VARIATIONS IN THE NUCLEAR ABUNDANCES IN SOLAR PARTICLE EVENTS

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Measurements of the flux of helium nuclei in the 24 January 1971 event and of helium and (C,N,O) nuclei in the 1 September 1971 event are combined with previous measurements to obtain the relative abundances of helium, (C,N,O), and Fe-group nuclei in these events. These data are then summarized together with previously reported results to show that, even when the same detector system using a dE/dx plus range technique is used, differences in the He/(C,N,O) value in the same energy/nucleon interval are observed in solar cosmic ray events. Further, when the He/(C,N,O) value is lower the He/(Fe-group nuclei) value is also systematically lower in these large events.

1. Introduction. The earliest measurements on the relative abundances of the energetic solar cosmic ray multicharged nuclei of the same charge-to-mass ratio, particularly He, C, and O showed a remarkable similarity from event to event (e.g., Biswas and Fichtel, 1965 and Bertsch et al., 1972), especially in view of the dramatic variation in the proton to helium ratio. This latter ratio showed variations of well over an order of magnitude from event to event and with energy in a given event in the range from 10 to 100 MeV/nucleon. The variability of the proton abundance relative to that of He^4 nuclei was not unexpected because, having very different charge-to-mass ratios, they have very different rigidities for the same velocity, and both the acceleration and propagation of solar particles are thought to be velocity and rigidity dependent. On the other hand, the He to (C,N,O) ratio was so similar in the earlier measurements mentioned that over a total of six events no variation was seen above about 15 MeV/nucleon (40 MeV/nucleon in the earlier events) within the accuracy that the ratio could be determined, about 25%. Further, within very limited statistics, the nuclei heavier than oxygen seemed to be present in about the same abundance each time.

Especially within the last two years, however, a number of observations have been made supporting a variability of the relative abundances of these heavier nuclei, although the variability is apparently small compared to that of the proton to helium ratio. Armstrong et al. (1972) summarized the He/(C,N,O) data available and showed that the values measured recently at low energies ($\leqslant$ 5 MeV/nucleon) were clearly different from those which had been determined at the higher energies. Teegarden et al. (1973) later measured a He/(C,N,O) value of 26 $\pm$2 at 8.5 to 23 MeV/nucleon similar to those at the lower energies rather than the values about twice as large measured pre-

*NASA/NAS Sr. Res. Res. Assoc., on leave from Tata Institute, Bombay viously at higher energies. At the same time Mogro-Campero and Simpson (1972), Teegarden et al. (1973) and Bertsch et al. (1973) began to notice possible differences in other heavy nuclei abundances, such as Mg, Si, and Fe. Crawford et al. (1972) also measured a small variation of Fe/Si with energy in a single event. This latter variability was not entirely unexpected, however, due to the somewhat different charge-to-mass ratio of Fe, namely .46 rather than 0.50 for Si, O, N, C, and He.

In this paper, abundance ratios of He, (C,N,O), and Fe-group nuclei are reported for the large solar particle events in January and September 1971. (Fe-group is defined to be the charge interval $22 \leq Z \leq 28$, but is expected to be predominantly iron; for simplicity this group will be referred to as iron for the remainder of the paper.) The data were obtained in the continuing nuclear emulsion sounding rocket program called SPICE (Solar Particle Intensity and Composition Experiment). When compared with abundance ratios measured by the same experimental technique in earlier flare events, the new results provide additional evidence of the variability of solar cosmic ray composition in that a significantly different He to (C,N,O) ratio, as well as correlated variations in the He to Fe nuclei ratio, are observed between the two 1971 events and earlier solar particle events. These results will be summarized along with other evidence for solar composition variability.

2. Experimental Technique. Charge identification and energy measurements of solar cosmic ray particles are made by analyzing tracks in nuclear emulsions exposed above the atmosphere during solar particle events. NIKE-APACHE sounding rockets are used to launch the SPICE payloads which are kept on standby at the Fort Churchill Research Range at Fort Churchill, Manitoba. During flight, the nosecone of the SPICE payload is open for a period of 245 sec. above an altitude of 60 km exposing two emulsion stacks of dimensions 6.4 cm x 7.1 cm, each protected by a thin, 27 mg/cm^2 stainless-steel cover. The payload is spin-stabilized to maintain the emulsion surfaces in a vertical plane. The useful exposure factor for particles entering the emulsion from the upper hemisphere is 1.5 m^2 sr. sec. Measurements reported here were obtained in flights at 0819 and 1512 UT on 25 January 1971 and at 0758 on 2 September 1971.

To obtain fluxes of helium nuclei a portion of the area of an emulsion plate was scanned for tracks of all particles whose direction of arrival was above the earth's horizon and whose dip angles are between 10 and 60 degrees from the emulsion surface. A minimum length projected in the emulsion plane of typically 130 microns was required for each track in order to assure an adequate track length for charge identification. Each track was followed to its endpoint to determine its residual range and grain counts were made near the entrance point in the scan emulsion. Plots of grain density as a function of range were used to resolve the helium nuclei from protons. (With this method approximately 50 protons must be measured for each helium nucleus.) Details on this technique and the resolution of helium that is obtainable with this method have been reported previously (Bertsch et al., 1972). Independent scans were made at different depths in each stack to provide improved information in the energy region between 10 and 50 MeV/nucleon where the (C,N,O) and Fe-group nuclei fluxes have been measured (Bertsch et al., 1973).

3. Results. Table I shows the flux measurements of helium nuclei at two different times during the 24 January 1971 particle event associated with a flare at 2309 UT. Also given in Table I are the helium and (C,N,O) fluxes in the 1 September 1971 event at approximately 12 hours after the flare. (C,N,O) spectra for the January event and Fe-group fluxes for both 1971 events have been reported previously (Bertsch et al., 1973).

Using these data and previously published results on helium, (C,N,O), and iron fluxes (Durgaprasad et al., 1968; Bertsch et al., 1972 and 1973), abundance ratios of helium to (C,N,O), helium to iron, and (C,N,O) to iron have been determined for all solar particle events studied during the current SPICE series and these are summarized in Table II. In the case of the 12 April 1969 event, no iron nuclei were detected and only lower limits (at a 95% confidence level) could be determined. Helium and iron were not observed in significantly overlapping energy regions in the second flight in January 1971. However, Crawford et al. (1972) measured heavy nuclei in plastic detectors flown aboard the same payload, and the energy spectrum for the iron nuclei which they observe agrees quantitatively with the iron spectrum measured in emulsions (Bertsch et al., 1973). For this reason, the iron data of Crawford et al. (1972) were combined with the iron data from the emulsions in order to estimate the helium to iron ratio shown in parenthesis in Table II.

Notice that all ratios (or lower limits) for the September 1966 and April 1969 events are significantly higher than the three measurements in the two 1971 events. In particular, the helium to (C,N,O) ratios for January and September 1971 are approximately a factor of two lower than the weighted average of 58 ± 5 for nine earlier measurements above 10 MeV/nucleon (including September 1966 and April 1969) summarized by Bertsch et al. (1969) and Armstrong et al. (1972).

Furthermore, the ratios in Table II show that when (C,N,O) nuclei are enhanced relative to helium that iron is enhanced relative to helium and apparently to (C,N,O) nuclei as well which implies a systematic enrichment of heavy nuclei relative to light nuclei, or alternately that light nuclei are suppressed with respect to heavy nuclei. If these data are analyzed in smaller energy intervals there is a tendency for the ratios in the January and September 1971 events to increase as a function of energy. Based on the helium to (C,N,O) ratios surveyed earlier (Bertsch et al., 1972) and the ratios given in Table II for the January 1971 event, no significant variation of relative abundances with time in an event is observed.

Evidence for variability of solar cosmic ray composition between flare events from the work of other groups will now be summarized. With regard to the relative abundances of He and (C,N,O) nuclei, Armstrong and Krimigis (1971) summarize the He/(C,N,O) ratio for 35 events during 1967 and 1968 in the energy region of 0.5 to 2.5 MeV/nucleon and conclude that significant variations exist. Armstrong et al. (1972) compare these satellite data for He/(C,N,O) which have an average value of 27 ± 9 with the SPICE emulsion results from 1960 to 1969 which average to 58 ± 5 for energies of 12 to 100 MeV/nucleon. The comparison of results suggest the possibility of energy and event-to-event time variations. Teegarden et al. (1973) report Fe/O ratios which differ significantly between the April 1971 and September 1971 events

Table I. DIFFERENTIAL HELIUM AND (C,N,O) NUCLEI FLUXES IN SOLAR PARTICLE EVENTS DURING 1971

Flight	Helium Nuclei E MeV/N	Helium Nuclei $\frac{dJ}{dE}$ (cm^2-sr-sec-MeV/N)$^{-1}$
25 Jan 1971 0819 UT	20	0.41±0.14
	26	0.38±0.14
	33	0.29±0.10
25 Jan 1971 1512 UT	17.8	0.97±0.24
	22.5	0.47±0.15
	27.5	0.08±0.08
2 Sept 1971 0758 UT	17	0.30±0.10
	25	0.11±0.03
	36	0.041±0.015

Flight	(C,N,O) Nuclei E MeV/N	(C,N,O) Nuclei $\frac{dJ}{dE}$ (cm^2-sr-sec-MeV/N)$^{-1}$
2 Sept 1971 0758 UT	13.2	0.0357±0.0042
	15.8	0.0254±0.0029
	18.4	0.0145±0.0023
	22.1	0.0073±0.0011
	26.2	0.0033±0.0006
	30.3	0.0024±0.0004
	34.1	0.0016±0.0004
	39.7	0.0007±0.0002
	47.0	0.0003±0.0001

TABLE II. SUMMARY OF ABUNDANCE RATIOS IN SOLAR PARTICLE EVENTS

Event	Time (Hr)	Helium-to-(C,N,O)		Helium-to Iron		(C,N,O)-to-Iron		Ref.
		Ratio	Energy (MeV/N)	Ratio	Energy (MeV/N)	Ratio	Energy (MeV/N	
2 Sept 1966	1443 UT	48±8	12 to 35	2540±540	21 to 38	57±18	21 to 40	a,b
12 Apr 1969	2319 UT	55±8	18 to 34	> 1900*	21 to 34	> 35*	21 to 50	c,b
25 Jan 1971	0819 UT	29±7	17 to 46	1070±280	21 to 50	28±6	21 to 50	d,b
25 Jan 1971	1512 UT	27±6	16 to 30	(810±270)	15 to 30	29±7	21 to 50	d,e,b
2 Sept 1971	0758 UT	22±4	14 to 42	810 ±290	21 to 42	30±9	21 to 50	d,c

*Based on 95% confidence limits

References: (a) Durgaprasad et al., 1968, (b) Bertsch et al., 1973, (c) Bertsch et al., 1972, (d) This paper; (e) Crawford et al., 1972.

in the latter case they obtain a He/(C,N,O) value of 26 $\pm$ 2 which agrees with the SPICE result for that event given in Table II. Teegarden et al. (1973) observe Fe/O ratios in the April and September 1971 events that differ by a factor of six, but are statistically consistent with a constant value. Generally, they conclude that the composition in these two events is similar to the solar photospheric estimates as are the earlier results of Biswas et al. (1962) and Bertsch et al. (1972). Mogro-Campero and Simpson (1972), on the other hand, derive Fe/O values above 5 MeV/nucleon for seven particle events that show significant variability by as much as a factor of 20. Their results are obtained by integrating over a major portion of an event, and by extrapolating the oxygen spectrum from 14 down to 5 MeV/nucleon using the spectral data from another satellite. Overall averages of all seven events imply that solar cosmic rays above Si are preferentially enhanced (10 to 20 times for iron) relative to solar photospheric values.

Crawford et al. (1972) using plastic detectors flown aboard SPICE sounding rockets find no evidence of composition variations between the January and September 1971 events, but do observe that the Fe/Si ratio decreases with energy by a factor $\approx$ 4 over the energy range from 1.5 to 40 MeV/nucleon. It is important to note that the charge-to-mass ratios Fe and Si differ by $\approx$ 8% at energies where the nuclei are fully stripped of electrons ($\approx$ 25 MeV/nucleon) and at lower energies where the nuclei may be only partially ionized even larger differences in the charge-to-mass ratio are possible so that variations in ratios from propagation and acceleration processes might be expected.

Based on analyses of a piece of Surveyor 3 camera filter exposed for 2.6 years on the moon, Price et al. (1971) compare the iron spectrum to a helium spectrum obtained from satellite data integrated over the same time interval in the energy region of 6-10/MeV nucleon. He/Fe inferred from their results range from $\approx$ 230 at 6 MeV/nucleon to $\approx$ 560 at 10 MeV/nucleon. The value at the higher energy does not differ appreciably from values in Table II, particularly in view of the difficulty in comparing different experimental results on steep spectral distributions.

4. Summary.

Differences in composition from event to event among the multiply charged nuclear abundances even those of the same charge-to-mass ratio clearly exist. Further, the results reported here which were obtained with the same detector system using a dE/dx vs. range technique, provide, we believe, the first evidence for a systematic variation of He, (C,N,O), and Fe abundances between different large events. In particular, the data summarized here show that for events where the He/(C,N,O) value is low, He/Fe is also low and most likely to a more pronounced degree. Additional research which is aimed at the study of the abundance of several multicharged nuclei in many different events, especially those which differ markedly in size, or in some other fundamental way, should assist in determining the nature of the variations and hence give very important clues to their cause.

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