CHARGE COMPOSITION OF MEDIUM ENERGY COSMIC-RAY NUCLEI FROM NEON TO IRON

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(Received 3 January, 1979)

Abstract. Charge composition of cosmic-ray nuclei from neon to iron has been studied in a stack of cellulose nitrate plastic detectors exposed in a balloon flight over Fort Churchill. 401 cosmic-ray nuclei of $10 \leqslant Z \leqslant 26$ stopping in the detector system have been analysed. Fluxes of individual nuclei have been extrapolated to the top of the atmosphere. Relative abundances, obtained from these fluxes, have been compared with those obtained by other investigators.

1. Introduction

In recent years a number of investigations have been made on the charge composition of cosmic rays of low, medium and high energies. Various kinds of detector, such as nuclear emulsions, plastic detectors and counter telescopes using Čerenkov counters, scintillation counters, semi-conductor detectors and ionization chambers, have been employed for this purpose. Plastic detectors, mostly Lexan polycarbonate, have been used to study low and medium energy heavy nuclei in cosmic rays. Only a few investigations on $Z \geqslant 10$ nuclei in cosmic rays have been made with cellulose nitrate (CN) detectors (Benton and Henke, 1968; Enge *et al.*, 1973; Tripier and Debeauvais, 1977). The present experiment was started with two objectives in mind: (i) to evolve suitable experimental procedures for obtaining optimum charge resolution in cellulose nitrate plastic detectors and (ii) to determine the elemental composition of $10 \leqslant Z \leqslant 26$ medium energy cosmic-ray nuclei with good charge resolution. The experimental procedures adopted for optimizing the charge resolution are given by Bhatia and Singh (1979). In this paper we shall present our results on the charge composition of $10 \leqslant Z \leqslant 26$ nuclei in medium energy cosmic rays.

2. Experimental Details

2.1. EXPOSURE AND PROCESSING OF THE STACK

A stack composed of 163 Daicel cellulose nitrate sheets has been used in the present experiment. Each plastic sheet has the dimensions 18.1 cm × 14.5 cm × 0.03 cm. The stack was exposed to primary cosmic rays for 11.15 hours in a balloon flight over Fort Churchill, Canada, on 3 July, 1968, at a residual atmospheric depth of 2.9 mb. On reaching its ceiling altitude the stack was flipped by 180° so that top surface of the stack was exposed horizontally.

Astrophysics and Space Science **62** (1979) 465–475. 0004-640X/79/0622-0465$01.65

The exposed CN sheets were chemically etched, in batches of fourteen sheets, in a 6.25N sodium hydroxide solution containing 0.03% Kodak wetting agent. For each batch of sheets a freshly prepared sodium hydroxide solution of exactly the same normality was used. The etching was done for 4 hours in a constant temperature bath at 40 ± 0.05 degC, employing vigorous mechanical stirring. After etching, the sheets were put in an ultrasonically agitated detergent bath for half an hour. This was done in order to remove etch products blocking the tips of the conical holes along the trajectories of cosmic-ray nuclei.

2.2. SCANNING AND SELECTION OF EVENTS

For scanning the etched sheets we employed the multiple sheet scanning method of Fukui *et al.* (1975). Scanning was done under a total magnification of 30. All the events found while scanning were picked up and followed in subsequent sheets until the incident particle stopped, interacted or left the stack. Only those tracks were selected which stopped in the stack and had dip angles between 20° and 80°.

2.3. ASSIGNMENT OF CHARGES

About 3000 conical pits, belonging to 1137 stopping cosmic-ray nuclei, were measured using water immersion objectives, under optimum setting of the analysing microscope. Investigators working with plastic detectors have, so far, been using the cone length as a measure of the rate of ionization loss. We have found that V_t/V_b is a much more dependable measure of the ionization than the cone length (Bhatia and Singh, 1979). V_t is the rate of chemical etching along the radiation damaged trail of the incident particle and V_b is the bulk etching rate in the normal plastic material. V_t/V_b was calculated from the measured cone parameters using set number 5 of the formulae given by Henke and Benton (1971). A plot of V_t/V_b versus residual range was made (see Figure 1) which clearly shows the clustering of individual charges. The thicker points correspond to 10.2 MeV n^{-1} ^{12}C ions from accelerator. These were used for calibration. The curves drawn in Figure 1 represent the semi-empirical fits to the experimental points. The procedure for drawing these curves has been described elsewhere (Bhatia and Singh, 1979). Using these V_t/V_b versus residual range curves, charge values were assigned on the basis of V_t/V_b values measured along the track of a given particle. Of all the tracks analysed, 401 were found to belong to nuclei with $10 \leqslant Z \leqslant 26$. Tracks belonging to $Z \geqslant 10$ nuclei have, in general, a number of separated cones. The mean of the charge values, obtained from measurements on these cones, was taken in all such cases. Standard error in the mean charge value is 0.2 charge units for $Z \leqslant 20$ and 0.3 charge units for $20 \leqslant Z \leqslant 30$. This charge resolution compares favourably with that obtained with some of the best detectors in use at present.

2.4. CORRECTIONS TO THE OBSERVED NUMBER OF TRACKS

In order to calculate the flux of cosmic-ray nuclei, of a given charge i, on top of the atmosphere the observed number of nuclei must be corrected for (i) the tracks missed

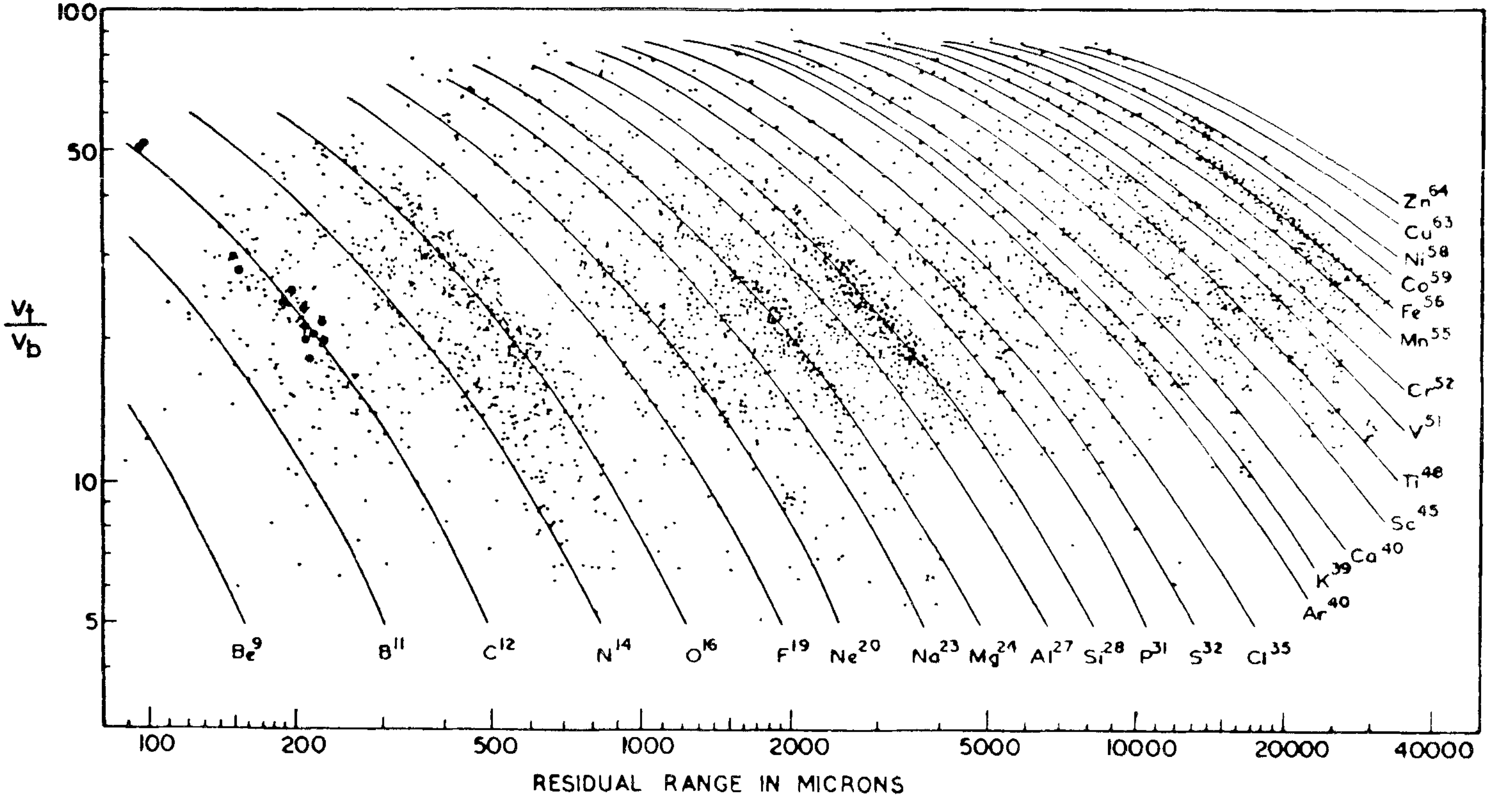

Fig. 1. V_t/V_b versus residual range plot for all the measured cones.

during scanning and (ii) the net loss due to nuclear interactions in the detector volume as well as in the overlying atmosphere.

In the multiple sheet scanning method employed by us, the observer can simultaneously see all the cones, belonging to a given track along an approximately straight line. It is almost impossible to miss such a sequence of cones. We rescanned about 10% of the total scanned area in order to find the scanning efficiency. No new $Z \geqslant 10$ track was observed during rescanning nor was any track which was found in the first scan missed in the rescan. Thus, our scanning efficiency for such events is 100% and no correction due to scanning loss is required.

In order to apply correction on account of fragmentations in the plastic detector we employed a diffusion equation which takes into account the production and absorption of given type of nuclei during the passage of cosmic rays. An approximate solution of such a diffusion equation is

$$N_i(x_p) = N_i(0) \exp(-x_p/\lambda_i) + \sum_{j>i} n\sigma_{ij} N_j(0) \left(\frac{\lambda_i \lambda_j}{\lambda_i - \lambda_j}\right) \times \\ \times [\exp(-x_p/\lambda_i) - \exp(-x_p/\lambda_j)], \quad (1)$$

where $N_i(0)$ is the number of nuclei of charge i incident on top of the detector, $N_i(x_p)$ the number of the nuclei after traversing x_p g cm^{-2} of plastic, λ_i the interaction mean free path of i-type nuclei in the plastic, σ_{ij} the partial cross-section for the production of an i-type nucleus due to interaction of a heavier j-type nucleus with a target nucleus, and n the density of the target nuclei. In Equation (1) the first term represents the loss due to breakup of i-type nuclei while the second term denotes the gain on account of production of i-type nuclei due to fragmentation of heavier nuclei. Values of λ_i, λ_j and σ_{ij} were calculated on the basis of partial cross-sections given by Silberberg and Tsao (1977) for Lexan. These values were also assumed to be approximately valid for cellulose nitrate. The relative abundances of nuclei with $Z = 10$ to 26, as given by Ormes *et al.* (1975), were used for $N_i(0)$. Using Equation (1) we define a correction factor $f_i(x_p)$ for a nucleus which has traversed x_p g cm^{-2} of plastic by

$$f_i(x_p) = \frac{N_i(0)}{N_i(x_p)}. \quad (2)$$

Proceeding in a similar manner, we define a correction factor $f_i(x_a)$ for an i-type nucleus which has traversed x_a g cm^{-2} of air. For this, the partial cross-sections, given by Silberberg and Tsao (1977) for air, were used.

For an i-type nucleus which has traversed x_a g cm^{-2} of air and x_p g cm^{-2} of plastic

$$(N_{\text{corr}})_i = f_i(x_a) f_i(x_p). \quad (3)$$

This corrected number represents the number of nuclei at the top of Earth's atmosphere.

Charge spectrum, based on the corrected number of nuclei, is shown in Figure 2 for $9 \leqslant Z \leqslant 30$. It is seen from this histogram that charges are well resolved right up to $Z \simeq 30$.

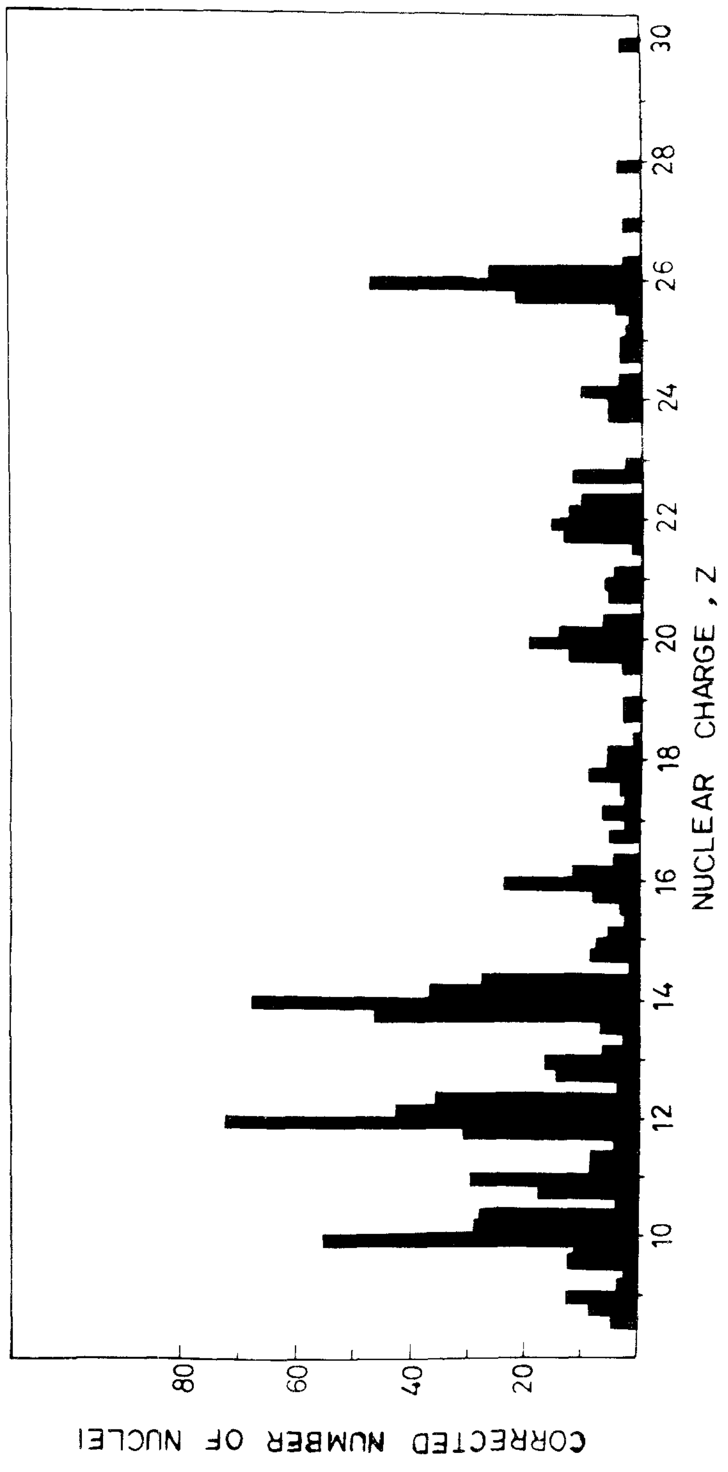

Fig. 2. Charge histogram for $Z \geqslant 9$ nuclei.

3. Calculation of Fluxes on Top of the Atmosphere

In a deep rectangular plastic stack the calculation of fluxes of individual nuclei in various energy intervals is, by no means, a simple task. To calculate the area × solid angle × time ($= A\Omega t$) factor for nuclei of a given charge, incident in a certain narrow energy interval (E to $E + \Delta E$) on a certain element of area of a plastic sheet within the stack and coming within certain intervals of zenith angle and azimuthal angle, one should make sure that (i) the particle enters the stack through the topmost sheet, (ii) it stops within the stack and (iii) it forms at least one separated cone in a sheet of the plastic stack.

We made an elaborate computer program which took into account the above conditions and the recording characteristics of our CN stack. These solid angle computations were performed on a DEC 10 computer. The calculated values of the factor $A\Omega t\ \Delta E$, as a function of the kinetic energy of the incident particle on top of the atmosphere, are shown in Figure 3 for various charges. Using these curves and the corrected number of nuclei, we calculated the differential fluxes of individual nuclei, on top of the atmosphere, in the allowed energy intervals. These differential

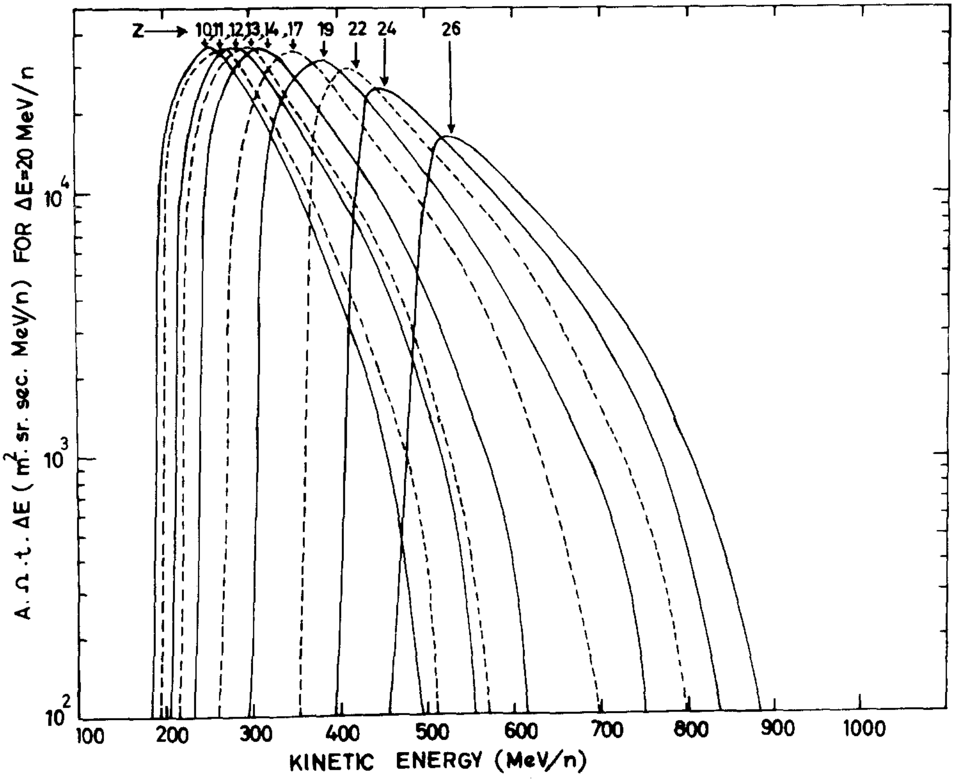

Fig. 3. $A\Omega t\ \Delta E$ versus kinetic energy per nucleon curves.

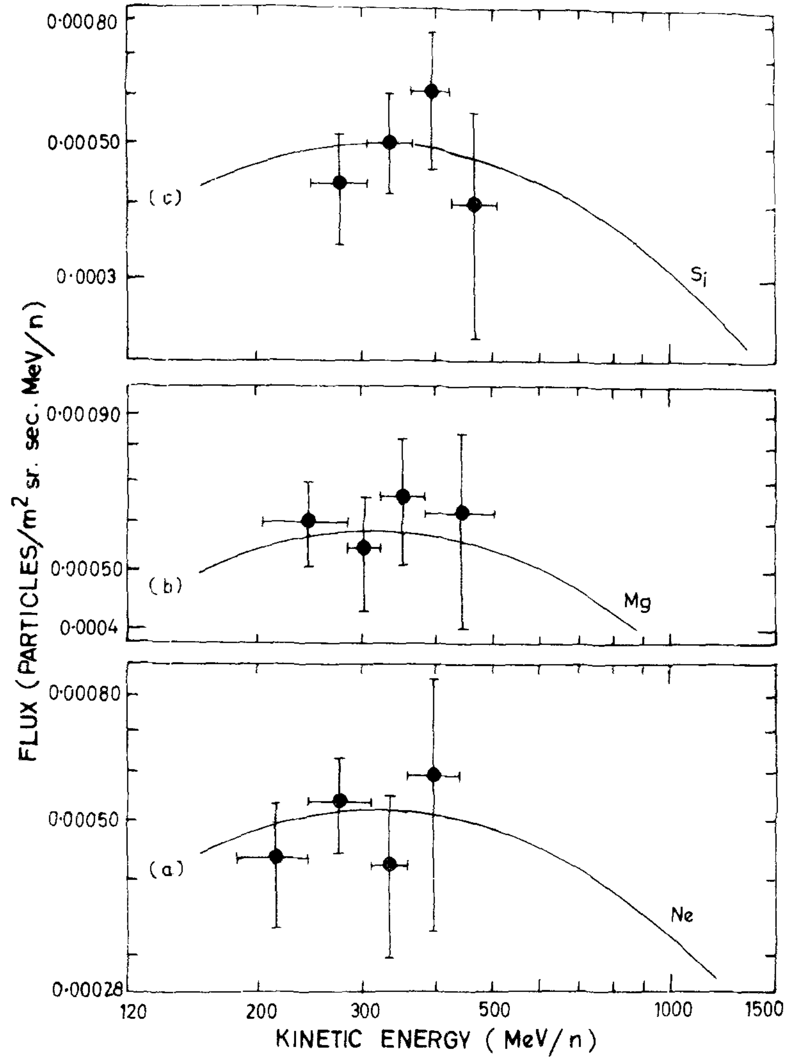

Fig. 4. Differential energy spectra for Ne, Mg and Si nuclei.

fluxes are shown in Figure 4 for the three most abundant nuclei – namely, silicon, magnesium and neon. The continuous curves represent the near-Earth spectra of these nuclei, theoretically calculated on the basis of a Fermi-type source spectrum (Ramadurai and Biswas, 1974) and the nested leaky box model (Cowsik and Wilson, 1975) of cosmic-ray propagation. For the Fermi-type spectrum we used the same parameters as given by Ramadurai and Biswas (1974). In the propagation calculations involving the leaky box model we assumed a leakage mean free path in the source region (λ_s) as 1.0 g cm^{-2} and a leakage mean free path in the galaxy (λ_g) as 5.0 g cm^{-2}.

TABLE I

Differential fluxes on top of atmosphere in the standard energy window (200–650 MeV n^{-1}).

Nucleus	Flux p/($m^2 \cdot sr \cdot s \cdot$ MeV n^{-1})	Nucleus	Flux · p/($m^2 \cdot sr \cdot s \cdot$ MeV n^{-1})
Ne	0.218 ± 0.027	K	0.005 ± 0.004
Na	0.098 ± 0.016	Ca	0.041 ± 0.012
Mg	0.248 ± 0.027	Sc	0.017 ± 0.005
Al	0.058 ± 0.013	Ti	0.067 ± 0.015
Si	0.213 ± 0.025	V	0.024 ± 0.009
P	0.028 ± 0.008	Cr	0.037 ± 0.012
S	0.061 ± 0.013	Mn	0.014 ± 0.008
Cl	0.013 ± 0.005	Fe	0.125 ± 0.038
Ar	0.030 ± 0.008		

The normalized probability, $p(x)$, for a particle to reach near Earth, after a traversal of x g cm^{-2} of interstellar matter, is then given by

$$p(x) = \tfrac{1}{4}[\exp(-x/5) - \exp(-x)]. \tag{4}$$

A plastic detector is sensitive to various charges in energy windows of different widths and locations. For this reason the fluxes of various nuclei, as obtained in a plastic stack, cannot be directly compared with each other. In order to draw meaningful inference from the comparison of their abundances, the fluxes must be normalized to a standard energy window, common to all charges. We have chosen this standard window as 200–650 MeV n^{-1}. Fluxes of all nuclei from neon to iron were normalized to this standard window by making use of their experimentally obtained fluxes and their theoretically calculated near-Earth spectra. These flux values are given in Table I. It may be mentioned that, as the correction factors are small, the flux values are not sensitive to the theoretical propagation models used. The errors quoted in the table represent statistical errors, calculated on the basis of the observed number of tracks of the respective charges. From this table the ratio of the abundance of even Z nuclei to that of odd Z nuclei for $10 \leqslant Z \leqslant 26$ is found to be approximately 4.0.

4. Comparison with Results of Other Investigations

In Table II we compare the relative abundances of $10 \leqslant Z \leqslant 26$ nuclei obtained in our experiment with those determined by other investigators. To facilitate the comparison, the abundances have been normalized to silicon abundance, taken as 100. As can be seen from the table, these investigations cover different energy intervals. Moreover, different kinds of detectors were employed in these investigations. Chohan *et al.* (1973) and Behrnetz *et al.* (1976) used nuclear emulsions. Benegas *et al.* (1975), Israel *et al.* (1973), Fisher *et al.* (1976), Webber *et al.* (1972) and Lund *et al.* (1975a,

TABLE II

Relative abundances of cosmic-ray nuclei of $Z = 10$ to 26 normalized with respect to Si (taken as 100).

Nucleus	Energy (MeV n^{-1})												
	200–650 (a)	72–450 (b)	250–850 (c)	350–600 (d)	870–1400 (e)	600–2000 (f)	150–400 (g)	40–450 (h)	100–300 (i)	250–1000 (j)	800–1600 (k)	400–800 (l)	> 400 (m)
Ne	102.5	104.0	142.0	114.3	—	103.7	—	—	117.0	141.7	—	—	99.4
Na	48.5	—	28.2	30.0	—	25.2	—	—	29.2	74.8	—	—	6.3
Mg	116.5	136.0	149.0	142.9	133.3	136.3	—	—	142.0	104.6	—	—	126.9
Al	27.1	—	25.0	25.7	29.4	25.2	—	—	29.2	50.7	—	—	14.9
Si	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
P	13.1	2.7	4.4	7.9	6.5	4.2	22.5	6.7	7.5	40.7	3.5	1.6	—
S	28.6	15.9	20.1	22.9	22.2	19.3	4.3	16.7	19.2	24.0	23.5	15.9	22.3
Cl	6.1	2.9	3.1	5.0	5.2	6.6	11.9	2.5	3.3	17.0	3.8	1.6	3.1
Ar	13.9	5.8	9.6	8.6	9.2	10.2	13.2	9.2	8.3	22.2	10.5	12.7	11.4
K	2.3	4.2	6.7	5.0	5.9	6.0	0.9	3.3	5.8	7.0	4.5	11.9	4.0
Ca	19.1	13.3	21.5	15.0	17.6	13.9	34.0	10.8	15.0	20.4	20.1	20.6	16.9
Sc	8.2	2.5	4.2	2.9	3.4	3.6	17.0	1.7	3.3	4.0	4.3	3.2	2.9
Ti	31.3	9.5	14.1	10.0	11.1	10.2	35.7	10.5	15.8	22.0	14.1	7.9	11.8
V	11.4	5.0	5.2	3.6	5.9	4.8	10.2	3.3	6.7	10.6	5.1	8.7	3.6
Cr	17.5	8.9	14.8	10.7	8.5	8.4	34.5	10.4	20.0	15.2	13.1	15.9	9.3
Mn	6.1	5.1	8.9	8.6	6.5	4.2	28.1	85.0	91.7	4.8	7.6	15.9	—
Fe	58.7	57.1	74.1	55.7	65.4	60.2	82.6			32.5	73.0	79.4	73.7

(a) This work
(b) Garcia-Munoz *et al.* (1977a)
(c) Webber *et al.* (1972)
(d) Fisher *et al.* (1976)
(e) Benegas *et al.* (1975)
(f) Lund *et al.* (1975a, 1975b)
(g) Bartholomä *et al.* (1972)
(h) Cartwright *et al.* (1973a)
(i) Cartwright *et al.* (1971)
(j) Chohan *et al.* (1973)
(k) Israel *et al.* (1973)
(l) Behrnetz *et al.* (1976)
(m) Julliot *et al.* (1975)

1975b) employed Čerenkov counter telescopes. Bartholomä *et al.* (1972) used plastic detectors. Garcia-Munoz *et al.* (1977), Cartwright *et al.* (1971, 1973) and Julliot *et al.* (1975) deployed counter telescopes aboard satellites. All abundances given in Table II represent the values extrapolated to the top of the atmosphere.

It can be seen from Table II that the relative abundances of the more abundant even Z nuclei, as obtained in the present experiment, roughly agree with those obtained in the majority of other investigations. However, in the case of Ti, we obtain a significantly higher abundance value as compared to the values obtained in most of the other investigations. As far as we can see, this high abundance of Ti cannot be explained on the basis of the errors associated with charge determination. Some Ti may be produced as a result of fragmentation of heavier nuclei during the passage through the overlying atmosphere. The relevant production cross-sections are not reliably known. Still, this factor may not be able to explain the observed abundance of Ti. Therefore, we feel that the abundance of Ti in primary cosmic rays may be at least as high as that of Ca. This is roughly in agreement with the results of Chohan *et al.* (1973), Cartwright *et al.* (1971) and Bartholomä *et al.* (1972). The relative abundance of Fe, obtained by us, is in good agreement with that obtained by Garcia-Munoz *et al.* (1977), Fisher *et al.* (1976) and Lund *et al.* (1975a, 1975b).

Earlier, Price *et al.* (1968, 1970), Enge *et al.* (1971) and Bartholomä *et al.* (1972, 1973) had obtained surprisingly high abundances of Mn using plastic detectors. Our Mn/Fe ratio of 0.11 ± 0.07 is much lower than the values obtained in the above-mentioned investigations and is in agreement with the values determined by Garcia-Munoz *et al.* (1977), Benges *et al.* (1975), Lund *et al.* (1975a, 1975b), Webber *et al.* (1972) and Meyer and Minagawa (1977).

The observed abundances of $Z = 10$ to 26 nuclei can be used to examine the current models of cosmic-ray propagation and origin. Some of these points of astrophysical interest will be discussed in the light of our experimental results in a separate paper.

Acknowledgements

The authors wish to thank Professor S. Biswas, T.I.F.R., Bombay, for the loan of the CN plastic stack and for his valuable comments on the manuscript. Exposures of our CN samples to the ^{12}C ions at HILAC were kindly made by Dr K. Fukui of AFCRL, Cambridge, U.S.A. Thanks are due to Messrs Joginder Pall and B. K. Anand for painstakingly scanning the plastic sheets. Financial assistance given by the Dept. of Atomic Energy and the University Grants Commission is gratefully acknowledged.

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