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COSMIC-RAY ABUNDANCES OF ELEMENTS WITH ATOMIC NUMBER $26 \leq Z \leq 40$ MEASURED ON *HEAO 3*

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ABSTRACT

Individual elements in the cosmic radiation of even atomic number (Z) in the interval $26 \leq Z \leq 40$ have been resolved and their relative abundances measured. The results are inconsistent with a cosmic-ray source whose composition in this charge interval is dominated by *r*-process nucleosynthesis. The ratios of cosmic-ray source abundances to solar system abundances in this interval follow the same general correlation with first ionization potential as for the lighter elements, although there are deviations in detail.

Subject headings: cosmic rays: abundances — nucleosynthesis

I. INTRODUCTION

The Heavy Nuclei Experiment flown on the third *High Energy Astronomy Observatory* (*HEAO 3*) has been used to measure the abundances of individual elements in the cosmic radiation with atomic number (Z) between 26 and 40. These measurements have produced definite abundance values for the even-Z elements and upper limits for the less abundant neighboring odd-Z elements.

For each of these even-Z elements (except $_{36}$Kr), the abundance is greater than that of the heavier elements, so the nuclei observed near Earth must be predominantly primary nuclei originating from the source, rather than secondaries produced during propagation by fragmentation of heavier nuclei. Consequently, conclusions about relative abundances at the cosmic-ray source for these elements are nearly independent of the specific model of interstellar propagation used to connect abundances measured near the Earth to the source values.

The relative abundances of these elements in the condensed bodies of the solar system are understood to result from a superposition of several distinct processes of nucleosynthesis (Cameron 1980; Wefel, Schramm, and Blake 1977; Wefel *et al.* 1981). For example, $_{38}$Sr in the solar system is almost entirely produced by slow neutron capture (the *s*-process), while $_{34}$Se has significant contributions both from the *s*-process and from rapid neutron capture (the *r*-process). Shirk *et al.* (1973) and Wefel, Schramm, and Blake (1977) noted that the abundances in the earliest cosmic-ray measurements in this charge range appeared similar to the solar system abundances, although individual elements were not resolved in those data. Similar conclusions were drawn from the data of Israel *et al.* (1979) and Tueller *et al.* (1979). More recently, Fowler *et al.* (1980) also noted this similarity in their *Ariel VI* data, although their preliminary fluxes were 2 to 3 times larger than those of Israel *et al.*

II. EXPERIMENTAL DESCRIPTION

HEAO 3 was launched 1979 September 20 into a circular orbit of altitude 495 km and inclination 43°.6. The detector system is composed of ionization chambers, a plastic Cerenkov counter, and a multiwire ionization hodoscope (Binns *et al.* 1981). Two subsets of these data are used in this analysis. The "low energy" data are for nuclei with kinetic energy between approximately 450 and 1200 MeV amu^{-1} at the top of the instrument. For these nuclei, Z and energy are assigned using the mean ionization chamber signal (I) and the mean Cerenkov signal (C). The functional form of I versus C for iron ($Z = 26$) is determined empirically using data collected in orbit. The second subset of data, designated "high rigidity," refers to nuclei whose geomagnetic cutoff rigidities are greater than 8 GV. At such high rigidities the Cerenkov response is nearly independent of energy, and we assign a value of Z based on the Cerenkov signal alone, using the iron as normalization. For the results presented here, both I and C are assumed to vary as Z^2. The well-defined peaks at even integer values of Z in Figure 1 demonstrate that the assumption of a pure Z^2 dependence of I and C is adequate.

These results are based on data from only the first $7\frac{1}{2}$ months of flight. Subsequent data will improve the statistical accuracy. In addition, refinements of the preliminary maps of areal nonuniformity of the detectors which were used here should produce an improved charge resolution. Further improvement in the resolution should result from use of the exact dependence of I and C on Z. Corrections to the Z^2 approximation for dE/dx (Morgan and Eby 1973; Ahlen 1978) imply an overestimate of Z in our low energy subset of approximately 0.3 charge units at $Z = 40$, decreasing mono-

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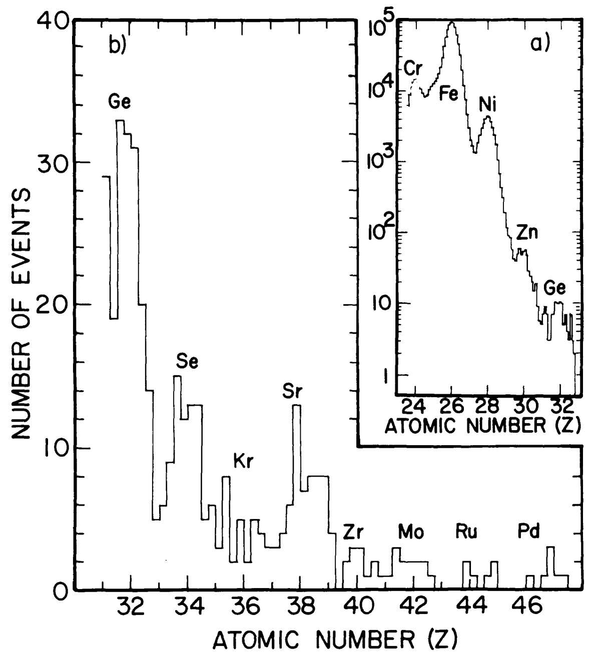

FIG. 1.—(*a*) Histogram of representative data for elements near iron. Ordinate is number of events per 0.1 charge-unit bin. Individual events have been weighted for instrument live time. (*b*) Histogram of data acquired over 216 days for $Z > 31$. Ordinate is number of events (unweighted) per 0.25 charge-unit bin. Normalization for this figure is 1.3×10^6 Fe.

tonically to zero at the normalization charge, $Z = 26$. The overestimate of Z in the high rigidity subset would be less. The resolution and statistics of our data do not yet permit a definitive test of these calculated deviations from a Z^2 response, so we have chosen to assume a simple Z^2 response for the analysis in this *Letter*. The conclusions presented here would not be significantly affected if these calculated deviations had been included in the analysis.

III. RESULTS

Figure 1*a* displays the combined results of the low energy and the high rigidity data for the elements near iron. Well-defined peaks at each even charge are apparent, despite the rapid decrease in abundances above iron. Figure 1*b* displays similar results for $Z > 31$. The histograms of these two figures have been fitted by a least-squares technique to give the relative abundances of individual elements shown in Table 1. (The low energy and the high rigidity subsets separately indicate no significant energy dependence of these abundances to within our current level of precision.)

In deriving our values for Table 1, we have applied the following corrections to the fit to these figures: (1) Some of the events with $Z \lesssim 35$ are recorded with low priority because of data-rate limitations; the resulting dead-time correction factor is 1.18, 1.12, and 1.04 for $Z = 32$, 33, and 34, respectively. (2) Nuclei of higher Z are more likely to fragment, and so be eliminated from

TABLE 1

RELATIVE ELEMENT ABUNDANCES

	NEAR EARTH			COSMIC RAY SOURCE (this experiment)
ELEMENTS	This Experiment[a]	*Ariel VI*[b]	Electronic Balloon-Borne[c]	
$_{26}$Fe	$\equiv 10^6$	$\equiv 10^6$	$\equiv 10^6$	$\equiv 10^6$
$_{27}$Co	$[1.7] < 2.0 \times 10^4$	...	$< 0.8 \times 10^4$	...
$_{28}$Ni	$4.95 \pm 0.05 \times 10^4$	...	$5.0 \pm 0.2 \times 10^4$	$5.10 \pm 0.05 \times 10^4$
$_{29}$Cu	$[1160] < 1300$	...	< 1000	...
$_{30}$Zn	584 ± 34	...	610 ± 90	586 ± 36
$_{31}$Ga	$[65] < 80$	...	103 ± 35	...
$_{32}$Ge	133 ± 14	...	94 ± 33	120 ± 18
$_{33}$As	$[15] < 29$	...	38 ± 13	...
$_{34}$Se	54 ± 8	117 ± 8	33 ± 12	47 ± 10
$_{35}$Br	$[17] < 25$	...	44 ± 15	...
$_{36}$Kr	17 ± 5	70 ± 6	34 ± 13	< 8
$_{37}$Rb	$[7] < 14$	...	23 ± 10	...
$_{38}$Sr	38 ± 7	61 ± 6	33 ± 13	42 ± 9
$_{39}$Y	$[15] < 25$	...	5 ± 5	...
$_{40}$Zr	7 ± 5	39 ± 5	16 ± 9	10 ± 6
$_{41}$Nb	$[4] < 7$	...	...	...
$_{42}$Mo	9 ± 4	13 ± 4	...	...
$_{44}$Ru	$[3] < 7$	20 ± 4	...	...

[a] The quoted rms uncertainties for the even-charge elements are statistical only; in addition there is a systematic uncertainty of as great as 20% in the Fe normalization for $Z \geq 32$. One sigma upper limits (see text) are given for odd-charge elements; the bracketed values are the formal results of the fit which gave the even-charge abundances; they are included only to permit proper summing of groups of elements.

[b] Fowler *et al.* 1980.

[c] Tueller *et al.* 1979 and Israel *et al.* 1979.

analysis, than are those of lower Z. To correct for this effect, observed relative abundances have been multiplied by a calculated factor which varies smoothly from 1.00 at $Z = 26$, the normalization element, to 1.12 at $Z = 44$. (3) Events in the low energy subset were all selected as having the same range of energies at the center of the instrument. A calculated correction factor which varies from 1.00 at $Z = 26$ to 0.95 at $Z = 44$ was applied, so Table 1 gives all abundances over the same rigidity interval.

This preliminary analysis does not give well-defined peaks at the odd charges, so their abundances cannot be determined without a complete understanding of the inherent charge resolution. Consequently, we report here only upper limits derived by assuming a Gaussian charge resolution characterized over the entire range by the observed resolution at Fe (0.33 charge units) and taking a 1 σ statistical upper limit on the resulting fit. Since this approach underestimates the width of the distribution at higher charges, and hence the spillover from the more abundant even elements, it overestimates the upper limits for the odd-charge elements. The quoted abundances for the even charges, where peaks are apparent in the data, are relatively insensitive to the assumed resolution.

Table 1 also gives preliminary results from the satellite *Ariel VI* which exhibit a monotonic decline in abundance with increasing charge. Their derived abundances are distinctly higher than ours over the entire charge range. Results from the electronic balloon-borne detector gave abundance levels similar to the *HEAO* values, although the poorer charge resolution of the balloon instrument led to overestimates of the odd-charge abundances.

Table 1 also shows our results propagated back to the cosmic-ray source, using a simple leaky-box model which neglects energy loss, assumes 5.0 g cm^{-2} of hydrogen as the mean leakage path length, uses fragmentation cross sections of Silberberg and Tsao (1973) and total interaction cross sections of Kirkby and Link (1966), and ignores elements with $Z > 40$. The calculation was carried out both with our best-fit values and with values at the limits of our error bars, providing an estimate of the uncertainties in the source abundances.

IV. CONCLUSIONS

Our results are plotted as data points in Figure 2. Shown for comparison with the cosmic-ray source abundances are the solar system abundances and the r-process contribution to these abundances for $Z \geq 33$, derived by subtracting from the solar system values an isotope-by-isotope s-process interpolation using the neutron capture cross sections of Allen, Gibbons, and Macklin (1971). It is apparent that the cosmic-rays in this charge interval are not dominated by the r-process. In particular, we observe Sr and Se having comparable abundances, while r-process Sr is approximately one-tenth as abundant as Se. Our results are more nearly comparable to the solar system abundances.

There are, however, significant differences. Figure 3

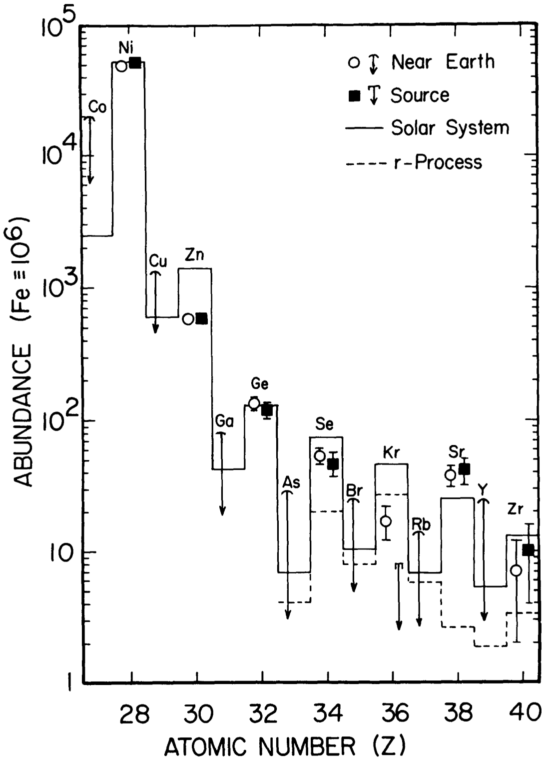

FIG. 2.—*Open circles:* this experiment. *Solid squares:* these results extrapolated to the cosmic-ray source. *Solid line:* solar system (Cameron 1980). *Dashed line:* r-process contribution to solar system.

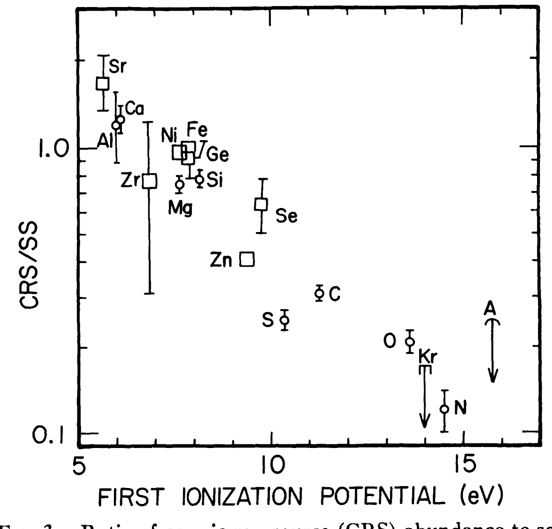

FIG. 3.—Ratio of cosmic-ray source (CRS) abundance to solar system (SS) abundance (Cameron 1980), normalized to Fe. Error bars indicate uncertainties only for cosmic-ray abundances. Squares are results of this experiment. Circles are data for lower Z from Lezniak and Webber (1978), except for Ca which is from Young *et al.* (1981). (If the isotope ^{40}Ca only were considered [Tarlé *et al.* 1979; Young *et al.* 1981] the Ca point would be at 0.92 ± 0.16. The higher value plotted is the result of including the ^{44}Ca source enrichment found by Young.)

indicates that the ratio of cosmic-ray source abundance to solar system abundance in the interval $26 \leq Z \leq 40$ follows the same general correlation with first ionization potential as was noted by Cassé and Goret (1978) for the lighter elements. It appears that the Sr extends the same correlation to lower I, although earlier Ca data (Tarlé *et al.* 1979) suggested otherwise.

Because the elements with high first ionization potential are either noble gases or are more likely to form volatile compounds, it has been suggested (Tueller *et al.* 1979; Cesarsky and Bibring 1980; Epstein 1980) that volatility may be a controlling factor in the comparison between cosmic-ray abundances and solar system abundances. However Figure 3 shows that Ge, which is volatile, is not significantly depleted with respect to Fe, which is not volatile.

The observation that the first ionization potential provides a general organization of the abundance ratios suggests that the abundances may be affected by a preferential injection mechanism during the acceleration process. However, there are discrepancies in the detailed correlation. For example, Zn, Se, and S have similar ionization potentials and similar volatility but quite different abundance ratios. Such discrepancies suggest that there may be differences, not related to first ionization potential, between the cosmic-ray source abundances and current estimates of solar system abundances. Improved statistics and extension of the current results to higher charges should permit the identification of any nucleosynthesis contribution to these abundance differences.

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