NUCLEI OF HEAVY ELEMENTS FROM SOLAR FLARES

C. Y. FAN
University of Arizona Tucson, Ariz., U.S.A.

G. GLOECKLER
University of Maryland, College Park, Md., U.S.A.

and

D. HOVESTADT
Max Planck Institut für Extraterrestrische Physik, Garching B. Munchen, F.R.G.

Abstract. This paper presents a comprehensive review of the up to date knowledge on nuclear species of $Z > 2$ from solar flares. It covers the following five topics:

(I) Solar flare particles of energies > 15 MeV n^{-1} and solar composition;
(II) solar flare particles of energies $\leqslant 15$ MeV n^{-1}, the enrichment of heavier elements;
(III) theoretical interpretation of the enrichment;
(IV) the charge states of solar particles; and
(V) isotopic abundances of solar flare particles.

I. Solar Flare Particles of Energies > 15 MeV n^{-1} and Solar Composition

The first evidence of the existence of nuclei heavier than helium among the energetic solar flare particles was detected in 1960, September 3 by Fichtel and Guss (1961), who used a sounding rocket to launch a recoverable nuclear emulsion stack above the Earth's atmosphere. Following this initial success, nine experiments were conducted by Fichtel and his associates over the period from 1960 to 1969 to study the composition of these heavy particles. In these measurements, the identification of the particles was accomplished by counting the number of δ-rays protruding from each primary track in the emulsion stack. The integral number of the δ-rays within a residual range R was then plotted as a function of R for each track. The result of such a plot has sufficient charge resolution to determine the composition of more abundant elements. Bertsch *et al.* (1972; 1973) summarized the results as follows:

(1) Within the experimental energy range from 12 to 100 MeV n^{-1}, the ratio of helium to medium nuclei is 58 ± 6 (Table I).

(2) The relative abundances, within experimental error, are almost invariant and are the same as the spectroscopic abundances of the Sun (shown in Table II).

In the energy ranges of these measurements, particles of nuclear charge $Z \leqslant 26$ are likely to be fully ionized, implying that all nuclear species from He to Fe have practically the same A/Z value. As a consequence, particles of the same velocity will not have their composition altered by the scatterings by the interplanetary magnetic fields, (including adiabatic deceleration and possible Fermi acceleration), as they propagate from the Sun to the Earth. Therefore, if (1) these elements were accelerated in the solar active regions *unbiased* and (2) particles of the same velocity were able to escape from

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TABLE I

Ratio of helium nuclei to medium nuclei

Time of measurements	Energy interval ($\mathrm{MeV\ n^{-1}}$)	He/M	Reference
1408 UT, 1960, Sept. 3	42.5–95	68 ± 21	Fichtel and Guss (1961)
1840 UT, 1960 Nov. 12	42.5–95	63 ± 14	Biswas *et al.* (1962)
1603 UT, 1960 Nov. 13	42.5–95	72 ± 16	Biswas *et al.* (1962)
1951 UT, 1960 Nov. 16	42.5–95	61 ± 13	Biswas *et al.* (1963)
0600 UT, 1960 Nov. 17	42.5–95	38 ± 10	Biswas *et al.* (1963)
0339 UT, 1960 Nov. 18	42.5–95	53 ± 14	Biswas *et al.* (1963)
1305–1918 UT, 1961 July 18	120–204	79 ± 16	Biswas *et al.* (1966)
1443 UT, 1966 Sept. 2	12–35	48 ± 8	Durgaprasad *et al.* (1968)
2233 UT, 1966 Sept. 2	14–35	53 ± 14	Durgaprasad *et al.* (1968)
2319 UT, 1969 April 12	18–34	55 ± 8	Bertsch *et al.* (1972)

Weighted average of above readings 58 ± 5,

the regions with *equal probability*, then their relative abundances would represent the composition of the medium of the active regions. The results shown in Table II seem to indicate that the two key criteria are indeed met.

The composition of solar flare particles was also measured by a number of other investigators, using various types of detector systems on different vehicles. Mogro-Campero and Simpson (1972a, 1972b) used a $\mathrm{d}E/\mathrm{d}x$ vs E solid state detector telescope on the OGO-5 satellite to study the particle composition of many flares observed from 1968, July 26 to 1971, February 1; Teegarden *et al.* (1973) measured the composition on the IMP-6 satellite of two flares occurring in 1971, April 6 and September 1, also with a $\mathrm{d}E/\mathrm{d}x$ vs E telescope; Price *et al.* (1973), Sullivan *et al.* (1973), and Crawford *et al.* (1974) reported the composition of particles from He to Ni in several flares of widely varying intensities. All these results indicate that, in the energy range $> 15\ \mathrm{MeV\ n^{-1}}$, the spectra of different nuclear species are approximately parallel with each other. The relative compositions thus determined are listed in column 3, 4, and 5 respectively of Table II for comparison. It is seen that, except for the measurement of Mogro-Campero and Simpson which shows abnormally high abundances of elements above Si the abundances agree with each other within experimental error. In view of this general agreement, one could then use the relative abundances in solar cosmic rays as the solar abundances of the elements for which no spectroscopic estimates of the photospheric abundances are available, or modify the photospheric abundances for which the spectroscopic method is of doubt. Thus, Bertsch *et al.* (1972) proposed

$$\frac{\mathrm{Ne}}{O} = 0.16 \pm 0.03\,, \qquad \frac{A}{O} \leqslant 0.017 \qquad \frac{\mathrm{He}}{O} = 103 \pm 10\,, \tag{1}$$

and Crawford *et al.* (1974) suggested the following revision:

$$\frac{A}{\mathrm{Si}} \leqslant 0.04 \qquad \frac{\mathrm{S}}{\mathrm{Si}} = 0.17\,. \tag{2}$$

TABLE II

Nuclear abundances relative to oxygen

Elements	Solar cosmic rays ($E > 15$ MeV n^{-1})				Photosphere	Corona
	Bertsch *et al.* (1972)	Mogro-Campero and Simpson (1972)	Teegarden *et al.* (1973), 1971, Sept. 1 flare	Crawford *et al.* (1974)		
He	$(1.03 \pm 1.0) \times 10^4$	–	$(4.2 \pm 0.25) \times 10^3$	$\sim 8.4 \times 10^3$	–	8.34×10^3
C	56 ± 6	57 ± 18	49 ± 3	50 ± 6	55.7	58.8
N	19^{+3}_{-7}	26 ± 19	11.6 ± 1.1	14.2 ± 2	17.2	19.2
O	100	100	100	100	100	100
F	<3	–	<0.6	–	–	–
Ne	16 ± 3	21 ± 8	12.7 ± 1.1	12.3 ± 2.0	–	10.3
Mg	5.6 ± 1.4	13 ± 6	18.2 ± 1.4	15.6 ± 2.5	5.16	7.05
Si	2.8 ± 1.0	36 ± 12	10.7 ± 1.1	9.1 ± 0.7	5.26	6.41
S	0.8 ± 0.6	–	2.5 ± 0.5	1.5 ± 0.3	2.47	1.54
A	<1.7	8 ± 5	<0.4	<0.4	–	0.96
Ca	<1.0	<2	<1.1	0.6 ± 0.2	0.32	0.26
Cr-Ni	1.1 ± 0.2	67 ± 16	2.8 ± 0.5	~ 8.5	4.1	5.8

II. Solar Flare Particles of Energies $\leqslant 15$ MeV n^{-1}, – The Enrichment of Heavies

The variability of He/M was first realized by Armstrong and Krimgisis (1971) and Krimigis *et al.* (1971). They made a statistical study of solar protons, α-particles and $Z \geqslant 3$ nuclei measured in 1967–1968 with a solid state detector aboard the Explorer-35 and the Mariner-5 spacecraft and found that the He/M ratio is 20 ± 10 instead of 60 as Bertsch *et al.* had indicated. The important difference between the earlier rocket experiments of Fichtel and his associates and the experiments of Krimigis *et al.* is the energy intervals of the measurements, the former covering the region of 12–204 MeV n^{-1} as opposed to the latter, which covers 0.5–2.5 MeV n^{-1}. It was then suggested that a mild energy dependence of the abundance ratio is one possible explanation of the observed difference (Armstrong *et al.*, 1972).

More conclusive evidence of the energy dependence of the abundances is shown by the results of Price *et al.* (1971), who studied the etched cosmic-ray particle tracks in a Surveyer-3 camera lens filter and an Apollo-12 spacecraft window brought back from the Moon. In both types of glass, tracks of heavily ionizing particles were revealed by chemical etching (Fleischer *et al.*, 1965; Price and Fleisher, 1971). Since these glasses are insensitive to particles of $Z < 16$ and the solar abundances of ions of $Z > 16$ is strongly peaked at Fe, the particle tracks must have been made by solar Fe nuclei. By comparing the energy spectrum of the Fe nuclei determined from the etched tracks with the solar He spectrum measured during the same time period by Lanzerotti (World Data Center A, *Rept UAG* **5**, 56; *UAG* **8**, 198; *UAG* **9**, 34) and by Hsieh and Simpson (1970), they found that Fe/He increases strongly with decreasing energies.

The enhancement of solar flare heavy nuclei in the low energy range is now established beyond any doubt. In Figure 1 we display the results of four solar flares, occurring 1971, January 25, and September 2 and 1972, April 18, and August 4, reported by Price *et al.* (1973). It is seen that above about 15 MeV n^{-1}, He, CNO, and Fe have similar spectra whereas towards lower energies their spectra diverge from each other with heaviers more abundant. These features were also observed by many others (Mogro-Campero and Simpson, 1972a; 1972b; Crawford *et al.*, 1972; Fleischer and Hart, 1973; Braddy *et al.*, 1973; Shirk and Price, 1972; Fleischer *et al.*, 1973; Biswas *et al.*, 1973; Nevatia *et al.*, 1973). The enhancement of solar heavy nuclei recorded in lunar rocks over the last half million years was reported by Bhandari *et al.* (1973).

The enrichment of heavy nuclei is usually expressed in terms of an enrichment factor of a species of nuclear charge Z at energy E, which is defined as

$$Q(Z, E) \equiv (Z/\mathrm{He})_{\mathrm{cr}} \ / \ (Z/\mathrm{He})_{\mathrm{s}}. \tag{3}$$

In this expression $(Z/\mathrm{He})_{\mathrm{cr}}$ and $(Z/\mathrm{He})_{\mathrm{s}}$ stand for the relative abundance of solar cosmic-ray particles and the solar photospheric composition respectively. Present experimental results show that Q increases with Z for a given E and decreased with

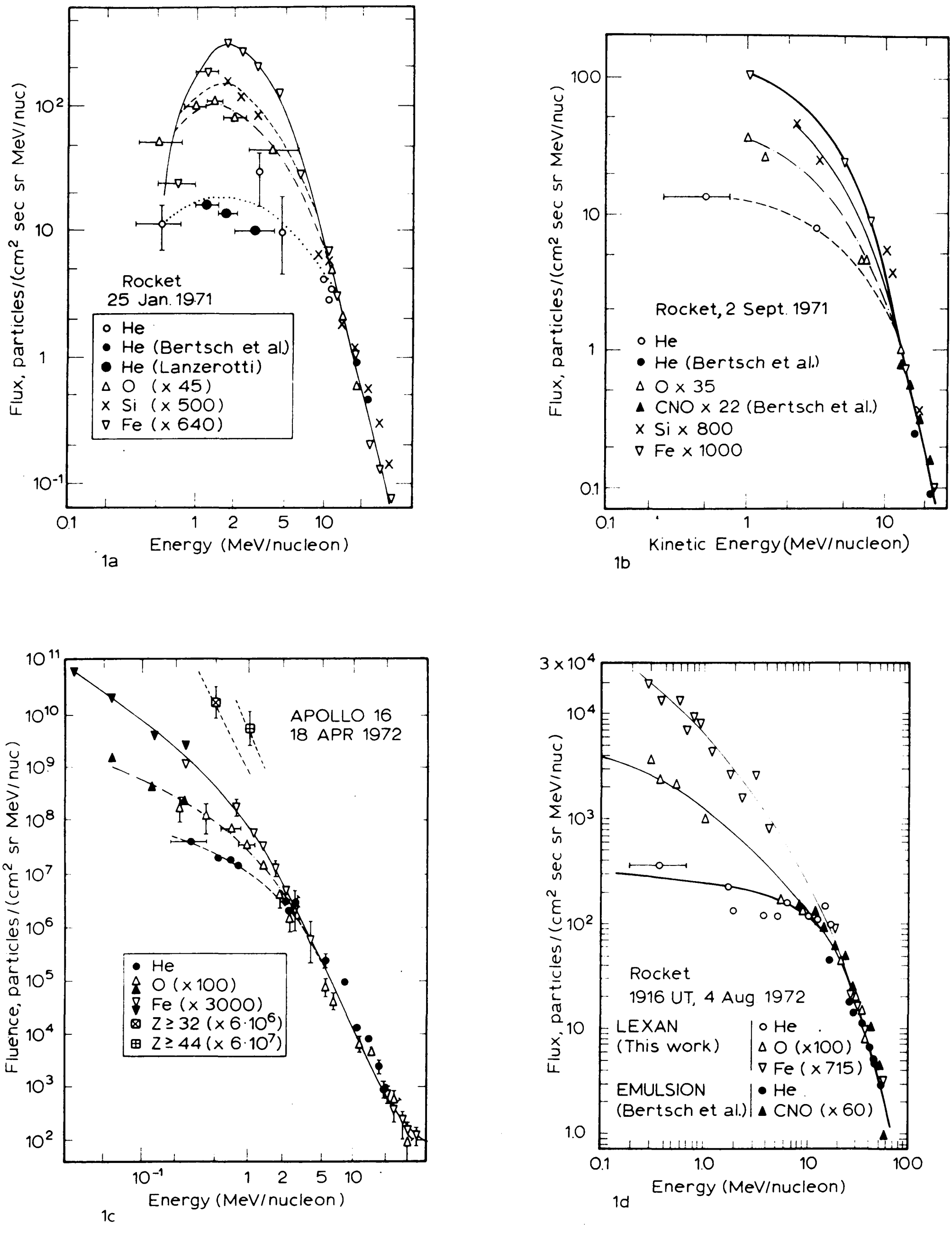

Fig. 1a–d. (a) Energy-dependent composition measured with Lexan stack during flare in 1971, January 25. – (b) Energy-dependent composition measured with Lexan stack during flare in 1971, September 2. – (c) Fe and heavier elements measured with SiO_2 glass, O and He measured with Lexan stack in 1972, April 18. – (d) Energy-dependent composition measured with Lexan stack during flare in 1972, August 4.

E for a given Z. One of the basic important questions is how does $Q(Z, E)$ vary from flare to flare and also within the same flare?

Mogro-Campero and Simpson (1972a; 1972b) first noted that Q varies from flare to flare. The variability is also apparent from the results of Price *et al.* as shown in Figure 1. A recent case which shows the variability is the 1972, October 29–November 4 event measured by Hovestadt *et al.* (1973) on the Imp-7 satellite. Their detector is a dE/dx vs. residual energy telescope, using a thin window isotubane filled proportional counter as dE/dx device and a surfcce barrier detector for the determination of residual energy. The lowest energy limit for each nuclear species is determined by the total thickness of material in front of the solid state detector, which amounts to about 0.328 μg cm^{-2} polyethylene equivalent, and the electronic thresholds. At entrance energies above about 400 keV n^{-1}, a clear separation of individual even Z nuclei is possible up to iron, a feature especially suitable for the study of low energy heavy particles. For this solar flare, the detector recorded a total of 24470 events. Figure 2 shows the differential energy spectra for C, O, and Fe. These spectra are practically

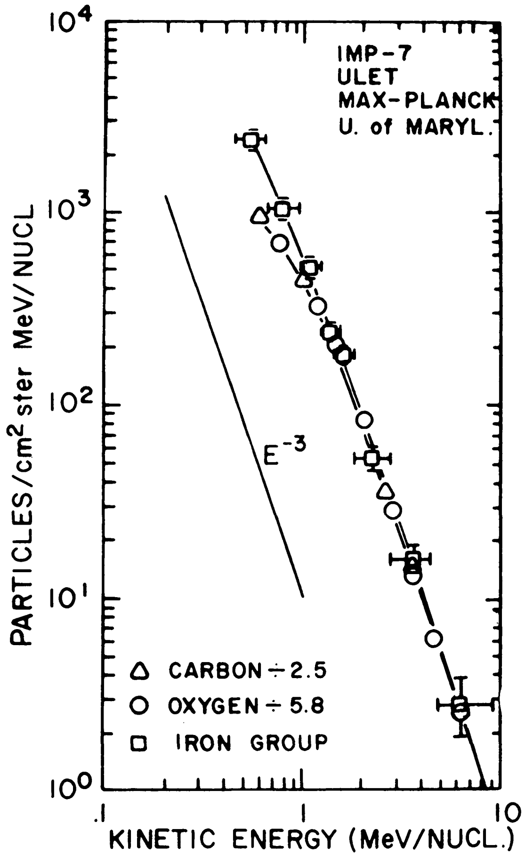

Fig. 2. Energy spectrum of C, O, and Fe- group measured on the IMP-7 satellite during the event in 1972, October 29–November 4. The E^{-3} spectrum is drawn for reference.

parallel down to ~ 1.5 MeV n^{-1} before they diverge. This feature is similar to that in Figure 1c but strikingly different from that in Figure 1a, b, and d, where the spectra diverge from each other at energy as high as 15 MeV n^{-1}. It is noted that the spectra in Figure 2 and those in Figure 1c were measured outside the magnetosphere and integrated over the entire event, whereas those in Figure 1a, b, and d were snapshots within the magnetosphere. Whether this is the cause for the difference in the spectral shape or the difference is merely a reflection of the variability of the enrichment factor Q, is not clear at this moment. For the same solar event, Armstrong and Krimigis (Armstrong and Krimigis, 1973; Krimigis and Armstrong, 1973) reported α/M in the energy range 1.6–3.2 MeV n^{-1} varied from 20 to 115 in six hour period and Fe/O in the energy range 3.3–7.6 MeV n^{-1} varied by a factor of 11.

III. Theoretical Interpretation of the Enrichment

Attempts have been made to explain qualitatively the enrichment of the heavier particles. Price *et al.* (1971) suggested that it may be due to preferential leakage of incompletely ionized heavy nuclei from the accelerating region. However, by using the Earth's magnetic field as a magnetic spectrometer, Sullivan and Price (1973) showed that the effective charge, Z^*, of 1.8 MeV n^{-1} Fe ions which they detected in 1971, January 25 (Figure 1a) is 22^{+4}_{-1} if the magnetic cut-off rigidity at Fort Churchill, where the rockets were launched, was at its normal daytime value, 150 MV. Therefore, if the explanation of Price *et al.* were correct, then the atomic electrons of the Fe ions must have been stripped off at a later stage of the escaping process (Mogro-Campero and Simpson, 1972a; Braddy *et al.*, 1973).

Cartwright and Mogro-Campero (1972) on the other hand suggested a three-stage model for the acceleration of solar particles to explain the enrichment. (1) Fully stripped ions are first accelerated to supra-thermal energies. (2) Subsequently a fraction of these ions are transported to a region for further acceleration. In this process, ions pick up electrons with their states determined by charge-exchange equilibrization process. (3) Finally ions are accelerated by hydromagnetic waves (Fermi-type acceleration) to the observed energies. The rigidity dependent efficiency of the final acceleration results in the observed enrichment of the heavier particles. This model has three functions which can be adjusted to explain the observed enrichment, but the requirement of three physically separated regions seems to be too artificial. Also this model fails to explain the energy dependence of the enrichment factor Q.

If one assumes that solar particles are accelerated in the lower chromosphere region where there are sufficient numbers of neutral hydrogen and helium atoms for the particles to establish their charge equilibrization by means of electron capture and loss in that medium, then the rate of the energy change of a particle can be expressed by the following general expression:

$$A\frac{d\varepsilon}{d\tau} = \alpha A\varepsilon - (Z^*)^2 f(\varepsilon). \tag{4}$$

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In this equation, A, ε and Z^* stand respectively for the mass number, the energy per nucleon, and the effective charge of the particle; the first term on the right hand side is the rate of acceleration with α as the acceleration efficiency and the second term is the rate of energy loss to the ambient medium. By assuming functional forms for both α and Z^*, one can in principle integrate the equation to obtain the energy spectra for various nuclear species to be compared with experimental measurements. It may be entirely possible that the enrichment is merely the reflection of the ε and Z^* dependence of the energy loss in the medium (Cowsik *et al.*, 1973; Sullivan, 1974, private communication).

IV. The Charge States of Solar Particles

We have seen that to explain the increasing enhancement of heavy nuclei, all the proposed models require an establishment of charge state equilibrium for ions in the acceleration process (see also Ginzburg and Syrovatskii, 1964; Ramadurai, 1971). The measurement of Gloeckler *et al.* (1973) provides the first direct evidence for partially stripped carbon and oxygen at 100 keV n^{-1}.

The data have been obtained using the University of Maryland electrostatic deflection spectrometer on board the IMP-7 satellite which was launched in 1972, September 22. The method of particle identification is based on the fact that the amount of deflection, d, of an ion with an effective charge Z^* and kinetic energy T in a known electrostatic field is given by $d = gZ^*/T$. The constant g is determined by the geometry and the voltage of the deflection system. By measuring T with a solid state detector, the value of Z^* can thus be determined.

Solar particles were observed near Earth on October 17 and 18. Analysis of the data indicated the existence of Z^* equal to 5, 6, 7, and 8 particles. Assuming that very little Be, B, N, and Ne are present, one can then take all $Z^* = 5$ to be C^{5+} and all $Z^* = 8$ to be O^{8+} and estimate the abundance of C^{6+} and O^{7+}. The abundance ratios are

$$C^{5+}/C^{6+} = 1.8, \text{ and } O^{7+}/O^{8+} = 1.6 \tag{5}$$

at 0.1 MeV n^{-1}, and $C/O = 0.8$ which is in reasonable agreement with measurement at higher energies. The results are plotted in Figure 3.

The charge states of accelerated particles depend on their energies and the physical condition of the medium in which the particles are accelerated. The equilibrium charge states of carbon and oxygen at 0.1 MeV n^{-1} are found to be 2.5 and 2.9 respectively in a *neutral medium*. The measurements of Gloeckler *et al.* on the other hand, indicate much higher values: 5.4 for carbon and 7.4 for oxygen. To account for this discrepancy, they proposed two alternatives.

(1) Accelerated ions traverse the hot coronal region where the probability for electron pickup is negligible, and are stripped off most of their remaining electrons.

(2) After acceleration and escape from the Sun, the particles are adiabatically decelerated. In this case, the measured charge states are the equilibrium values at energies ~ 1 MeV n^{-1}. The limited amount of data they have does not allow them to decide which of the two alternatives corresponds to the actual condition.

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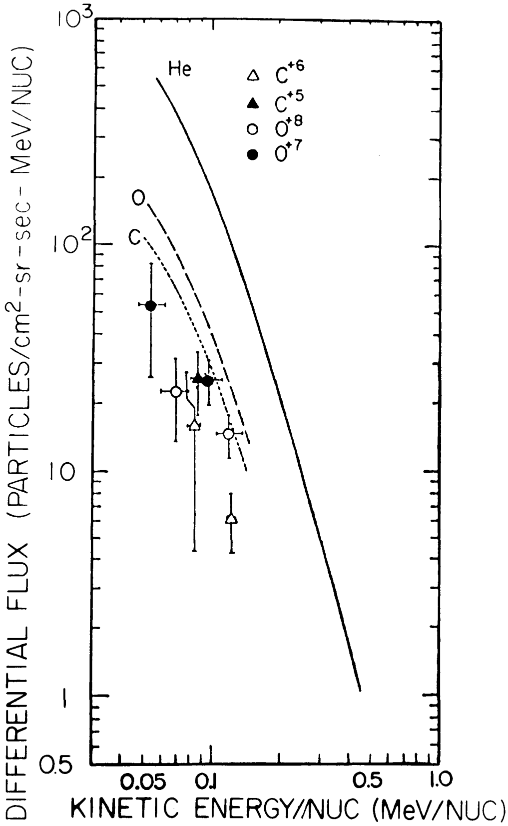

Fig. 3. The time averaged differential fluxes of C^{6+}, C^{5+}, O^{8+}, and O^{7+} ions measured on the Imp-7 satellite during 1972, October 17–18. Data have been corrected for energy defects in the solid state detectors and for background measured independently for each detector with deflection voltage commanded off. The C and O spectra are obtained by combining the measured fluxes of the partially stripped nuclei. The He spectrum is drawn for reference.

V. Isotopic Abundances of Solar Flare Particles

To conclude this paper, we would like to cite the isotopic composition of solar cosmic-ray particles measured during 1972, August 2–9 by Webber *et al.* (1973), to show that solar cosmic-ray measurement is a potentially powerful tool for solar physics research in other areas.

The measurement was done with a double dE/dx vs E telescope of the Goddard Space Flight Center – University of New Hampshire on the Pioneer-10 spacecraft. It consists of four solid state detectors, D_1, D_2, E, and F. F is used to reject penetrating particles while for stopping particles the energy losses in D_1 and D_2 and the residual energies in E are measured. The requirement of the D_1/D_2 pulse height ratios to follow the theoretical values within 5% provides a technique of background elimination, thereby improving impressively the mass resolution and making the isotopic composition measurement possible.

TABLE III

Isotopic abundance measurements (energy approximately 8–15 MeV n^{-1} for $Z \geqslant 2$ nuclei)

Isotope	Webber *et al.* Events	Webber *et al.* %	Natural Abundances[a]	Solar Abundances
He^3	20	1.3	0.01	~0.03 %[3]
He^4	1480	98.7	~100.0	99.9
C^{12}	173	98.8	98.9	98.9[b]
C^{13}	2	1.2	1.1	1.1[b]
N^{14}	42	97.6	99.6	
N^{15}	1	2.4	0.4	
O^{16}	312	96.6	99.7	99.65[b]
O^{17}	8?	2.5?	0.04	0.05[b]
O^{18}	2	0.6	0.26	0.30[b]
Ne^{20}	37	86.2	90.9	92.3[c]
Ne^{21}	2	4.6	0.25	0.3[c]
Ne^{22}	4	9.2	8.82	7.4[c]
Mg^{24}	30–33	81.1–89.2	78.7	
Mg^{25}	5	5.4–13.5	10.1	
Mg^{26}	2	5.4	11.2	

[a] From *Chart of the Nuclides* – 9th edn.
[b] Hall *et al.* (1972)
[c] Geiss (1972)

The results of the measurement are given in Table III. Assuming that He^3 nuclei are fragments of He^4 produced by the interaction with solar atmosphere, the amount of matter traversed by the He^4 nuclei would be about ~ 0.29 cm^{-2}. This path length would produce a negligible effect to alter the isotopic abundances of Mg, Ne, O, N, and C, that is, the following ratios listed in Table III may be tentatively regarded as the solar abundances:

$$Ne^{20}/Ne^{22} = 9 \pm 5, \qquad Mg^{24}/Mg^{26} = 16 \pm 6, \quad \text{and} \\ Mg^{24}/Mg^{25} = 10 \pm 6, \tag{6}$$

for which there is no spectroscopic determination available.

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