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ISOTOPIC COMPOSITION OF HEAVY COSMIC RAYS

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ABSTRACT

We have measured the mean isotopic composition of even-charge cosmic ray elements with $14 \leq Z \leq 26$ near 0.8 GeV/N using a balloon-borne ionization-chamber/Cerenkov-counter detector system. The experimental method makes use of the geomagnetic field as a magnetic spectrometer. Results indicate that the most abundant isotopes at the cosmic ray source are Si-28, S-32, and Ca-40, like the solar system; but Fe-54, unlike the solar system.

We report here the first results on the isotopic composition of cosmic ray elements of even charge (Z) in the interval $14 \leq Z \leq 26$ for energy near 0.8 GeV/Nucleon. Previous workers[1-6] have published results on the chemical composition in this charge and energy region, however this is the first report on the mean atomic weight (A) of these elements. Isotopic measurements of cosmic rays, in particular that of Fe, have great astrophysical significance since they have a direct bearing on the nucleosynthetic processes which create the heavy elements. The technique employed here was first described by Lund et al.[7-8] We make use of the geomagnetic rigidity cutoff and a detector which measures charge and velocity of individual nuclei to determine the relative mass to charge (A/Z) ratio for different elements.

The detector system (Figure 1) is comprised of pulsed ionization chambers, a Lucite Cerenkov counter, and a scintillation counter hodoscope; the geometry factor is 0.9 m^2ster. The system was flown on a balloon launched from Southeastern Missouri on 13 September 1972 which floated near 3.2 g/cm^2 residual atmosphere. Results on chemical composition and energy spectra derived from this flight will be published at a later date (see also Ref. 6 and Ref. 9). The data presented in this paper were gathered during a period of nine hours of flight when the balloon remained very near a line of constant geomagnetic cutoff (~3.0 GV vertical cutoff). This analysis includes about 4500 events due to Fe.

The important characteristics of the detector system for the isotope study are its good charge resolution, good velocity resolution, and large geometry factor. The charge resolution varies from σ = 0.32 charge units at Si to 0.34 charge units at Fe. Due to the relatively low abundance of the odd-Z elements the contamination of the even-Z elements is quite small (2% at Fe to 11% at Ar) and has been taken into account.

The Cerenkov counter areal non-uniformities have been measured in the laboratory so the velocity resolution is limited only by photo-electron statistics. For the range of elements and energies with which we are concerned the momentum-per-nucleon resolution is sufficiently narrow that it has a negligible effect on our isotope results.

The isotope analysis procedes as follows. The rigidity, ρ, of a nucleus is related to its momentum-per-nucleon, p, by

$$\rho = (A/Z)p \quad . \tag{1}$$

We fit the integral momentum-per-nucleon spectrum for the ith element to a power law over a range of p near the cutoff.

$$J_{ip} = \alpha_i p^{\gamma_i} \quad . \tag{2}$$

If the total observed flux of the ith element is J_{ic}, then we can define the effective cutoff rigidity, ρ_i, using

Eqs. (1) and (2), by

$$J_{ic} = \alpha_i (Z_i/A_i \ \rho_i)^{\gamma_i} \quad . \tag{3}$$

Combining Eqs. (2) and (3) we can write

$$A_i/Z_i = (J_{ip}/J_{ic})^{1/\gamma_i} \ (\rho_i/p) \tag{4}$$

for any p provided Eq. (2) holds for all allowable momenta less than p. Combining Eq. (4) for element i with the similar equation for element j we find

$$\frac{A_j}{Z_j} = \frac{A_i}{Z_i} \left(\frac{J_{jp} J_{ic}}{J_{jc} J_{ip}} \right)^{1/\gamma_i} \left(\frac{J_{jc}}{J_{jp}} \right)^{\varepsilon} \frac{\rho_j}{\rho_i} \tag{5}$$

where $\varepsilon \equiv 1/\gamma_i - 1/\gamma_j$. Although ρ_i is still not well known the ratio ρ_j/ρ_i is identically unity if $\gamma_i = \gamma_j$. In fact we find the spectra of Fe and Fe secondaries to be somewhat flatter than those of Si and S . We find $\gamma_{Si} = -1.50$ and $\gamma_{Fe} = -1.43$ in the momentum-per-nucleon region near geomagnetic cutoff. Using these γ's, a penumbral width of 15% (typical for cutoffs near 3.0 GV), and a worst case penumbral structure[8] we find ρ_{Fe}/ρ_{Si} differing from unity by less than 5×10^{-4}. Thus by comparing two elements, measured at the same location by the same detector, we essentially eliminate the ρ_i in Eq. (4). Equation (5) therefore permits us to determine relative values of A/Z for two elements from the observed total fluxes (J_c) above cutoff and the fluxes (J_p) above some arbitrarily chosen momentum-per-nucleon (p). The value of p must be chosen high enough to insure J_p is unaffected by the geomagnetic cutoff. Since we find the Si spectrum to fit the power law down to at least 1.53 GeV/c,[9] we select this as the value of p used for determination of J_{ip}. We have also analyzed the data using larger values of p and find similar results but with larger statistical errors. (If the flux of one element consists of several isotopes, the A_k in Eq. (5) should be replaced by $\langle A_k^{\gamma_k} \rangle^{-\gamma_k}$ where the brackets denote the average over the isotopes and the same γ_k is assumed to hold for all isotopes. However, the precision of our results does not warrant this distinction, and we treat A_k simply as the mean atomic weight.)

In Table 1 we present results of the analysis. Column 1 shows the relative values of A/Z with respect to that of Si, errors include statistical uncertainties on the J's and the experimental uncertainty on the ε. Column 2 shows the same data as column 1 corrected for contamination due to atmospheric secondaries. This correction is due to the small fraction of nuclei (ranging from 6% of the S to 15% of the Cr) observed at the detector which are the results of interactions in the atmosphere. These nuclei passed through the geomagnetic field as one element, with a specific A/Z, interacted, and were detected as secondaries with a lower Z.

Column 3 shows the resultant values of the mean A calculated from Column 2 with arbitrary assumption of a mean A of 28.5 for Si. Thus far we have determined only <u>relative</u> values of A but we note that the relative values of A for Si and Fe are not consistent with the solar system values.[12] If cosmic ray Si is primarily Si-28 then Fe must have a large portion of Fe-54.

In order to determine absolute value of A/Z we need prior knowledge of the mean A for some element or elements. We use the fact that the observed Ar, Ti, and Cr at earth are almost entirely spallation products of Fe on the interstellar gas.[1] We have calculated the mean A expected for each of these spallation products and shown that the result is insensitive to the isotopic composition of the source. This result was derived from a propagation calculation consisting of solving the set of coupled equations

$$N_j/X + N_j/\lambda_j = Q_j + \sum_i (N_i/\lambda_i)p_{ij} \tag{7}$$

where Q_j and N_j refer to the source strength and observed abundance, respectively, of a given isotope of a given element. p_{ij} are the fragmentation parameters derived from the semi-empirical cross-section formulae of Silberberg and Tsao,[11] assuming unstable fragments with $t_{1/2} \lesssim 10^6$ year decay to the stable daughter. The λ_i are the interaction mean free paths;[13] X is the mean leakage length for escape from the galaxy. By assuming that the elements with $21 \leq Z \leq 25$ have a negligible abundance at the source we find that a leakage length of 4.5 g/cm^2 allows us to account for the observed abundances of each of these secondaries. Using this leakage length we can account for all the observed elemental abundances for ($14 \leq Z \leq 26$) with a source consisting only of Si, S, Ca, and Fe in the ratio of 0.97:0.18: 0.15:1.00. (As has previously been noted[1,14] there are differences between the chemical composition of the cosmic ray source and the solar system.[12] The solar system values are given in Column 6 for comparison.) Results of chemical composition from the propagation calculation are shown in Column 5. Column 4 shows the observed chemical abundances extrapolated to the top of the atmosphere.

Since Ar, Ti and Cr are negligible at the source we can determine a theoretical value for the mean A of these elements at earth from this propagation calculation. We find the mean A of these secondaries varies only by 0.3 AMU for Cr and 0.1 AMU for Ti and Ar as we vary the source Fe from pure Fe-54 to pure Fe-56 and the source Ca from pure Ca-40 to pure Ca-48. Our best theoretical estimates for these mean A are; Ar-37.3, Ti-47.1, Cr-51.4. Assuming the mean A of Ar is 37.3, and using our measured fluxes with

Eq. (5), we calculate the mean A of Fe to be 54.3 ± 0.7. Similarly, using Ti and Cr as references we find 54.2 ± 0.7 and 55.2 ± 0.7 respectively, in agreement within the statistical errors. From these three we derive our best estimate of the mean A of Fe at earth to be 54.6 ± 0.5. Similarly using the theoretical values of Ar, Ti, and Cr as references, our best estimates for the mean A of Si, S and Ca at earth are 28.5 ± 0.5, 32.1 ± 0.6 and 41.8 ± 0.5. These results are summarized in Column 7.

We have used the same propagation model to investigate the source isotopic composition of Si, S, Ca, and Fe. The mean values of A at the source to give the observed values of A at earth are shown in Column 8.

The above analysis assumed that all isotopes of a given element have the same γ. Calcium presents a special problem in this regard. We observe $\gamma_{Ca} = -1.47$, midway between that of Si (-1.50) and that of Fe and the Fe secondaries (-1.43).[9] Since the Ca at earth is about 60% primary and 40% secondary it seems likely that the observed γ_{Ca} can be explained by assuming the primary Ca has $\gamma = -1.50$ and the secondary Ca has $\gamma = -1.43$. Using these assumptions we can account for the spectral differences in the analysis. In this particular case, since the γ's are not very different, the uncertainties introduced by this effect are small.

For the sake of comparison we show in Column 9 mean atomic masses in the solar system.[12] Note that Si, S and Ca at the cosmic ray source are mostly alpha-particle nuclei, similar to the solar system. However, while the solar system Fe is overwhelmingly Fe-56, a very significant fraction of the cosmic-ray Fe is Fe-54. The implications of this result have serious ramifications with respect to the properties of cosmic-ray sources and cosmic-ray nucleosynthesis which warrant further theoretical and experimental investigation.

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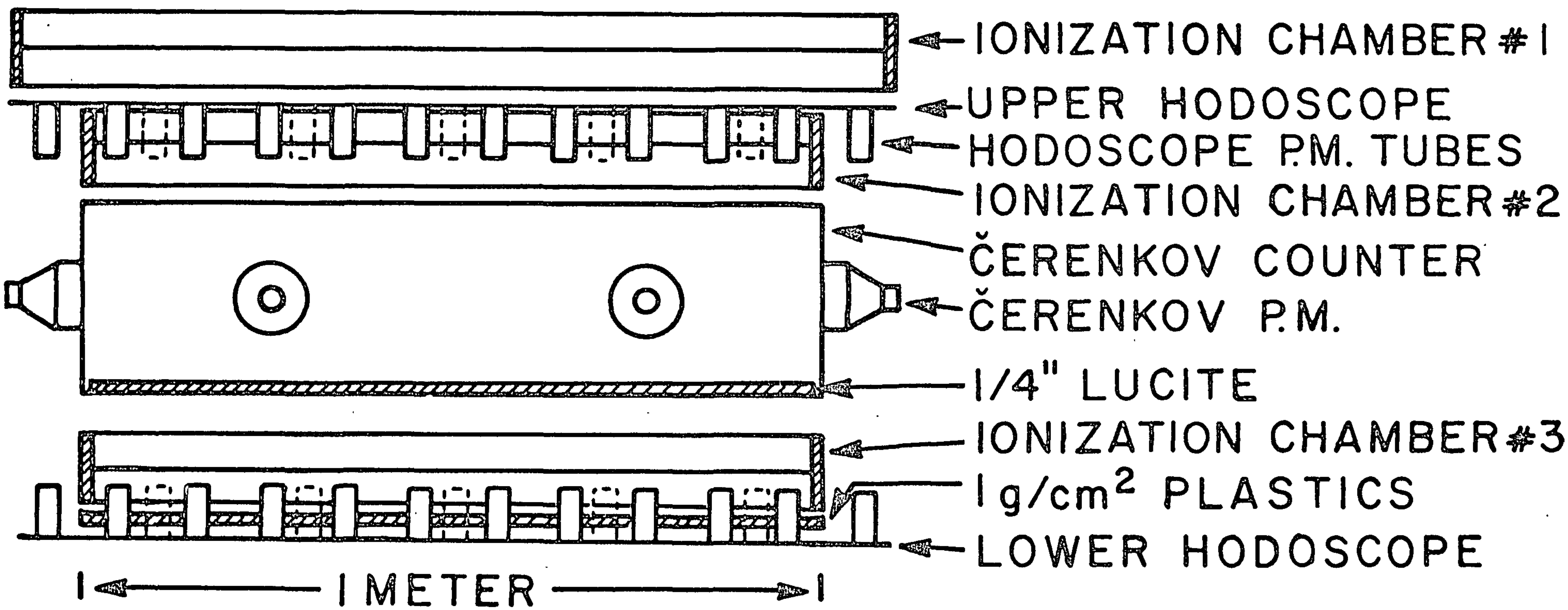
CAPTIONS

Figure 1 Detector System

Table 1 Chemical and isotopic composition of cosmic rays with $14 \leq Z \leq 26$ at 800 MeV/N.



IONIZATION CHAMBER #1
UPPER HODOSCOPE
HODOSCOPE P.M. TUBES
IONIZATION CHAMBER #2
ČERENKOV COUNTER
ČERENKOV P.M.
1/4" LUCITE
IONIZATION CHAMBER #3
1 g/cm² PLASTICS
LOWER HODOSCOPE
1 METER

Z	(A/Z)/(A/Z)Si at 3.2 g/cm^2	(A/Z)/(A/Z)Si Top of Atmos.	$\bar{A}$ Relative to Si-28.5	Observed Chemical Composition (Top of Atmosphere)	Propagation Results χ = 4.5 g/cm^2	Solar System Chemical Abundance	Cosmic Ray $\bar{A}$ at Earth	Source $\bar{A}$	Solar System $\bar{A}$
14	1.000*	1.000*	28.5*	1.37±0.04	1.39	1.12	28.5±0.5	28.4±0.5	28.27
15	-	-	-	0.048±0.019	0.057	0.014	-	-	-
16	0.989±0.011	0.987±0.011	32.2±0.4	0.322±0.017	0.332	0.569	32.1±0.6	31.7±0.9	32.27
17	-	-	-	0.052±0.014	0.051	0.002	-	-	-
18	1.025±0.015	1.024±0.015	37.6±0.6	0.144±0.015	0.117	0.256	37.3*	-	36.59
19	-	-	-	0.062±0.022	0.068	0.004	-	-	-
20	1.026±0.015	1.026±0.015	41.8±0.6	0.275±0.016	0.284	0.082	41.8±0.5	40.9±1.0	41.54
21	-	-	-	0.059±0.015	0.039	0.00004	-	-	-
22	1.056±0.017	1.060±0.017	47.3±0.8	0.193±0.013	0.185	0.003	47.1*	-	47.20
23	-	-	-	0.070±0.018	0.097	0.001	-	-	-
24	1.039±0.016	1.040±0.016	50.8±0.8	0.179±0.013	0.182	0.014	51.4*	-	52.62
25	-	-	-	0.104±0.019	0.107	0.010	-	-	-
26	1.032±0.012	1.032±0.012	54.6±0.6	1.000*	1.000*	1.000*	54.6±0.5	54.6±0.5	55.96

*Reference Elements