stellar acceleration or escape dependence on Z are possibilities, it is very likely that the differences detected represent source characteristics.

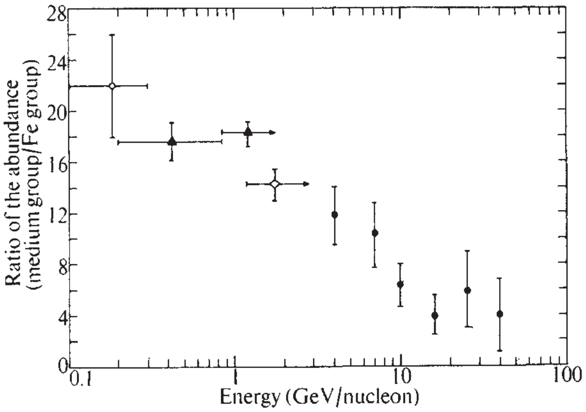

Fig. 1 The ratio of the abundance of the medium nuclei ($6 \leq Z \leq 9$) to the Fe group ($23 \leq Z \leq 28$) is plotted as a function of energy/nucleon. The open circle represents a satellite measurement, the remainder of the data was obtained on balloons and is corrected to the top of the atmosphere. ▲, Webber, Damle and Kish[12]; ○, Cartwright, Garcia-Munoz and Simpson[13]; ◇, Smith *et al.*[8]; ●, this paper.

With these provisos, we conclude that the source spectra of heavy nuclei are flatter than those of lighter nuclei. If all cosmic rays come from the same source then preferential acceleration of heavy nuclei is implied by this result. It does not seem that a Z-dependent injection process[3,4] can explain the data as the enhancement is most pronounced at energies well beyond any possible injection energy. The result would suggest a Z dependence of the acceleration process itself. Another possibility is that the spectral differences are due to different sources, and that the iron nuclei are produced in closer sources with flatter spectra.

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Received October 13, 1972.

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Evidence for Differences in the Energy Spectra of Cosmic Ray Nuclei

The existence of differences in the energy spectra of the various cosmic ray nuclei at energies $\gtrsim 1$ GeV nucleon^{-1} would have important implications for the method of acceleration of the cosmic rays and their propagation in interstellar space. But only recently has it been possible to isolate and compare the spectra of particular charges or charge groups with the requisite statistical accuracy over a broad enough energy range.

It seems natural to expect that any spectral differences would be greatest for charges or charge groups widely separated in Z. Comparisons of the He/VH and M/VH ratios as a function of energy[1,2] (M nuclei: $Z=6$–9, VH nuclei: $Z=20$–28) give some indications that the spectral index γ (for power law spectra of the form $J(>E)=K/E^{\gamma}$) for VH nuclei was ~ 0.1 less than that for He or M nuclei in the energy range 1–20 GeV nucleon^{-1}, but these results were certainly not convincing.

As the charge measurements have improved it has been recognized that about half of the VH group nuclei are in fact nuclei with $Z=20$–25, and current models of cosmic ray propagation suggest that these latter nuclei are "secondary" nuclei produced by the fragmentation of Fe and Ni in interstellar hydrogen[3]. Of the VH group nuclei then, only Fe and Ni should be mostly "primary" or cosmic ray source nuclei. To look for possible spectral differences, perhaps related to the acceleration process in the cosmic ray sources, it seems more appropriate to compare ratios of mainly primary or source nuclei such as He, C+O, and Fe+Ni.

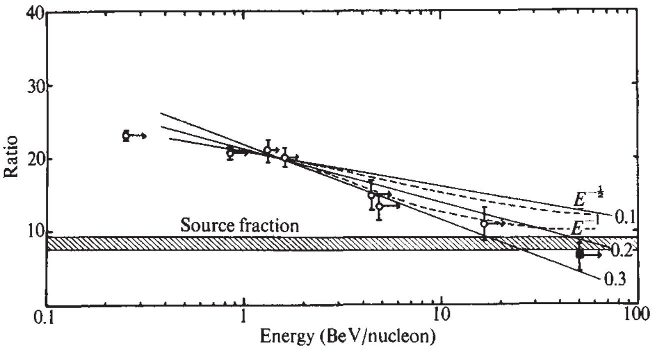

Fig. 1 Ratio of C+O to Fe+Ni nuclei as a function of energy. Open circles are these data plus those of ref. 2. Solid square is data from ref. 5. Solid lines are drawn for differences in the spectral exponent γ of 0.1, 0.2, and 0.3. Dashed lines are for escape length varying as $E^{-\frac{1}{2}}$ and E^{-1}.

In Table 1 we show data on the intensities of these nuclei measured at several energies from ~ 1 to 50 GeV nucleon^{-1}. Included here are previously unpublished data that we have obtained recently from balloon flights in Canada and Argentina using a large area, high charge resolution, double dE/dx· Čerenkov detector[4] covering the energy range up to $\gtrsim 5$ GeV nucleon^{-1}. Table 1 also includes some of our previously reported data[2], re-analysed to obtain the charge distribution in more detail, and recent data presented by Juliusson *et al.*[5] and Smith *et al.*[6].

The data in this table show a very interesting behaviour. The fraction of $Z=17$–25 to Fe+Ni nuclei changes from $\gtrsim 1$ at energies $\lesssim 1$ GeV nucleon^{-1} to values $\lesssim 0.2$ at the highest energies measured. We will return to this specific point shortly; first, however, consider what effect a variation of this type will have on the previously determined VH nuclei spectrum as compared with a spectrum of only Fe+Ni nuclei. As the Fe+Ni nuclei spectrum will have relatively fewer low energy particles than the corresponding VH spectrum, the

Fe+Ni spectrum will therefore be even flatter than the earlier VH nuclei spectra that were determined[1,2]. The earlier spectral differences between He, M, and VH nuclei will thus tend to be enhanced.

To show this effect more clearly we present in Fig. 1 the integral C+O/Fe+Ni ratio as a function of energy as determined from the data in Table 1. A comparison of the He/Fe+Ni ratio reveals a quite similar behaviour. The C+O/Fe+Ni ratio changes from values ~22 at energies ~1 GeV nucleon^{-1} to values $\lesssim 10$ at energies $\gtrsim 10$ GeV nucleon^{-1}. The solid lines in Fig. 1 refer to the ratios to be expected as a function of energy, calculated for the differences in the spectral index, γ, of 0.1, 0.2, and 0.3. The ratio is normalized to 22 at 1 GeV nucleon^{-1} and it is assumed that the spectral differences are constant as a function of energy. The data are consistent with an average Fe+Ni spectral index which is 0.26 ± 0.04 less than the corresponding C+O index. In comparison with He nuclei, the Fe+Ni spectral index is 0.32 ± 0.06 less. The errors quoted here are statistical errors only and represent combined spectral differences of over ten standard deviations.

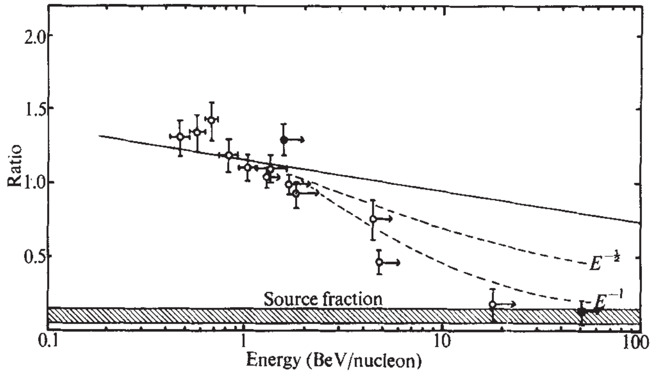

Fig. 2 Ratio of $Z=17$–25 to Fe+Ni nuclei as a function of energy. The symbols are as in Fig. *1*, with the addition of solid circles from Ref. 7. Solid line has arbitrary slope.

It should be emphasized that, at high energies, Fe+Ni nuclei are relatively more abundant than at low energies, comprising nearly 10% of all nuclei with a charge $\gtrsim 3$.

What is the cause for these differences in spectra? An immediate conclusion might be to relate them to possible acceleration effects in the cosmic ray sources as, after all, we are comparing mainly source nuclei. Under some circumstances, as noted later, the differences could be caused by propagational effects, however.

Recall again the variation with energy of the $Z=17$–25/Fe+Ni ratio. To illustrate this variation more explicitly we show in Fig. 2 the $Z=17$–25/Fe+Ni ratio as a function of energy. This ratio is observed to change from ~1.2 at low energies to a much smaller value at energies >5–10 GeV nucleon^{-1}.

Because of the known energy dependence of the fragmentation parameters for Fe and Ni nuclei at low energies we should expect some increase (~20–30%) in the fraction of secondary nuclei ($Z=17$–25) at energies below ~1 GeV nucleon^{-1}. Indeed this effect is observed in the data. To the best of our knowledge, however, the fragmentation parameters should remain nearly constant with energy above ~1 GeV nucleon^{-1} (ref. 3). The most obvious explanation for the large decrease in the $Z=17$–25/Fe+Ni ratio above 1 GeV nucleon^{-1} must be that these higher energy Fe+Ni nuclei have travelled through less matter than those at lower energies. If this is true we must be sampling a nearly unmodified cosmic ray source composition at high energies.

Current propagation models for cosmic rays in the Galaxy can adequately explain the details of the cosmic ray charge composition at energies $\lesssim 1.5$ GeV nucleon^{-1} in terms of an exponential distribution of material path lengths in the Galaxy with a characteristic value ~5 g cm^{-2} (ref. 3) (for example, $N(x) \sim \exp - X/X_e$, where X_e is the characteristic material path length, or also age T_e if one writes $X_e = \beta c \rho T_e$, where βc is particle velocity and ρ is the interstellar hydrogen density).

The concept of an energy dependent material length may be made more explicit by adopting an equilibrium model for cosmic ray production and leakage from the Galaxy where the diffusion term is approximated in terms of a leakage time $T_e(E)$. Neglecting energy changes the appropriate transfer equation yields the following relation[7,8].

$$j_i(E) = \frac{q_i(E) + \sum_{j \neq i} \frac{1}{\lambda_j} j_j(E)\, P_{ji}(E)}{\left(\frac{1}{\lambda_i} + \frac{1}{\lambda_e(E)}\right)}$$

where $j_i(E)$ is the intensity of the ith nucleus at the Earth, $q_i(E)$ is the cosmic ray source term, $P_{ji}(E)$ is the fragmentation probability of producing an ith nucleus in an interaction of a jth nucleus, λ_i and λ_j are the interaction mean free path of the ith or jth nucleus in interstellar hydrogen, and λ_e is the escape length, which is the same for all nuclei of a given energy, but is now assumed to be a function of energy as in the earlier work of Cowsik *et al.*[7]. We have assumed that $\lambda_e = \lambda_0 \cdot f(E)$ where λ_0 is taken to be 10 g cm^{-2} at 1 GeV nucleon^{-1} and $f(E)$ is taken to be $\sim E^{-1/2}$ and E^{-1} respectively.

The calculated variations in the C+O/Fe+Ni and $Z=17$–25/Fe+Ni ratios for these variations in matter path length are shown as dashed lines in Figs. 1 and 2. A variation of escape length $\sim E^{-1}$ provides an adequate fit to both sets of ratios. If this explanation in terms of an energy-dependent matter

Table 1 Measured Intensities

Energy/rigidity	He nuclei	C+O nuclei	$Z=17$–25 nuclei (particles m^{-2} sr^{-1} s^{-1})	Fe+Ni nuclei
>4.1 GV		5.07 ± 0.11	0.250 ± 0.016	0.239 ± 0.016
>4.35 GV	91.5 ± 2	4.66 ± 0.14		
			0.228 ± 0.014	0.207 ± 0.014
>5.00 GV	79.7 ± 1.6	3.86 ± 0.11		
>8.3 GV (6)	39 ± 2	1.92 ± 0.10	—	—
>11.0 GV	25.1 ± 0.8	1.46 ± 0.06	0.081 ± 0.010	0.104 ± 0.011
>11.2 GV	25.5 ± 0.3	1.42 ± 0.04	0.049 ± 0.005	0.113 ± 0.008
>16.5 GV (1 and 10)	14.8 ± 0.6	—	VH=0.090 ± 0.06	
>21.2 GV (10)	9.9 ± 0.6			
>25.7 GV (10)	6.5 ± 0.7			
>33.3 GV (10)	4.3 ± 0.6			
>0.85 GeV nucleon^{-1}	—	7.24 ± 0.25	0.345 ± 0.019	0.352 ± 0.018
>1.6 GeV nucleon^{-1}	—	4.51 ± 0.2	0.185 ± 0.015	0.210 ± 0.012
>18 GeV nucleon^{-1}	3.51 ± 0.2	0.152 ± 0.011	0.004 ± 0.002	0.017 ± 0.006
>50 GeV nucleon^{-1} (5)		141 events	1 event	16 events

path length is correct, a variation in the Li+Be+B/C+O ratio should also be observed, for Li, Be, and B are also secondary nuclei and are produced mainly by C+O nuclei. The data on this ratio and the predictions are shown in Fig. 3. There is some evidence for a decreasing ratio with increasing energy above a few GeV nucleon^{-1} although this conclusion is much less convincing than for the other ratios presented and is dependent on the rather inconsistent high energy data of Smith *et al.*[6]. In any case the variation in Li+Be+B/C+O ratio does not seem to be as drastic as predicted by an escape matter length $\sim E^{-1}$ which will explain the variations of the C+O/Fe+Ni and Z=17–25/Fe+Ni ratios.

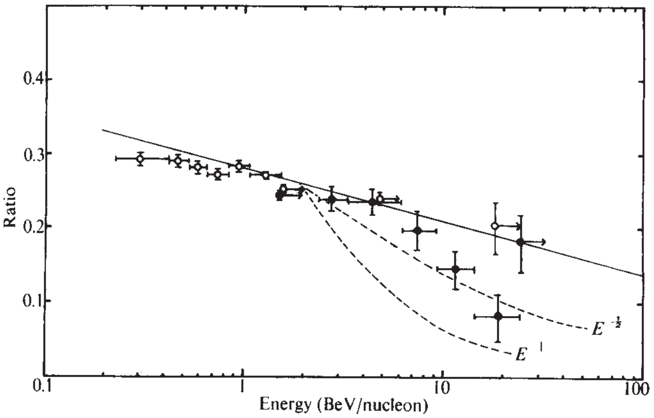

Fig. 3 Ratio of Li+Be+B to C+O nuclei as a function of energy. Symbols are as in Fig. 2. Solid line has same arbitrary slope as in Fig. 2.

It may be that this picture is too simple. We recognize that the concept of a leakage length is only a crude approximation to the actual diffusion of cosmic rays in the Galaxy[9], and one should more correctly be dealing with the energy dependence of the related diffusion coefficients to describe the data. It is also possible that the charge ratios could be highly dependent on the cosmic ray source distribution, which is assumed to be uniform in the model we have chosen.

An energy dependent leakage length will predict changing C/O and B+N/C+O ratios, however, and these may have already been observed[2,5]. It will also predict variations of the proton and helium nuclei spectra and the P/He ratio which could be observed. And finally, it will predict important changes in the charge ratios at energies $\lesssim 1$ GeV nucleon^{-1}, if the energy dependence extends to lower energies.

We are investigating some of these possibilities at present. We thank Dr Catherine Cesarsky and Dr J. A. de Freitas Pacheco for discussions. This work was supported by NASA.

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Received October 24, 1972.

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Mean Path Length of High Energy Galactic Cosmic Rays in the Galactic Disk

An important measurement of the composition of cosmic ray nuclei at high energy ($20 < E < 100$ GeV nucleon^{-1}) has been reported by Juliusson, Meyer and Müller[1]. They show that the ratio of galactic secondary nuclei to primary nuclei decreases very steeply when the energy of the observed nuclei is above 30 GeV nucleon^{-1}. The ratio of predominantly secondary nuclei to predominantly primary nuclei

$$\frac{\mathrm{B+N+F+Na+Al}+(14<Z<26)}{\mathrm{C+O+Ne+Mg+Si+Fe}}$$

which is ~0.31 at energies of 1.5 GeV/N is found to be 0.23 ± 0.03 at 25 and 30 GeV/N and $0.12^{+0.05}_{-0.07}$ at 90 GeV/N. Juliusson *et al.*[1] conclude that this effect may be explained in terms of particle propagation in the Galaxy: the leakage term which describes the probability that galactic cosmic rays leave the Galaxy must be energy dependent. Here we present a quantitative estimation of this dependence and discuss the implications of such a dependence.

Because this effect has been observed at high energy where the energy losses of the cosmic ray nuclei to ionization are negligible, a simple relation derived from the general transport equation[2] used by Meneguzzi, Audouze and Reeves[3] relates the leakage path λ_e with the primary and secondary component of the galactic cosmic rays

$$\varphi_j = \frac{\dfrac{Q_j}{n_H} + \sum_i \varphi_i \left(\sigma_{pij} + \dfrac{n_{He}}{n_H} \sigma_{\alpha ij} \right)}{\sigma_{pj} + \dfrac{n_{He}}{n_H} \sigma_{\alpha j} + \left(M_H + \dfrac{n_{He}}{n_H} M_{He} \right) / \lambda_e} \qquad (1)$$

where λ_e is the escape path expressed in g cm^{-2}; φ_j is the flux of an element j; φ_i represent the fluxes of all the nuclei which contribute to the secondary production of the element j; where Q_j is the source term of the element j; n_H and n_{He} are the mean number densities of the hydrogen and helium atoms in the interstellar gas (here n_{He}/n_H has been taken equal to 0.1); M_H and M_{He} are respectively the masses of the H and He atoms; σ_{pij} and $\sigma_{\alpha ij}$ are the cross sections of the spallation reactions i(p,) j and i(α,) j induced respectively by the elements i on the hydrogen and helium atoms of the interstellar gas, and σ_{pj} and $\sigma_{\alpha j}$ are the total destruction cross sections of j by the hydrogen and the helium atoms respectively.

At energies of a few GeV nucleon^{-1} and below, the fluxes of the different chemical species have been measured[4–9]. For elements which are purely secondary, like lithium, beryllium, boron and fluorine, the source term $Q_j = 0$ and the knowledge of the relative fluxes φ_i (refs 10, 11) and of the cross sections[3,10] involved are sufficient to determine the leakage path λ_e for energies of a few GeV nucleon^{-1}.

The calculation of λ_e at such energies is mainly based on the B/parents ratio because (i) B is an abundant secondary