THE ORIGIN AND PROPAGATION OF VVH PRIMARY COSMIC RAY PARTICLES

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In an attempt to match the observed charge spectrum of VVH particles, several source spectra have been constructed from combinations of r- and s-process nuclei. Their propagation has then been followed, allowing for interactions and decay, and comparisons have been made between the calculated near-Earth spectra and those observed during high altitude balloon flights. None of the models yet used leads to good agreement with observation, suggesting either that more complicated models need to be examined, or that different components (for instance the r- and s-process nuclei) have different histories.

1. Introduction. In the two preceding papers, we have described our observations of cosmic ray primaries having $Z > 35$, and we have pointed to several significant features of the charge spectrum. In the present report, we confine our attention to the charge region from $Z > 50$, and we examine in more detail some inferences that can be drawn regarding the origin and history of these particles.

2. Experimental Aspects. The data for the charge region $Z > 50$ were those described in the two preceding papers. Attention has been confined to those events that were clearly due to particles that were fast primaries recorded at altitude. The distribution of detector and absorber layers in the flight systems allows us to be certain that the present sample of events contains no unrecognised slow secondary particles such as those we have described elsewhere (Blanford et al, 1972).

In Table I, we have displayed the data. It should be emphasised that the major features of the charge spectrum at the top of the atmosphere are already exhibited in the raw data at flight altitude, and are not the result of any artifact of the propagation calculations that correct for collisions in the atmosphere.

3. Discussion and Conclusion. As first suggested by Mewaldt et al, (1970) and discussed in detail by Schramm (1972), there are some ratios of abundances that may provide an indication of the region of cosmic ray confinement by measuring the competition between fragmentation and radioactive decay for nuclei with $Z \geq 86$. Thus the ratios (≥86)/(81-85) and (≥86)/(76-85) in principle might be used, but the statistical accuracy of the present experimentally

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Table I
Relative Abundances at the Top of the Atmosphere

Charge Group	This Work	Model Predictions Case 1 r	Case 1 s	Case 2 r	Case 2 s
$\geq$ 86	6 ± 3	6	-	2	-
81-85	6 ± 3	5	16	4	13
76-80	9 ± 4	12	4	11	5
71-75	11 ± 4	4	4	3	4
61-70	16 ± 5	11	4	8	3
56-60	29 ± 6	12	55	8	51
51-55	23 ± 5	50	17	64	24

Note: All abundances are expressed as % of the total number of particles with $Z > 50$.

based ratios is not sufficient to permit any firm conclusions to be drawn.

We have observed three particles in the $Z \geq 86$ region; their most probable charge assignments were $Z = 90$. These ultra-heavy nuclei can be produced only in the r-process of nucleosynthesis. We have found no events that can be identified as due to transuranic nuclei, whose production is also expected during the r-process. Other groups, in a total flight exposure approximately equal to ours, have observed two probable transuranic nuclei. (Fowler et al, 1967, 1970; Price et al, 1971). Combining all results we obtain a ratio

$$(Z \geq 92)/(90 \leq Z \leq 92) = 0.3 \pm 0.2$$

for cosmic rays with kinetic energies 1.0 GeV/nucleon.

Schramm and Fowler (1971) have recalculated the yields of actinide elements in the r-process, and from their results we expect a ratio $(Z > 92)/(90 \leq Z \leq 92)$ between 0.5 and 1.0, depending on the length of the time during which these elements have undergone radioactive decay. The low experimental ratio might be taken as evidence for an underabundance of transuranic nuclei, but this conclusion must be tempered with the realities of charge resolution. The elements with $Z = 93$ and 94 are major components of the expected transuranic nuclei, and, in order to draw conclusions based on the $(Z > 92)/(90 \leq Z \leq 92)$ ratio, the experimental data require a charge resolution of <u>at least</u> $\Delta Z = 1$. Our charge resolution of $\Delta Z = ^{+3}_{-6}\%$ is insufficient to separate the lighter transuranic nuclei from the uranium and thorium nuclei. Better resolution and greatly increased statistics will be required before the situation with regard to transuranic nuclei is clarified.

If the r-process is regarded as the sole synthesising mechanism for VVH cosmic rays, we would anticipate peaks in the relative abundances in the 76-80 and 51-55 charge groups. As shown in Table I, however, we observed approximately equal abundances for the (71-75) and (76-80) groups and for the (51-55) and (56-60) nuclei. We have therefore investigated the possibility that there might also be some s-process material contributing to the VVH particle spectrum.

The large abundance of (71-75) nuclei cannot be explained by poor charge resolution, nor by spill-over from the (61-70) group, since many of the (71-75) events have identified charge values of 74 or 75. Some of the (71-75) events may more properly belong in the (76-80) group, but it seems unlikely that this effect can be large enough to explain the overabundance in (71-75). Similarly, the abundances of (51-60) nuclei cannot be explained through spillover from neighboring groups. The problem of charge resolution affects the (51-55) and (56-60) groups, since the main contributors are expected to be at Z = 54 and 56. Our measured charge resolution in this region is $\Delta Z = {}^{+1.6}_{-3.2}$ which implies that there is a greater probability of mis-identifying a true Z = 56 particle as Z = 54 than vice versa. Thus although we cannot exclude the possibility that a few events may have been assigned to the wrong groups, it seems unlikely that the majority of these (51-60) events have been wrongly identified. We can also rule out a systematic effect that would move the entire charge scale up or down by several units. (See preceding paper.)

In Table I, we have listed the relative abundances to be expected from pure r- and s-process sources, for two different cases, and compare these with the observed abundances. The r- and s-spectra have been computed as follows. The relative element abundances for a given case have been propagated to the Earth using a steady-state model. We investigated leakage lengths between 4 and 10 gm/cm^2 and found little change in the relative abundances. The spectra listed in Table I were obtained using a leakage length of 6.5 gm/cm^2.

Seeger, Fowler and Clayton (1965) determined the relative fraction of each isotope that is produced by the r or s process. Combining these with solar system element abundances yields relative abundance spectra from r and s material. The solar system element abundances used by Seeger, Fowler and Clayton differ markedly in some case from a more recent compilation of abundances by Cameron (1968). In addition Allen, et al, (1971) have summarized recent measurements of neutron captive cross sections and have suggested some modifications in both the isotopic r and s fractions and the solar system abundances.

We have therefore used two sets of r and s abundances in the calculations. Case 1 refers to the abundances as given by Seeger, Fowler and Clayton with the r-process abundance of Pb, Bi , and the actinide elements computed by the method of Clayton and Rossbach (1967) using the normalization parameters r = r' = 0.4. The second case covers the r and s spectra derived from the Cameron abundances taking into account the modifications suggested by Allen et al, including the normalization parameter r = 0.6. The actinide element abundances for case 2 were derived from the work of Schramm and Fowler (1971) normalized to the r-process abundance of Pt^{195} as suggested by Schramm (1971). These cases represent, nearly, the extremes of relative r and s process abundances for material whose history is the same as the material of the solar system.

There are several conclusions that can be drawn from Table I. First, the ratio (56-60)/(51-55) provides a very sensitive test for the presence of s-process nuclei in the VVH charge spectrum. This ratio varies from < 0.25 for a pure r-process source to > 2.0 for an s-process source. On the other hand the ratio (76-80)/(71-75) varies from approximately 1 to 3 with the lower values representing the s-process. In addition, for both cases considered the abundance of (71-75) nuclei is expected to be quite low.

Except for the (71-75) group, the experimental abundances for $Z > 60$ agree reasonably well with either a pure r-process or a combination of r and s-process source abundances. However, the (51-60) data requires a substantial contribution of s-process material. Within the experimental uncertainties, it is not possible to determine precisely the proportion of s-process nuclei in the VVH spectrum. The (56-60)/(51-55) ratio is consistent with approximately half of the material having seen formed in an s-process, but this combination does not adequately explain the $Z > 60$ abundances.

Our data thus seem to indicate the presence of both r and s process nuclei, while also suggesting that the VVH charge spectrum is probably the result of something more complicated than a simple r and s process combination with identical propagation histries.

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