COSMIC-RAY ENERGY SPECTRA BETWEEN TEN AND SEVERAL HUNDRED GeV/amu FOR ELEMENTS FROM $_{18}$Ar TO $_{28}$Ni — RESULTS FROM HEAO-3

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Abstract. Using the relativistic rise of energy loss as a measure of energy, we have determined the energy dependence of the abundances relative to $_{26}$Fe of the elements $_{18}$Ar, $_{19}$K, $_{20}$Ca, $_{21}$Sc, $_{22}$Ti, $_{23}$V, and $_{28}$Ni, from 10 to several hundred GeV/amu. From the energy dependence of the observed Ar/Fe and Ca/Fe ratios we infer primary source ratios for these elements.

1. Introduction. The energy-loss of a charged particle in gas exhibits a logarithmic increase with increasing energy over the interval from a few GeV/amu to several hundred GeV/amu. We have used this relativistic rise in the ionization chambers of the Heavy Nuclei Experiment (HNE) on HEAO-3 [1] to measure particle energies above 10 GeV/amu. For more detail see [2,3]. The present paper differs from preliminary results [4] in that we have evaluated the uncertainties caused by various assumptions and we have corrected an error in the calculation of the effects of interactions in the detector.

2. Instrument Description and Data Selection. The HNE had six ionization chambers, a Cherenkov detector, and four multiwire ionization hodoscopes. The results presented here come from a 1 m^{2}sr·yr, high resolution subset of our data, consisting of nuclei that penetrated the Cherenkov detector and all six ionization chambers. We consider only particles with geomagnetic cutoff >8 GV. The atomic number, Z, of each nucleus is determined from Z_C, the square-root of the Cherenkov signal, normalized so Z_C=Z for high energy. The energy of each nucleus is derived from the relativistic rise, ρ, defined by $\rho = Z_I/Z$, where Z_I is the square-root of the ionization signal normalized so that Z_I=Z near 2.5 GeV/amu. Consistency checks were applied to exclude most of the nuclei which suffered nuclear interactions in the instrument.

3. Analysis. We found the number of events of each Z in narrow intervals of ρ. We derived an energy calibration of ρ by comparing our Fe observations with those expected from folding a trial calibration with a differential Fe energy spectrum derived from a compilation of previously published measurements [5]. While the implied energy calibration curve depended upon the assumed Fe energy spectrum, our results for the energy dependence of secondary-to-primary abundance ratios and primary values of Ar/Fe and Ca/Fe were insensitive to the shape of the assumed Fe spectrum. We adopted a spectrum which went as $E^{-2.7}$ at high energy, but our final results were essentially the same if we used $E^{-2.5}$.

The slope of the calibration curve (heavy line in fig. 1), implies that the Z_I resolution, 0.4 charge units (cu) rms, corresponds to an energy resolution of a factor of 1.5 below 50 GeV/amu and 1.9 above 50 GeV/amu. When this resolution and the steep energy spectrum are taken into account, the mean energy of particles observed in any ρ bin is significantly lower than that corresponding to the center of the bin. The light solid line in fig. 1 shows the mean energy for particles observed within a bin of width 0.2 cu in Z_I centered at each value of ρ, using our assumed energy spectrum for Fe. Since secondary elements are observed to have a steeper energy spectrum, the mean energy corresponding to the same value of ρ is slightly different for each element. For example, the dashed curve is the corresponding one for Ti.

The abundance for each (Z,ρ) bin was corrected for interactions in the detector system and then divided by the number in the Fe bin at the ρ corresponding to the same energy.

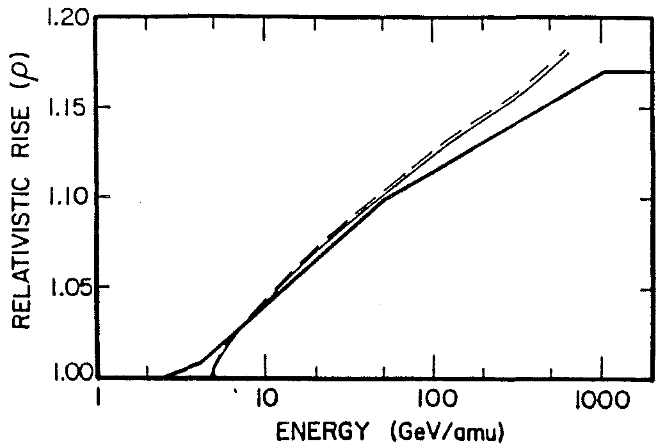

Fig. 1. Calibration of relativistic rise (ρ) as a function of energy.

Figures 2, 3, and 4 show (•, o) our resulting abundances relative to Fe. Also shown (X) are the results from the Danish-French (DF) experiment on the same spacecraft [6]. The two sets of data display good agreement where they overlap, 10 to 25 GeV/amu. The error bars on our data are statistical only. The light lines indicate the sensitivity of our results to the uncertainty of the corrections for interactions, by showing the locations of our data points under the extreme assumptions for the cross-sections.

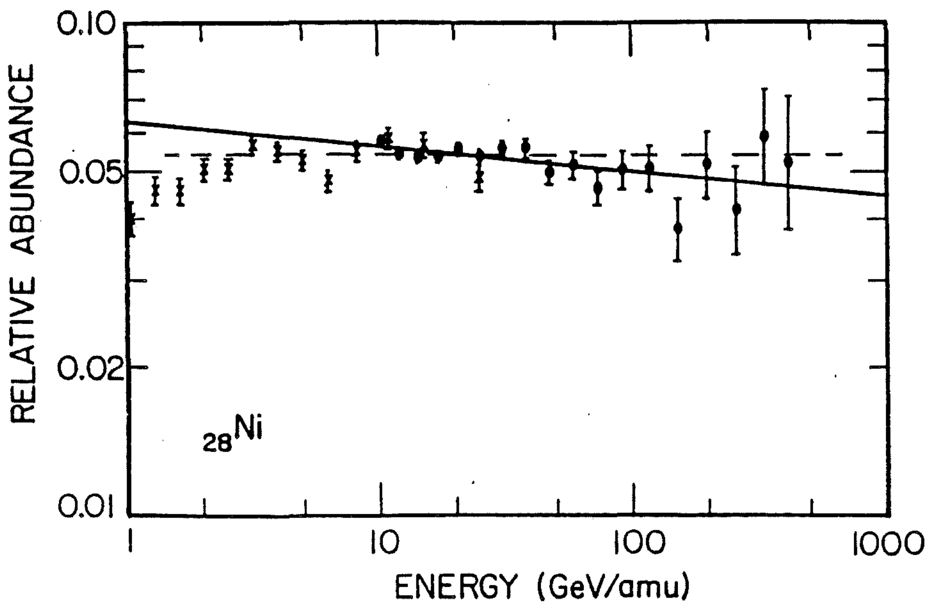

Fig. 2. Abundance of Ni relative to Fe (Ni/Fe ratio) vs energy.

4. Discussion. Our data for the Ni/Fe ratio between 10 and 500 GeV/amu (fig. 2) suggest a slight energy dependence, with a best fit power law of exponent -0.050 ± 0.016. Ignoring this slight energy dependence, our data give a mean Ni/Fe ratio above 10 GeV/amu of 0.054 ± 0.001. This result agrees with the highest energy points of the DF experiment. However, the data of that experiment suggest an energy dependence of this ratio, rising from about 0.045 at about 1 GeV/amu to about 0.055 at about 10 GeV/amu. Data from our HNE between 0.5 and 1 GeV/amu [2,7] also indicate a Ni/Fe ratio of about 0.045.

For K/Fe, Sc/Fe, Ti/Fe, and V/Fe (fig. 3), our data indicate an extension to about 150 GeV/amu of the same power-law dependence as indicated by the DF data. The best fit exponents for these four ratios, combining the data plotted here from both experiments, are respectively -0.31 ± 0.01, -0.25 ± 0.02, -0.28 ± 0.01, and -0.23 ± 0.02.

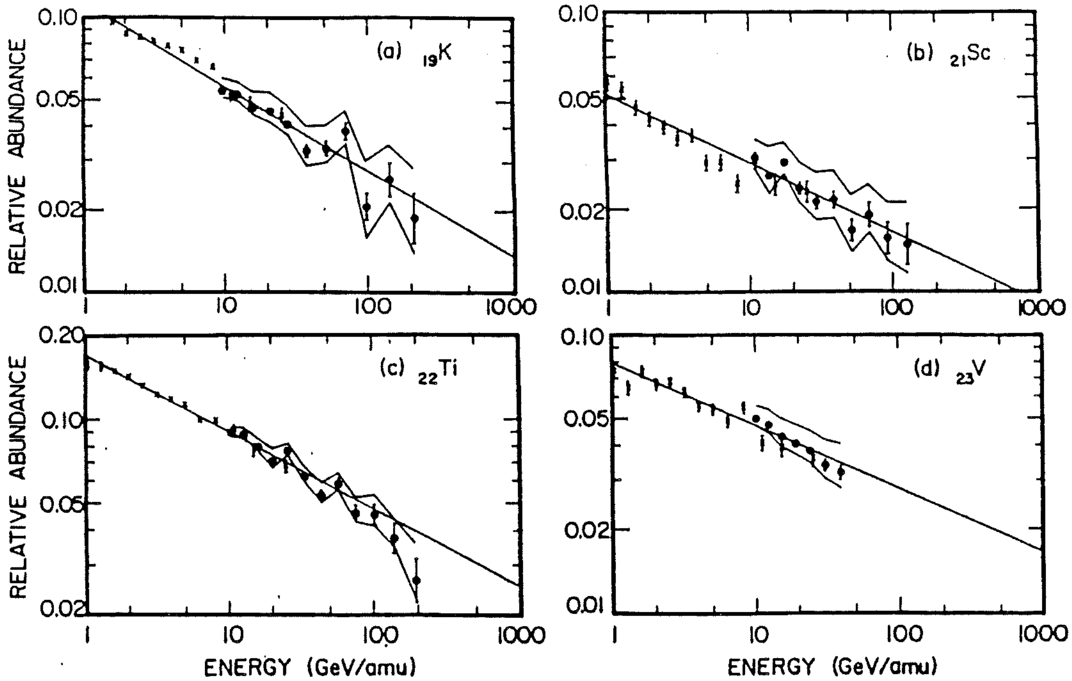

Fig. 3. Abundances of secondary elements relative to Fe.

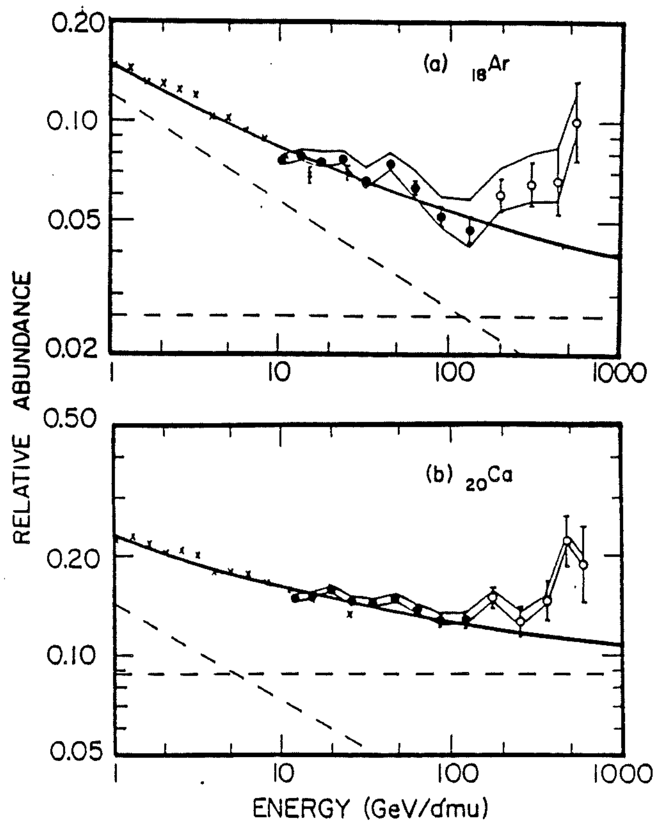

Fig. 4. Abundances relative to Fe of elements with primary and secondary components.

Our data for the Ar/Fe and Ca/Fe ratios (fig. 4) indicate a leveling above the energies of the DF experiment, as would be expected for an energy-independent primary component that becomes increasingly significant at higher energies as the secondary component becomes less abundant. We fitted the combined data from the two experiments to a function aE^p+b, with $p = -0.321 \pm 0.028$ for Ar/Fe and -0.291 ± 0.010 for Ca/Fe, and found primary abundance ratios, Ar/Fe = 0.026 ± 0.007 and Ca/Fe = 0.088 ± 0.007. These primary ratios are insensitive to whether or not we included our four or five highest energy points (○) in the fitting, due to their low statistical weights.

Our Ar/Fe and Ca/Fe primary ratios relative to the solar system value [8], are shown in fig. 5. The other points are from galactic propagation calculations on the DF data [9], a measurement of ^{40}Ca/Fe [10], and solar coronal abundances inferred from solar energetic particles [11]. Also, for Ar we display an upper limit taken directly from our data at 100 GeV/amu. It is clear that the Ar abundance has been subjected to a fractionation process.

The highest energy points in fig. 4 suggest that the Ar/Fe and Ca/Fe ratios increase significantly above about 200 GeV/amu. These apparent increases could be due to (a) a real increase in the primary abundance ratios, (b) a flattening or upturn in the secondary/primary ratios, or (c) an instrumental artifact.

One possible instrumental effect could be: If the ρ vs energy calibration curve for elements lighter than Fe did not flatten off at the highest energies quite as much as did the curve for Fe, then at these highest energies the ratio of Ca at some ρ to Fe at the same ρ would be a ratio of Ca at some energy to Fe at a *higher* energy. Because of the steepness of the energy spectra and the flatness of the ρ vs energy curve at these highest energies, only a small difference is necessary to change the ratio by a factor of two. We do not believe that this problem affects the results below about 150 GeV/amu, because at these energies the different elements show different energy dependences (flat for Ni/Fe, power-law fall for secondaries/Fe) in a way that is not surprising.

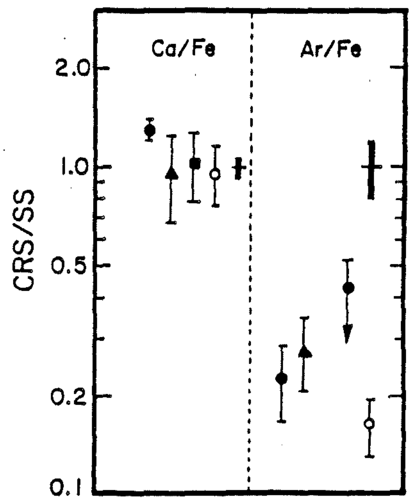

Fig. 5. Cosmic-ray source ratio divided by solar system ratio [8] for Ca/Fe and for Ar/Fe. Solid points are for galactic cosmic rays: circles, this experiment; triangles, [9]; square, [10]. Open circles, solar energetic particles [11]. Error bars plotted on data points ignore uncertainties in the solar-system ratio. Solid bars centered at 1.0 indicate uncertainties of solar-system ratios. Note that our Ar/Fe ratio derived from the fit in fig. 4 indicates a significant fractionation relative to Ca/Fe. This fractionation is also apparent in our upper limit to Ar/Fe which we derived by assuming that the entire observed abundance at 100 GeV/amu is primary.

If future studies demonstrate that our calibration is correct above 150 GeV/amu then the turn-up in the data would imply a real effect in the cosmic rays. Because we have no data for the pure secondary elements above about 150 GeV/amu, we cannot exclude the possibility of a flattening or turn-up of the secondary/primary ratio at these higher energies. Indeed such an effect is predicted by the closed-galaxy model [12].

If the turn-up is due neither to an instrumental artifact nor to a change in the slope of the secondary/primary ratio, then it would indicate a difference between the cosmic-ray source composition at several hundred GeV/amu and that at lower energies. Evidence for such a heterogeneity of cosmic-ray sources would be important.

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