COSMIC-RAY ABUNDANCES OF THE EVEN CHARGE ELEMENTS FROM $_{50}$Sn TO $_{58}$Ce MEASURED ON HEAO-3

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ABSTRACT

Elements with even atomic number (Z) in the interval $50 \leqslant Z \leqslant 58$ 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 that $_{52}$Te and $_{54}$Xe indicates a substantial s-process contribution to the cosmic ray source. A significant abundance of $_{58}$Ce provides further support for this finding.

1. Introduction

The processes believed primarily responsible for the formation of the ultra-heavy cosmic rays (atomic number $Z > 30$) have conventionally been represented by the two extremes of a more generalized neutron capture process with each extreme the result of a different nucleosynthesis environment. The classical s-process, characterized by low fluxes of neutrons and believed to occur in red giants, forms those nuclides which lie along its neutron capture path in the valley of beta stability. The other extreme, the r-process, is characterized by high neutron fluxes and has usually been associated with supernovae. It forms highly neutron rich nuclei which decay back to the valley of beta stability. The Sn-Ce region is particularly suited for studying the relative contributions of these two processes to the cosmic radiation because in this charge range the s-process predominantly produces $_{50}$Sn, $_{56}$Ba, and $_{58}$Ce, while the r-process, as deduced from solar system abundances, produces mainly $_{52}$Te and $_{54}$Xe.

2. Data

Figure 1 shows a histogram, in 0.25 charge unit bins, of data obtained with the Heavy Nuclei Experiment on the HEAO-3 satellite (Binns et al. 1981). This data set has been selected from events with energies above about 2.5 GeV/nuc in the same manner as the one presented in Binns et al. (1983). However, as a result of a reanalysis of the data, some additional time periods were included (~4% increase) and a restriction on event location in the Cerenkov radiator was relaxed (~12%). Additionally, events having ambiguous trajectories (a total of 58 in the Sn-Ce region), previously included in the data, were eliminated here. These adjustments did not significantly change any of the relative abundances in the Sn-Ce region.

TABLE 1
OBSERVED ABUNDANCES
(normalized to $_{52}$Te $\equiv$ 1)

Element	Abundance
Sn	1.65 ± 0.38
Te	1.00 ± 0.28
Xe	1.02 ± 0.27
Ba	1.80 ± 0.30
Ce	0.81 ± 0.25
Fe/10^6	0.29 ± 0.05

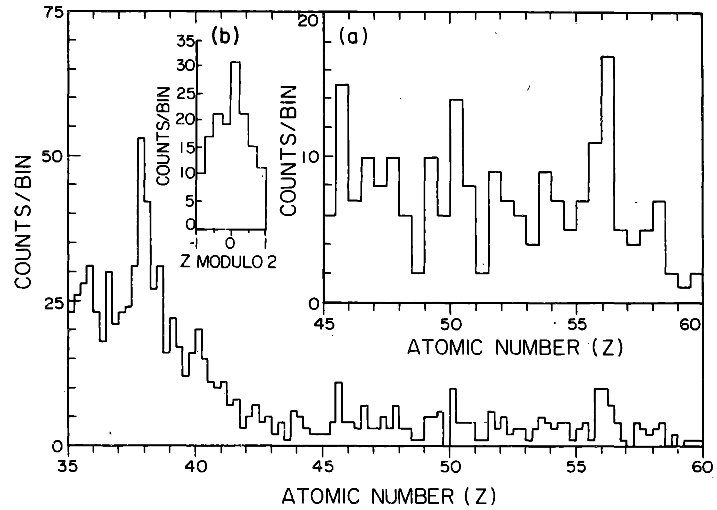

Figure 1. Charge histograms. Inset (a) expands the Sn-Ce region. Inset (b) shows a modulo 2 superposition of the even charge peaks in that region.

As in the previous analysis, charge has been determined from the Cerenkov signal using Z^2 scaling normalized at iron. Although negligible over the limited range from $_{50}$Sn to $_{58}$Ce, charge dependent biases in the consistency and energy selections may affect the relative abundances of widely separated charges. The two insets in Figure 1 show the region of interest in 0.5 charge unit bins (a), illustrating the resolution of the even charge elements, and a modulo 2 superposition of the even charge peaks (b) which implies a charge resolution of 0.55 charge units. Table 1 gives the abundances of $_{50}$Sn, $_{54}$Xe, $_{56}$Ba, and $_{58}$Ce normalized to our best estimate of the abundance of $_{52}$Te using similar fitting procedures as in Binns et al. (1983).

3. Discussion

As comparison nucleosynthesis sources we have used the s-process of Kappeler et al. (1982), the solar system abundances of Anders and Ebihara (1982), and a hybrid r-process derived from both by means of an isotope by isotope decomposition (Krombel 1983). The assumed source abundances were converted to flux observed at earth using the propagation calculations of Brewster, Freier, and Waddington (1983 and private communication) for a 5.5 gm/cm^2 simple exponential pathlength distribution. The results for the even charge elements in this region are shown in the upper half of Figure 2 along with our observations (filled circles with error bars). Because of the possibility of first ionization potential effects in the cosmic ray abundances (Casse and Goret 1978 and references therein), we have also performed the same comparison for sources which have been adjusted for possible first ionization potential (FIP) biases using the model of Brewster, Freier, and Waddington (1983), an exponential in first ionization potential I (9.31exp[-0.288I] where I is in eV). These results are shown in the lower panels of Figure 2.

Since we are examining only a limited charge region, the overall normalization between the model and our data was allowed to vary to obtain a minimum in the χ^2. The abundance of $_{52}$Te was defined to be one for all the propagation results. As can be seen from the figures, the pure r-process result is in disagreement with our data (at the > 99% level) both with and without the first ionization potential biases included.

In order to examine the question of what fraction of the cosmic ray source may be the result of r-process nucleosynthesis, we consider as possible sources linear combinations of pure r-process material and pure s-process material of the form

$$X_i = k{\cdot}S_i + (1 - k){\cdot}R_i$$

where S_i denotes the s-process abundance of element i, R_i denotes its r-process abundance, and k is a "mixing" parameter which varies from 0 to 1 as X_i goes from pure r-process to pure s-process. If S_i and R_i are chosen to be those s- and r-process abundances present in the solar system, X_i is proportional to the solar system abundances when k = 0.5 (neglecting possible p-process contributions). For each value of k, we find the best fit χ^2 between the data and the mixture by allowing the overall normalization to be a free parameter. The curve labeled NO FIP in Figure 3 shows the results of applying this procedure to the propagated sources without FIP adjustments applied.

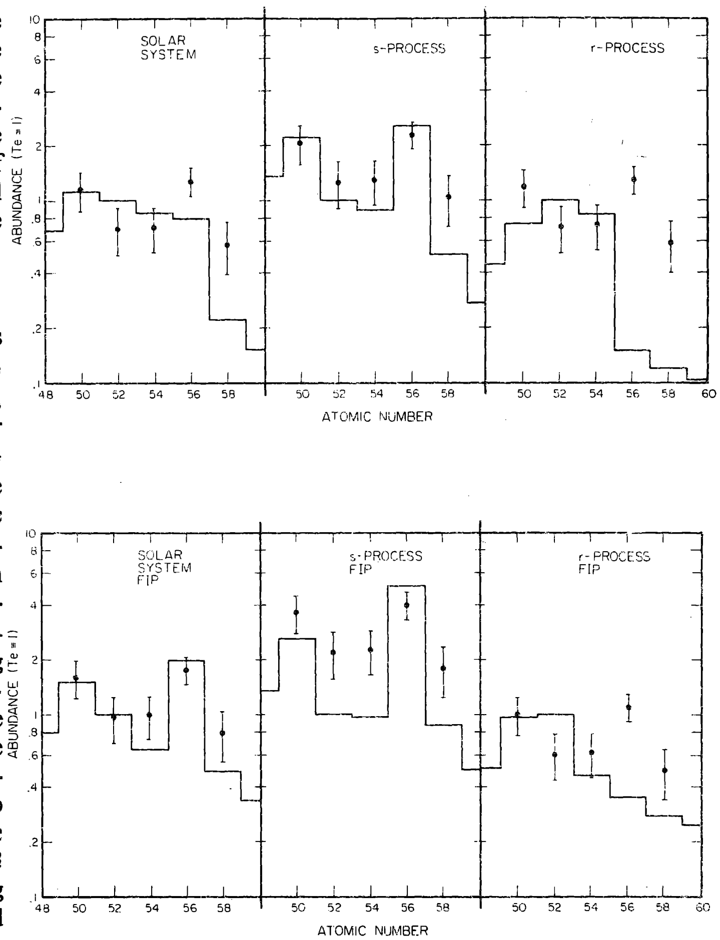

Figure 2. Measured (points) and calculated (lines) abundances normalized at Te plotted as a function of charge. The calculations assume r, s, or solar-system sources as labeled. The curves in the lower panels are adjusted for FIP effects; those in the upper panels are not.

Note that the best fit is obtained for a k value of 0.83 ± 0.11 which corresponds to an r-process to s-process ratio which is 0.20 $^{+0.18}_{-0.14}$ times that of the solar system. The errors are the χ^2 + 1 points of the illustrated curve. The curve labeled FIP uses FIP adjusted sources and obtains a bestfit k value of 0.40 $^{+0.11}_{-0.10}$, corresponding to an r-process to s-process ratio of

1.5 $^{+0.8}_{-0.5}$ that of the solar system. Thus if no first ionization potential effects are considered, our data are most consistent with an s-process dominated mixture. Inclusion of FIP effects yields a result which is consistent with a solar system type mixture. With the specific form for FIP assumed here, a modest r-process enhancement is suggested.

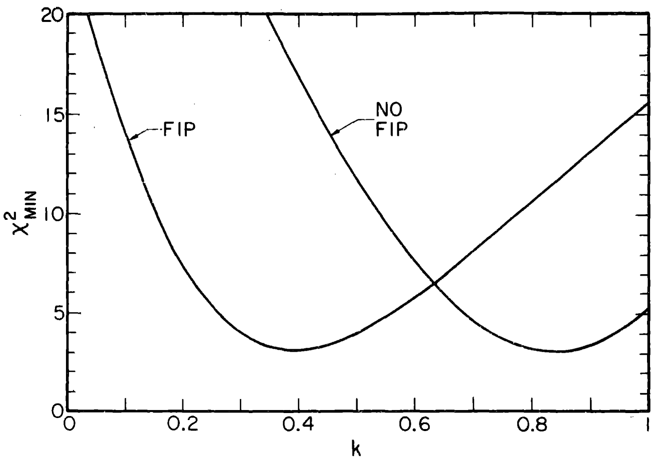

Figure 3. The χ^2 of the fit of a mixture of r- and s-process material to the cosmic-ray abundances as a function of the mixing parameter k, with and without adjustment for first ionization potential effects (FIP). The value k = 0 corresponds to pure r-process; k = 1 to pure s-process.

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