Burbidge *et al.* (1957), the elements heavier than iron and nickel are assumed to have been formed primarily by neutron capture nucleosynthesis processes. These processes can be separated into two extreme classes depending on the intensity of the neutron flux involved. The *r*, or rapid, process, characterized by a high neutron flux, forms highly neutron-rich nuclei which decay back to the valley of beta stability only after the completion of nucleosynthesis. The *s*, or slow, process has a much lower flux of neutrons and allows for the decay of beta unstable nuclides before subsequent neutron captures. A specific astrophysical site for a pure *r*-process has not yet been established, but it has usually been associated with supernova explosions, which are also often assumed to be a source of cosmic rays. The *s*-process, on the other hand, is usually attributed to milder environments.

Both these processes produce a characteristic signature in the resulting elemental composition. These signatures are particularly evident in the relative abundances of $_{50}$Sn, $_{52}$Te, $_{54}$Xe, and $_{56}$Ba. The *s*-process produces a greater abundance of Sn and Ba than of Te and Xe, while the *r*-process results in an overabundance of Te and Xe. A decomposition of solar system material into *r*-process and *s*-process contributions (e.g., Cameron 1982*a*) clearly shows these differences. In both processes, the odd-charge elements are significantly less abundant than the adjacent even-charge elements.

The *HEAO 3* Heavy Nuclei Experiment was designed to measure the abundances of the elements heavier than iron in the cosmic radiation. We report here on the results of an analysis in the Sn to Ba region of a subset of data obtained over approximately 440 days of operation.

II. DATA

The detector was a large area particle telescope on the third *High Energy Astronomy Observatory* which was placed in orbit at 43°6 inclination and 495 km altitude on 1979 September 20. It consisted of six parallel plate ionization chambers, four pairs of multiwire ionization hodoscopes, and a dual radiator Cerenkov detector arranged symmetrically about the detector midplane (Binns *et al.* 1981*b*).

In this data subset, all the particles triggered the Cerenkov detector, at least one of the six ion chambers, and a minimum of two hodoscopes. Background from nuclear interactions within the instrument has been suppressed by requiring consistency between the signals from the ion chambers and the Cerenkov counter. Charge has been determined from the Cerenkov signal using Z-squared scaling normalized at iron. Sixty percent of the particles have been collected from directions and locations which correspond to a high geomagnetic cutoff (> 8 GV), ensuring that the Cerenkov signal is nearly independent of energy ($\beta \gtrsim 0.96$). The remainder of the particles have been selected to be high energy by comparing the Cerenkov and ion signals.

The resulting data set is shown in Figure 1. The main histogram exhibits peaks in the lower charges, thereby establishing our charge scale. Figure 1*a* is an enlargement of the region of interest which shows peaks at the even elements Sn, Te, Xe, and Ba. This measurement is the first to show resolved even-element peaks in this charge region.

The particles with assigned charge between 49.0 and 59.0 have been superposed in the modulo 2 histogram in

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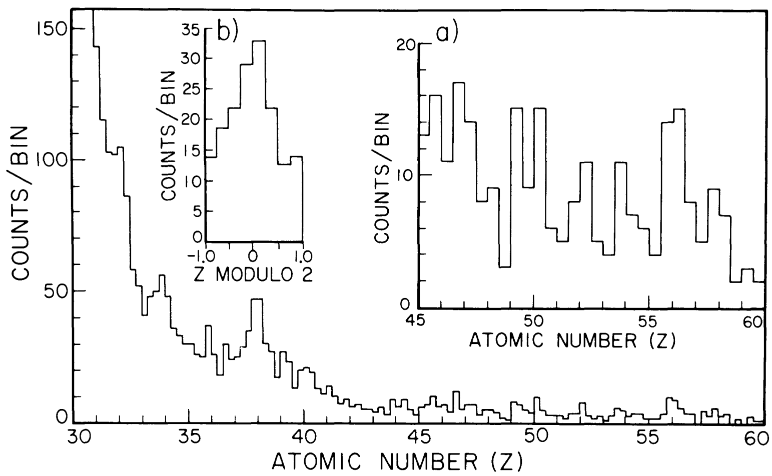

FIG. 1.—Histogram of the data from charge 30.0 to 60.0 in 0.25 charge unit bins. Although negligible over the limited range from $_{50}$Sn to $_{56}$Ba, charge-dependent biases in the consistency and energy selections are such that relative abundances of widely separated charges cannot be determined from this plot. Insets show (*a*) the region of interest in 0.5 charge unit bins and (*b*) a modulo 2 histogram of the data from charge 49.0–59.0 in 0.25 charge unit bins.

Figure 1*b*. This procedure, which bins each particle according to the difference between its assigned charge and the nearest even integer, superposes the even (and odd) element charge peaks, thus allowing a statistically significant determination of the instrument resolution. A Gaussian fit to this modulo 2 histogram, taking into account the spillover from the neighboring elements, indicates an rms charge resolution of 0.56 charge units. This verification of a peak at even charges, coupled with the peak at charge 38, shows that our assumption of Z-squared scaling cannot be significantly in error. Since elements with even charge dominate any suggested source, we are not likely to have an error of one charge unit, but an error of approximately two charge units cannot immediately be ruled out. However, if there were a two-charge unit error for any one of the peaks in Figure 1*a*, while the peak at 38 was correct, then the separation between even-element peaks in this interval would be approximately 1.7 or 2.3 charge units (depending of the direction of the error) rather than 2.0, with the result that the modulo 2 histogram would not have such a well-defined structure. Furthermore, such a large error in the charge estimate is not consistent with calculations of non-Z-squared Cerenkov effects by Derrickson, Eby, and Watts (1981). Our own earlier results (Binns *et al.* 1981*a*) using a different data subset have also shown the approximate validity of Z-squared scaling up to charge 40.

Table 1 gives the abundances of $_{50}$Sn, $_{54}$Xe, and $_{56}$Ba (normalized to our best estimate of the abundance of $_{52}$Te) obtained from a least-squares Gaussian fit to the data in Figure 1 having an assigned charge between 45.0 and 60.0 using 0.25 charge unit bins. The fit was made to both odd and even charge abundances, and the standard deviation of the assumed Gaussian charge resolution was parametrically varied to obtain a minimum χ^2. The χ^2 value as a function of the assumed standard deviation has a wide minimum between 0.4 and 0.6 charge units. The relative abundances of the even charge elements typically vary by less than 10% within this minimum, while the odd charge elements show a much greater variation, consistent with their not being resolved. The errors cited in the table are derived from this fit. No corrections have been applied to the abundances for fragmentation in the instrument since, over such a limited charge range, the relative adjustment factors for the even elements are less than ~ 3%. Also shown are results from *Ariel 6* and balloons (Fowler *et al.* 1981). The balloon data are "subject to significant and rapidly charge-dependent corrections" (Fowler *et al.*), while there has been no claim of resolution of the individual even-element peaks in the Sn-Ba region for the *Ariel 6* data.

TABLE 1

RELATIVE ABUNDANCES ($_{52}$Te ≡ 1)

Element	*HEAO*	*Ariel 6*	Balloon
$_{50}$Sn	1.33 ± 0.31	0.66 ± 0.22	1.21 ± 0.37
$_{52}$Te	1.00 ± 0.27	1.00 ± 0.23	1.00 ± 0.32
$_{54}$Xe	1.03 ± 0.25	0.34 ± 0.17	0.89 ± 0.27
$_{56}$Ba	1.52 ± 0.32	1.18 ± 0.23	0.87 ± 0.27

III. DISCUSSION

Figure 2 shows the data and the propagated abundances of the even elements from a calculation by

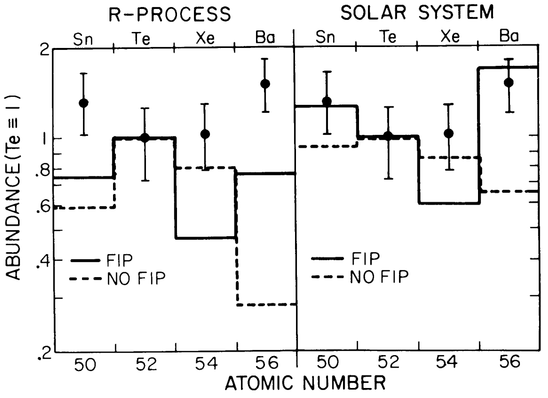

FIG. 2.—Our data compared to results of propagating an assumed *r*-process source and a solar system source through 5.5 g cm^{-2} of hydrogen (Brewster *et al.*, private communication; Brewster, Freier, and Waddington 1983). Solid line has adjustments applied for first-ionization-potential effects (FIP); dotted line does not.

Brewster *et al.* (private communication; see also Brewster, Freier, and Waddington 1983) using various sources and an exponential pathlength distribution with a mean of 5.5 g cm^{-2} of hydrogen. Since other results from lower charge regions indicate that there is an anticorrelation between first ionization potential and cosmic-ray elemental abundances relative to those of the solar system (Cassé and Goret 1978; Binns *et al.* 1981*a*), Figure 2 also includes the results of propagating *r*-process and solar system source abundances which have been adjusted to account for first-ionization-potential effects (Brewster, Freier, and Waddington 1983). The data are not consistent with the assumed *r*-process source material in either case, but reasonable agreement is obtained with solar system source material adjusted for first-ionization-potential effects. Although the large abundance of $_{58}$Ce shown in Figure 1 is also consistent with this conclusion, we have not considered it further here because its abundance is more affected by fragmentation of heavier nuclei.

The large abundance of either Sn or Ba relative to the other elements in this group argues against a source dominated by the *r*-process. This conclusion is emphasized in Figure 3, which compares the ratio of Sn to Te with the Ba/Te ratio. Our observed values are shown as the large diamond surrounded by error ellipses. Also shown are various calculated values derived from several assumptions regarding the source composition. Points are plotted for pure *r*-process abundances, pure *s*-process abundances, and for solar system source abundances, both with and without a bias due to first-ionization-potential effects. Two different predictions are shown (Brewster, Freier, and Waddington 1983; and Blake and Margolis 1981, also private communication), and the differences between corresponding points from the two calculations are an indication of the range of uncertainty in the expectations due to different source assumptions and propagation models. (Note that, for a given propagation model and given assumption about first ionization bias, the three calculated points fall on a straight "mixing line" whose ends represent pure *r* or pure *s* material, with varying *r/s* mixtures falling along the line.)

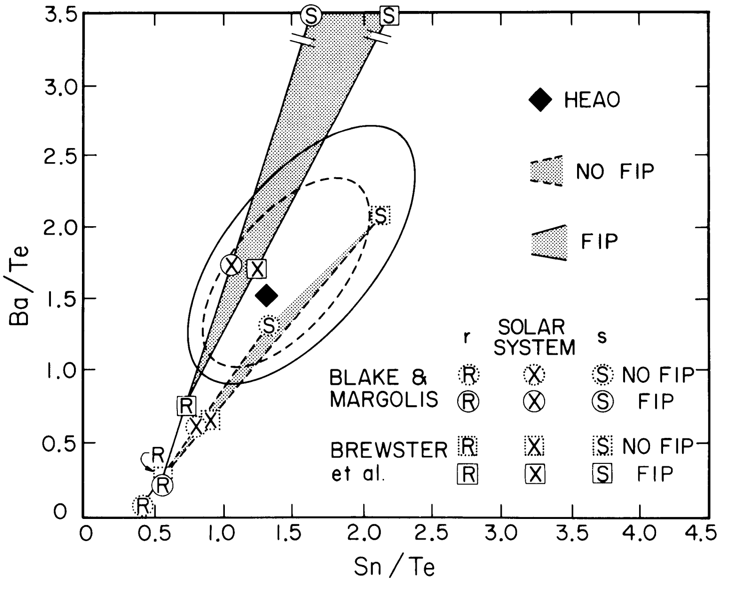

FIG. 3.—Our measurement of the abundance ratios plotted along with two propagations of *r*, *s*, and solar system material both with and without first-ionization-potential effects (FIP) included (see text). The solid error contour is the locus of abundance ratios which fit the data with the same χ^2 value such that there is a 68% probability that the actual value lies within the contour (50% for the dotted contour).

It is clear from this plot that our results are not consistent with pure *r*-process material either with or without first-ionization-potential effects. The difference between the closest *r*-process point and our measurement is significant at the 93% level. When due account is taken of first-ionization-potential effects, our data are in reasonable agreement with solar system material, whereas ignoring these effects suggests an *s*-process–dominated mixture.

In Figure 3 we chose to plot ratios formed from Sn, Te, and Ba; the solar system Xe abundance is less certain than the other three because it is based on an interpolation of adjacent nuclides (Cameron 1982*b*) rather than on measurements. However, our conclusions are not significantly altered if we include Xe. For each of the models represented by a point in Figure 3, we have made a least squares fit of the abundances of these four elements to our data. For any of the pure *r*-process models, the difference from our data is significant at least at the 93% level (reduced $\chi^2 \gtrsim 2.4$), while models with solar system source abundances and first-ionization-potential biases give reasonable fits to the data (reduced $\chi^2 \lesssim 1$).

The results in this charge interval are therefore consistent with conclusions from measurements in other charge intervals since the measured elemental abundances in the charge 26 to 40 region (Binns *et al.* 1981*a*) show a similarity with solar system material adjusted for first-ionization-potential effects. Additionally, the low abundance of the "actinides" ($88 \leq Z \leq 100$) (Binns *et al.* 1982) is consistent with solar system material but not with freshly synthesized pure *r*-process sources.

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Note added in proof.—Our results are also inconsistent at the $\gtrsim$ 99% level with the *r*-process abundances derived by subtracting the *s*-process values of F. Käppeler, H. Beer, K. Wisshak, D. D. Clayton, R. L. Macklin, and Richard A. Ward (1982, *Ap. J.*, **257**, 821) from those of the solar system recently compiled by Edward Anders and Mitsuru Ebihara (1982, *Geochim. Cosmochim. Acta*, **46**, 2363).

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