A Comparison of Measurements of the Charge Spectrum of Solar Cosmic Rays from Nuclear Emulsions and the Explorer 35 Solid-State Detector

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SUMMARY

Recent measurements relating to the He/M (medium) nuclei abundance ratio in solar cosmic rays from solid-state detectors carried aboard the lunar orbiting Explorer 35 have been compared with earlier measurements using nuclear emulsions. The He/M ratio of 27 ± 9 obtained from Explorer 35 in the energy range of 0.5–~2.5 Mev/nucleon for solar events in 1967–1968 is lower than the value 58 ± 5 measured earlier for large events in the 1960–1969 period in the 12- to 200-Mev/nucleon range with emulsions. A mild energy dependence of the abundance ratio is one possible explanation of the observed differences.

Measurements pertaining to the charge spectrum of solar cosmic rays have recently been extended with a solid-state detector on Explorer 35 down to the 0.5-Mev/nucleon range [*Armstrong and Krimigis*, 1971; *Van Allen et al.*, 1971]. Because the measurements do not yield the charge and energy spectra for the various nuclear species separately (see the following section for a description of the experiment), the comparison of the Explorer 35 data with the emulsion results necessitates calculating the Explorer 35 responses expected by using the abundances derived by the emulsion measurements for various assumed forms of energy spectra. This paper reports the results of such a comparison and includes a review of the

measurements and the calculations and a discussion of the results of the comparison.

OBSERVATIONS

Explorer 35. The detector is a 20-μm-thick totally depleted silicon surface barrier detector. It has a 10-mm^2 area located behind a conical collimator of a 60° full vertex angle with a shielding equivalent to the range of a 50-Mev proton over the remaining solid angle. The detector is protected from sunlight by a nickel foil with a stopping power of 0.35 mg/cm^2. Four threshold discrimination levels of energy deposited in the sensitive volume of the detector are measured with fast 120-nsec resolving time double-delay line clipped electronics. The passbands of the detectors are determined by the foil thickness, the detector thickness, and the discriminator levels, all of which are accurately known from laboratory calibrations. The passbands are illustrated in Figure 1 [after *Armstrong and Krimigis*, 1971]. The lowest level is set well above the electron maximum energy loss; hence there is no response of the instrument to electrons of any energy at any flux level encountered in flight. Levels P1 and P2 are set to respond to protons and heavier nuclei, P4 to α particles and heavier nuclei, and P3 to nuclei with $Z \geq 3$. In this study we will use the responses of P1 and P2 only to provide a measure of the proton energy spectrum, P1 measuring 0.32–6.3 Mev and P2 measuring 0.48–3.0 Mev. The principal data for this study are provided by the P3 and P4 channels for which
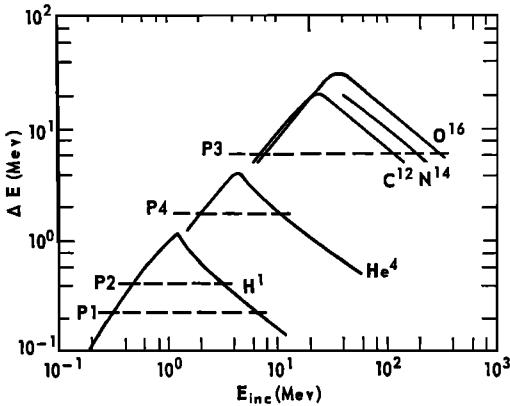
Fig. 1. Energy deposited in 20-μm detector aboard Explorer 35 (ΔE) versus incident particle energy for protons, $_2He^4$, $_6C^{12}$, $_7N^{14}$, and $_8O^{16}$ nuclei. Discriminator levels P1, P2, P3, and P4 are also shown.

the passbands are shown in Table 1 for the main species present in solar cosmic rays.

Possible spurious contributions to the responses of P3 from protons or α particles have been considered [Armstrong and Krimigis, 1971], and it has been found that scattering or inelastic events in the detector volume are insufficient to account for the observed responses and that the observed counting rate of P3 can be taken to be only that due to $Z \geq 3$ nuclei.

Emulsion measurements. The charge and energy spectra in large solar cosmic-ray events have been measured in a series of experiments beginning in 1960 with rocket- and balloon-borne nuclear emulsions launched from Fort Churchill. The results to date as well as aspects

TABLE 1.   Response of the Explorer 35 Solid-State Detector

Species	P3, Mev/nucleon		P4, Mev/nucleon	
	Lower	Upper	Lower	Upper
$_2He^4$	No response	No response	0.50	2.5
$_6C^{12}$	0.58	9.5	0.238	44.
$_7N^{14}$	0.51	14.	0.211	67.
$_8O^{16}$	0.46	19.	0.187	98.
$_{10}Ne^{20}$	0.40	45.	0.142	180.
$_{12}Mg^{24}$	0.35	70.	0.126	320.
$_{14}Si^{28}$	0.31	105.	0.107	710.
$_{16}S^{32}$	0.28	155.	0.095	∞
$_{26}Fe^{56}$	0.175	880.	0.0565	∞

of the experimental techniques are summarized by *Bertsch et al.* [1972]. Table 2 shows the elemental abundances as derived from the aggregate of those measurements. An important feature of the emulsion measurements has been that, when the energy spectra of He and M nuclei are measured in the energy above about 12 Mev/nucleon, they have been found to be identical to within experimental error. In addition, the ratio of the intensity of He nuclei to M nuclei (CNO) has been found to be consistent with a value of 58 ± 5 in all cases observed.

Comparison. An attempt will now be made to compare the Explorer 35 measurements with the emulsion measurements by calculating the expected ratio of P4/P3 from Explorer 35 for an assumed form for the energy spectra. The results for other spectral shapes will also be considered.

For the purpose of comparison the differential spectral shape is assumed to be of the form

$$dj_Z(E)/dE = a_Z E^{-\gamma} \qquad (1)$$

where a_z is the 'abundance' of the Zth nuclear species and γ is independent of Z. This form is used because of its simplicity and because it seems often to be a fair representation of the low-energy spectrum in solar-particle events. In the nonrelativistic region being discussed here this shape is equivalent to a power law spectrum in rigidity for particles of the same charge-to-mass ratio. For such a power law differential energy-per-nucleon spectrum it can be shown that

$$\frac{P4}{P3} = \frac{\sum_{Z=2} a_Z(E_{ZH4}^{-\gamma+1} - E_{ZL4}^{-\gamma+1})}{\sum_{Z=3} a_Z(E_{ZH3}^{-\gamma+1} - E_{ZL3}^{-\gamma+1})} \qquad (2)$$

where the a_z used here are given in Table 2 and the high- and low-passband edges for the various nuclear species E_{ZH4}, E_{ZL4} (channel 4), E_{ZH3}, and E_{ZL3} (channel 3) are defined and listed in Table 1. We assume that the same spectral form applies for all nuclear species with $Z \geq 2$. This assumption seems to be the natural first step to try, since identical spectra have been measured down to 12 Mev/nucleon. As has been pointed out by *Bertsch et al.* [1972], if the energy-per-nucleon spectra are not identical, there is ambiguity in interpreting how the relative abundances are to be formed. By using (2)

a series of values for P4/P3 for various values of γ can be calculated. The result of that calculation is shown in Figure 2, where we have plotted the calculated P4/P3 values versus γ. Also shown in Figure 2 are the results from two other calculations: the result from taking an enhancement of a factor of 10 of the iron group nuclei abundance and the result from taking a diminution of a factor of ½ of the He abundance.

Figure 2 also shows the values of P4/P3 obtained from Explorer 35 during the period July 20, 1967, to May 20, 1968. The values of γ for the α and $Z \geq 3$ spectra are unknown for the Explorer 35 measurements. As an indication of the relative steepness of the spectrum the values of γ from the protons were used. The abscissas of the plotted points must therefore be regarded as uncertain by as much as ± 1 in γ. The uncertainties in the ordinates of the observational points are the statistical counting uncertainties. The band of uncertainty around the calculated 'normal' P4/P3 arises from the uncertainty in the relative abundances, principally the uncertainty of approximately 10% in the He/O ratio.

Other spectral forms may be assumed and the values of P4/P3 calculated. For an exponential energy-per-nucleon spectrum the results do not differ in any significant quantitative or qualitative way from those in Figure 2, and, in general, the nature of the problem demands that the range of P4/P3 values cannot be greatly different.

The curve labeled normal in Figure 2 includes only the species for which an abundance is known and not those for which only an upper limit is known, namely, Be, B, F, A, Ca. If all the species were included at their upper limits, the resulting curve would be very close to the curve labeled 10 × iron.

It is clear from Figure 2 that the measured values of P4/P3 lie predominantly below the range of values one can predict by using the abundances of *Bertsch et al.* [1972], with identical power law differential energy-per-nucleon spectra for all $Z \geq 2$ species. Despite the fact that the abscissas of the plotted points are uncertain because only the proton spectral parameter, and not the parameters of the α particles or heavier nuclei, was observed, the measured values of P4/P3 cannot be brought into agreement with the expected values based on the

TABLE 2. Solar Cosmic Ray Relative Abundances for a Range of $12 \leq E \leq 95$ Mev/Nucleon
[after *Bertsch et al.*, 1971]

Element	Solar Cosmic-Ray Relative Abundance
²He	103 ± 10
⁴Be	<0.02
⁵B	<0.02
⁶C	0.56 ± 0.06
⁷N	$0.19 \pm ^{0.03}_{0.07}$
⁸O	1.0^*
⁹F	<0.03
¹⁰Ne	0.16 ± 0.03
¹²Mg	0.056 ± 0.014
¹⁴Si	0.028 ± 0.010
¹⁶S	0.008 ± 0.006
¹⁸A	<0.017
²⁰Ca	<0.010
²²Ti-²⁸Ni	0.011 ± 0.003

* Normalization reference.

calculation using normal abundances by any rearrangement of the abscissas that seems reasonable. Several hypotheses suggest themselves at this point: (1) the abundances used may not be appropriate for the energy range measured by Explorer 35; i.e., not all the energy spectra are identical; (2) the assumption of power law differential energy-per-nucleon spectra for all $Z \geq 2$ species may not be correct; and (3) there may be biases due to the temporal or spatial
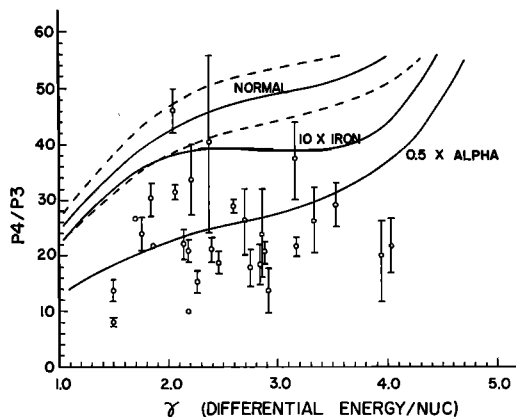

Fig. 2. Plot of calculated P4/P3 versus γ using the abundances of *Bertsch et al.* [1972]. The 'normal' calculation with its statistical uncertainty (dashed line) uses the iron group abundance enhanced 10 times (10 × iron) and a ½ He abundance (0.5 × α). Also shown are the observed values of P4/P3 (points).

TABLE 3. He/M Nuclei Ratio [after *Bertsch et al.*, 1971]

Time, UT	Date	Energy Interval Mev/ Nucleon	He/M
1408	Sept. 3, 1960	42.5–95	68 ± 21
1840	Nov. 12, 1960	42.5–95	63 ± 14
1603	Nov. 13, 1960	42.5–95	72 ± 16
0600	Nov. 17, 1960	42.5–95	38 ± 10
0339	Nov. 18, 1960	42.5–95	53 ± 14
1305–1918	July 18, 1961	120–204	79 ± 16
1443	Sept. 2, 1966	12–35	48 ± 8
2233	Sept. 2, 1966	14–35	53 ± 14
2319	April 12, 1969	18–34	55 ± 8
			58 ± 5*
1225–2345	July 12, 1959	150–200	≥100 ± 35
1030–1230	Nov. 15, 1960	175–280	~100^{+100}_{-50}

*Weighted average of first nine readings.

characteristics of the events or of the observing process. We consider these possibilities in order.

1. The value of He/M has been measured in several energy-per-nucleon intervals by emulsion techniques. The results are shown in Table 3 [after *Bertsch et al.*, 1972]. In the 0.5- to ~2.5-Mev/nucleon range the value of He/M can be estimated from Explorer 35 by using Figure 2 as a guide. By varying the amount of He assumed to be present and holding the distribution of all other nuclei constant a series of curves similar to that shown for 0.5 × α in Figure 2 can be generated. For normal abundances, namely, those of *Bertsch et al.* [1972], the value of He/M is 58 ± 5; for 0.5 × α, a

He/M value of 29 was used. A family of curves with varying amounts of He and hence varying He/M ratios has been calculated and compared to the observed P4/P3 points. Most of the observed points are included between the curves corresponding to a range in He/M of 18–35. Hence, subject to the validity of the assumptions indicated above that are inherent in the procedure, the Explorer 35 measurements in the ≳0.5-Mev/nucleon range are more consistent with a value for He/M of 27 ± 9 than with the value 58 ± 5 obtained from the emulsion measurements at ≥12 Mev/nucleon. A comparison of the results from the high-energy measurements (given in Table 3) and the lower-energy measurement described above is given in Figure 3. If one accepts, for the sake of argument, that the He/M ratio in the 0.5- to ~2.5-Mev/nucleon range is different from that in the 12- to 95-Mev/nucleon range, it follows that not all the principal nuclear species with $Z \geq 2$ can have identical energy-per-nucleon spectra in the inclusive energy range 0.5–95 Mev/nucleon. Accepting the He/M ratio to be dependent on the energy per nucleon necessitates examining the assumption of identical energy-per-nucleon spectra over the passbands of the Explorer 35 instrument, namely, 0.5–~2.5 Mev/nucleon. If one supposes that the He/M ratio increases linearly with energy and that the dominant contribution to the measurements comes from nuclei with energies at or just above the lower thresholds, one can estimate that the He/M ratio might change over the 0.5- to 2.5-Mev/nucleon passband of Explorer 35 by as
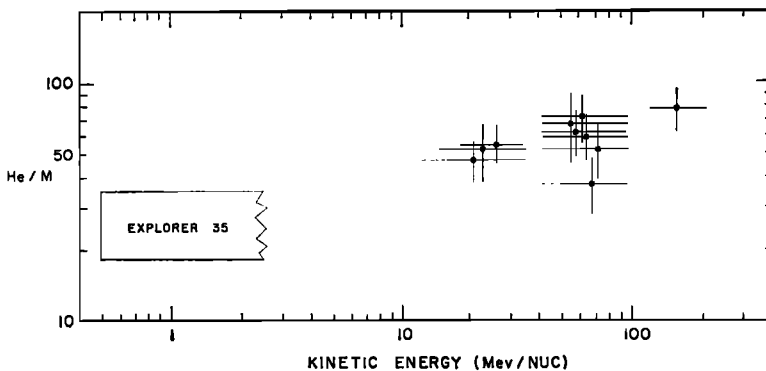

Fig. 3. Plot of observed values of He/M versus energy per nucleon. Points for >10 Mev/ nucleon are from *Bertsch et al.* [1972]. The 0.5- to 2.5-Mev/nucleon interval is from *Armstrong and Krimigis* [1971].

much as 20%, less than the $\approx 33\%$ uncertainty range necessary to include most of the observed values of P4/P3. In summary, then, a weak energy dependence on the He/M ratio such as that suggested by Figure 3 does not seem to be precluded at this time, nor does such a variation of He/M with energy of the magnitude suggested by Figure 3 materially affect the technique used for estimating the He/M ratio from the Explorer 35 observations.

2. The energy spectrum for $Z \geq 3$ nuclei in the energy range from 0.5 to a few Mev per nucleon has not yet been directly measured, and so the effect of spectral shape on the measured values of P4/P3 cannot be uniquely estimated at this time. The measurements of He and M nuclei spectra above 12 Mev/nucleon do not reveal any statistically significant departures from being identical and monotonically decreasing. Further, the proton spectral measurements for the event-integrated observations of Explorer 35 can be fit at least 90% of the time with a power law spectrum (including all events shown in Figure 2). The proton and α-particle spectra in the 1.2- to 12-Mev/nucleon range have been measured by *Lanzerotti* [1971] during six events in 1966, 1968, and 1969. Of the seven spectra he displays, one spectrum is peaked. The protons and α particles tend to have similar spectra with γ differing by <1 where a power law can be used to represent the data. It should be emphasized at this point that protons and α particles may or may not have the same spectra in all events, because their charge-to-mass ratios differ by a factor of 2. From Lanzerotti's observations we are led to the conclusion that the α spectrum is usually monotonically decreasing in the 1.2- to 12-Mev/nucleon range and, when it is not, the proton spectrum also shows a peak. Thus the value of using the proton spectrum as a rough guide to study the variations in P4/P3 is reinforced. However, the scatter in the observed values of P4/P3 is large, and it seems not unlikely that variations in the energy-per-nucleon spectral shape contribute. For the reasons outlined above it seems unlikely that the difference between the average values of He/M in the 0.5- to 2.5-Mev/nucleon range and the 12- to 95-Mev/nucleon range can be accounted for on the basis of spectral shape alone.

3. The events on which the emulsion measurements of the charge spectrum are based were

six of the largest events occurring in the 1960–1969 time period. Most of them have an identified flare association. The Explorer 35 data are from all events that have a >0.5-Mev proton rate of 12.7 cm^2 sec $ster^{-1}$ on a daily average basis during the period July 20 to May 20, 1968. Whereas these events are significantly smaller than the six large (peak intensities typically $\geq 10^3$ cm^{-2} sec^{-1} $ster^{-1}$ at $E > 10$ Mev) events in which the nuclear emulsion data were obtained, in at least two solar-particle events whose size was comparable to the six large events a P4/P3 ratio similar to the ratios discussed here was observed [*Venkatarangan et al.*, 1970]. As one may ascertain from Figure 2 by using the size of the error bars on the P4/P3 points as a rough guide to the total number of counts received in the event, no trend of P4/P3 versus size is evident here either. At the present time then there does not seem to be observational evidence that the He/M ratio in an event depends on the intensity of radiation received at 1 AU. One should note, however, that the two data samples discussed correspond to different times and were selected according to different size criteria. The observations were also made at 1 AU, and the comments in this paper refer directly to the prevailing circumstances at 1 AU. The relationships to sources and models of the propagation process are purposely not discussed here.

In summary, the composition in the 0.5- to $\sim$2.5-Mev/nucleon range observed on Explorer 35 appears to differ from that in the 12- to 95-Mev/nucleon range observed with nuclear emulsions on sounding rockets. It has not yet been determined whether this difference occurs in any single event or whether it is characteristic of different events.

Note added in proof. Additional measurements of He/M = 46 $\pm$ 9 for the April 6, 1971, event and 26 $\pm$ 1.5 for the September 1971 event in the energy range of 8–23 Mev/nucleon have been reported recently by *von Rosenvinge et al.* [1971] and *McDonald* [1972].

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