ENRICHMENT OF HEAVY NUCLEI IN ³He-RICH FLARES

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ABSTRACT

Five ³He-rich solar-flare particle events were observed in 1973-1974 with ³He/⁴He ranging from 0.2 to ~8 at 2.9-12.7 MeV per nucleon. In all five events the (Z ≥ 6)/¹H ratio at ~3 MeV per nucleon was enriched by ~10 to ~100 times and the (Z ≥ 6)/⁴He ratio was enriched by ~3 to ~30 times, when compared with average solar-particle abundances measured over this 2-year period. It is suggested that the simultaneous enhancement of Z ≥ 6 and ³He nuclei and the absence of ²H and ³H may be partly due to a preferential acceleration process which depends on the Z²/A of the nuclei.

Subject headings: abundances, solar — cosmic rays — flares, solar

I. INTRODUCTION

Observations of the isotopic composition of hydrogen and helium nuclei in solar cosmic rays have shown that the energetic particles accelerated in some solar flares are extraordinarily rich in the normally rare isotope ³He with no corresponding enrichment in ²H or ³H (Garrard *et al.* 1973; Anglin *et al.* 1974; Hurford 1974; Serlemitsos and Balasubrahmanyam 1975). While the ratio ³He/⁴He in the solar wind and prominences is ~4 × 10⁻⁴ (Geiss and Reeves 1972; Hall 1975), in ³He-rich flares the solar cosmic-ray ³He/⁴He ratio typically exceeds 0.2, and in some cases is greater than 1. In this Letter we present observations which show that such ³He-rich events are also enriched in Z ≥ 6 nuclei. The implications of this result are then briefly considered.

II. OBSERVATIONS

The observations were made with the Caltech Electron/Isotope Spectrometer on the IMP-7 spacecraft. The instrumentation is described elsewhere (Hurford *et al.* 1974). Nuclei with Z > 2 in the energy interval ~2 to 6 MeV per nucleon penetrate a 2.4 mg cm⁻² Mylar window and stop in a single 50-μ solid state detector (D2) which is actively collimated with a geometrical factor of 0.2 cm² sr. These nuclei can be distinguished from the more numerous hydrogen and helium nuclei by an energy loss in D2 which exceeds the maximum ⁴He energy loss of 8 MeV. Table 1 summarizes the energy intervals for nuclei which lose ≥ 9.6 MeV in D2. Note that the characteristic energy interval for Z ≥ 6 nuclei is 2 to ~5 MeV per nucleon. While the charge (Z) of individual heavy nuclei cannot be identified by such a single parameter measurement, other evidence to be discussed below implies that only a small fraction of such events in ³He-rich flares are Li, Be, or B.

The ¹H and ⁴He nuclei between 2.4 and 12.7 MeV per nucleon penetrate D2 and are stopped by a subsequent detector (D5) which has a geometrical factor of 0.067 cm² sr. The isotopic composition of such nuclei is determined by a conventional dE/dx-E technique.

TABLE 1

ENERGY INTERVALS FOR TYPICAL
NUCLEI STOPPING IN D2 WITH
ENERGY LOSSES ≥ 9.6 MeV

Nucleus	Energy Interval (MeV per nucleon)
⁶ Li.....	1.9-2.7
¹¹ B.....	1.9-3.6
¹² C.....	2.0-4.2
¹⁶ O.....	2.1-4.8
²⁸ Si.....	2.1-5.6
⁵⁶ Fe.....	1.7-6.0

In order to minimize the effects of selection criteria on our data base, the daily average flux of Z ≥ 6 nuclei and of 2.4-6.0 MeV per nucleon ¹H and ⁴He were determined for each day between 1972 September 30 and 1974 October 22 for which there were more than 10 H or 5 He nuclei detected. In calculating the Z ≥ 6 fluxes we assumed a nominal energy interval of 2-5 MeV per nucleon. These daily average fluxes are plotted in Figure 1. Note that large solar-flare particle events may last for several days. This figure also includes an indication of the average quiet-time flux of ¹H and ⁴He, and the 2σ upper limit to the average quiet-time Z ≥ 6 flux. During this period five ³He-rich events, summarized in Table 2, were identified with this experiment (see, e.g., Hurford 1974; Hurford *et al.* 1975). There were no other events in which more than three ³He were identified and the ³He/⁴He ratio was greater than 0.1. Data acquired on the six days during which these five flares occurred are shown in Figure 1 by the filled circles (solar cosmic rays from the 1974 February 20 event were observed for two successive days). Note that because of the more restricted time intervals, the data in Table 2 cannot be compared directly with the daily averages in Figure 1.

The top panel in Figure 1 shows the correlation between the Z ≥ 6 and ¹H fluxes. While the average (Z ≥ 6)/¹H ratio for this data is ~2 × 10⁻³ (see Table 2),

FIG. 1.—Cross-correlation plots of daily average fluxes of ${}^1\text{H}$, ${}^4\text{He}$, and $Z \geq 6$ nuclei, for selected days during the period 1972 September 30 to 1974 October 22. The selection criteria were: *top and bottom panels*, days with ≥ 10 H nuclei; *middle panel*, days with ≥ 5 He nuclei. Days on which ${}^3\text{He}$ -rich flares occurred are identified by heavy filled circles. Days on which no ${}^4\text{He}$ or $Z \geq 6$ nuclei were observed have been plotted assuming 0.5 events. The average quiet-time ${}^1\text{H}$ and ${}^4\text{He}$ fluxes, and the 2σ upper limit to the quiet-time $Z \geq 6$ flux are indicated by "Q." Lines of constant ratios are also shown.

days on which there are ${}^3\text{He}$ -rich flares have ratios that are ~ 10 to ~ 100 times higher. Similarly, the center panel shows that the $(Z \geq 6)/{}^4\text{He}$ ratio is enhanced by ~ 3 to ~ 30 times its average value of ~ 0.05 . In the bottom panel we see that the ${}^4\text{He}/{}^1\text{H}$ ratio tends to be enhanced in such flares as well, although not always as strikingly as the heavy nuclei.

Table 2 and the correlations in Figure 1 show that

heavy nuclei are significantly enhanced in all five ${}^3\text{He}$ -rich flares, with respect to both ${}^1\text{H}$ and ${}^4\text{He}$. There are, however, heavy-nuclei enhancements which do not show corresponding ${}^3\text{He}$ enrichments. For example, there is one day in Figure 1 with fluxes of ${}^1\text{H} = 0.09$, ${}^4\text{He} = 0.008$, and $Z \geq 6 = 0.006$, for which we find ${}^3\text{He}/{}^4\text{He} \leq 0.08$. It is interesting that this event occurred only 5 days after the ${}^3\text{He}$ -rich event of 1974 May 9 and was during a period of iron-rich solar-particle emission identified by Gloeckler *et al.* (1975).

Additional information on the composition of the enhanced heavy nuclei can be obtained from other analysis modes. In the ~ 3 – 15 MeV per nucleon energy range Li, Be, and B can be individually identified by two-parameter analysis. Combining such data from our similar instruments on both IMP-7 and IMP-8, we find that less than 0.1 of the $Z > 2$ nuclei observed during the ${}^3\text{He}$ -rich flares were Li, Be, or B. There is independent evidence that in at least two of these events iron nuclei comprised a substantial percentage of the $Z \geq 6$ nuclei (Gloeckler 1975).

III. DISCUSSION

The ${}^3\text{He}$ nuclei observed in these events are presumably the result of nuclear reactions of high-energy (≥ 20 MeV per nucleon) solar particles. However, the enhanced abundances of $Z \geq 6$ nuclei is a feature of ${}^3\text{He}$ -rich flares which would require an augmentation of present theoretical models (Ramaty and Kozlovsky 1974; Rothwell 1974) which rely upon nuclear reaction kinematics to explain the ${}^3\text{He}$ enrichment with respect to ${}^2\text{H}$.

Enhancements of heavy nuclei have been observed in other events (see, e.g., Mogro-Campero and Simpson 1972; Crawford *et al.* 1975). However, models designed to explain heavy-element enhancements in those solar flares (Price *et al.* 1971; Cartwright and Mogro-Campero 1972) have not addressed the question of ${}^3\text{He}$ enrichment.

It is possible that such heavy-nucleus enhancements are the result of a preferential acceleration process which depends on the A/Z of the nuclei, since that ratio determines the magnetic rigidity at a given velocity. It has been noted, however, that such a preferential acceleration would not be expected to favor ${}^3\text{He}$ since its A/Z is between that of ${}^1\text{H}$ and ${}^2\text{H}$, neither of which is enhanced (Garrard *et al.* 1973). On the other hand, a preferential acceleration process based on Z^2/A might produce enhancements in ${}^3\text{He}$ and $Z \geq 6$ nuclei with respect to ${}^1\text{H}$, ${}^2\text{H}$, and ${}^4\text{He}$ nuclei. Such a Z^2/A dependence might result if phenomena involving Coulomb collisions were important.

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TABLE 2
3He-RICH SOLAR-PARTICLE EVENT DATA

TIME INTERVAL	OBSERVED NUMBER OF NUCLEI AND ASSOCIATED RATIOS (Energy intervals indicated in MeV/nucleon)								
	³ He/ ⁴ He 2.9- 12.7	³ He 2.9- 12.7	³ H+ ³ H 2-12.7	¹ H 2.4-6	⁴ He 2.4-6	Z≥6 2-5	$\frac{Z \geq 6(2-5)}{{}^1\text{H}(2.4-6)}$	$\frac{Z \geq 6(2-5)}{{}^4\text{He}(2.4-6)}$	$\frac{{}^4\text{He}(2.4-6)}{{}^1\text{H}(2.4-6)}$
1973 Feb. 15 0000-2100..	0.2	12	0	392	105	34	0.029 ± 0.005	0.11 ± 0.02	0.27 ± 0.03
1973 June 29 0400-1400..	~2	9	0	212	11	12	0.019 ± 0.006	0.36 ± 0.15	0.05 ± 0.02
1973 Sept. 5 0600-1200..	~6	12	0	13	2	2	~0.05	~0.3	~0.15
1974 Feb. 20 1600- Feb. 21 2000.....	0.4	14	0	694	58	61	0.029 ± 0.004	0.35 ± 0.07	0.08 ± 0.01
1974 May 9 1300-2100..	~8	15	0	27	2	19	0.24 ± 0.07	~3	~0.07
Average of other days..	0.01	...	...	...	...	...	0.0017 ± 0.0001	0.048 ± 0.001	0.032 ± 0.001

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