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Enhancement of Solar Heavy Nuclei at High Energies in the 4 July 1974 Event

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ABSTRACT

Relative abundances of energetic nuclei in the 4 July 1974 solar event are presented. The results show a marked enhancement of abundances that systematically increase with nuclear charge numbers in the range of the observation, $6 \leq Z \leq 26$ for energies above 15 MeV/nucleon. While such enhancements are commonly seen below 10 MeV/nucleon, most observations at higher energies are found to be consistent with solar system abundances. The energy spectrum of oxygen is observed to be significantly steeper than most other solar events studied in this energy region. It is proposed that these observations are characteristic of particle populations at energies ~ 1 MeV/nucleon, and that the anomalous features observed here may be the result of the high energy extension of such a population that is commonly masked by other processes or populations that might occur in larger solar events.

I. INTRODUCTION

The elemental composition of energetic charged particles emitted by the sun has been observed in a variety of experiments in an effort to describe the nature of the particle radiation and its relationship to other observed phenomena. Such information is desired to aid in understanding the nature of the solar environment and the dynamical processes that accelerate charged particles and govern their transport in the interstellar medium.

Generally, two rather different descriptions of the relative composition of multiply-charged nuclei are found, depending on the energy region in which measurements are made (e.g. see review by Fan et al., 1975). Below about 10 MeV/nucleon, the composition varies significantly in different solar events (Armstrong and Krimigis, 1971; Crawford et al., 1975). Temporal variations within individual solar particle events (Armstrong and Krimigis, 1975) and more recently spatial variations (Armstrong et al., 1976) are also observed at low energies. In addition, the composition below 10 MeV/nucleon is found to be systematically enriched in heavy nuclei (Crawford et al., 1972 and 1975; Hovestadt et al., 1973) compared with photospheric (Withbroe, 1971) or solar system (Cameron, 1973) abundances. Specifically, the enrichment factor appears to increase with the nuclear charge number and increases as energy decreases.

At higher energies, above ~ 25 MeV/nucleon, the relative abundances are much more consistent among many of the solar events studied (e.g. Biswas et al., 1962; Durgaprasad et al., 1968; Bertsch et al., 1972; Crawford et al., 1972; Teegarden et al., 1973). The composition here does not exhibit appreciable temporal variations nor does it vary appreciably with energy. Moreover, the abundances agree within statistical uncertainties with the photospheric abundances (Withbroe, 1971) measured spectroscopically.

Small differences in composition, however, have been found even at high energies. Bertsch et al. (1973b) and Pellerin (1975) observe abundance ratio variations that are within factors of ~ 2 between different flare events. Also, in the large solar event on 4 August 1972, Bertsch et al. (1974) report a small systematic variation of abundance ratios as a function of energy for energies up to 50 MeV/nucleon. On the other hand, Mogro-Campero and Simpson (1972a,b) found a substantial enhancement of heavy nuclei in a measurement that was made by integrating over seven small solar particle events. Their results have not been confirmed as yet, and it is not clear whether strong enhancements of heavy nuclei can be produced in the same processes that contribute to the "usual" composition observed above 25 MeV/nucleon, or whether the enhancement is somehow the result of a modified acceleration process that is exhibited only in very low intensity events or is due perhaps to a temporal variation in composition that is sampled by their technique.

In this paper results are presented from measurements made in the 4 July 1974 solar event using the SPICE (Solar Particle Sounding Rocket Experiment) technique to sample the solar radiation. The measurements indicate a pronounced enhancement of heavy nuclei at high energies that is similar to the results of Mogro-Campero and Simpson (1972b).

II. EXPERIMENTAL PROCEDURE

The technique used in this experiment to study solar particle composition employed sounding rocket payloads that were maintained on standby at the Churchill Research Range in Manitoba, Canada to carry the nuclear emulsion detectors above the atmosphere for an exposure period of 240 seconds. Details of this technique have been reported earlier (see Bertsch et al., 1974). The main difference between the current experiment and earlier studies in the program is in the size of the emulsion stacks. A new payload was used that permitted an increase of emulsion area by a factor of 18 and this in turn makes it possible to study events of correspondingly lower intensity.

The flight from which the results of this paper were obtained occurred at 0804 UT on 4 July 1974, following a relative maximum intensity of multiply-charged nuclei (Armstrong et al., 1976). Two flare events were observed on 3 July at S15, E08; one, a class 2B began at 0258 UT and the other a class 3N at 0802 UT. The exposure was made before the first sudden commencement that occurred ~ 1533 UT on 4 July where Armstrong et al., (1976) note a dramatic increase in the Fe/O ratio at lower energies.

The analysis of composition was made on events recorded in Ilford type K.5 emulsion stacks. Six stacks 6.6 x 17.8 x 0.6 cm were recovered and were used for the analysis. The emulsions were covered by a 1/2 mil titanium foil and 1 mil polyethylene film together equivalent to a 34μ emulsion layer in stopping power. Only particles that entered the emulsion from above the horizon plane with angles 10 to 60 degrees from the emulsion plane were accepted. In addition, a minimum projected emulsion range of 78μ was required to provide adequate track length for analysis. These criteria, together with the cover material, resulted in a minimum energy that varies with particle charge ranging from 9 MeV/nucleon for carbon to 17 MeV/nucleon for Fe. A total area of 421.1 cm^2 was scanned and the solid angle of acceptance was 1.06 sr giving a total area-solid angle-time factor of 1.07 x 10^5 $cm^2 sr$.

Scanning was aided by a motorized three-axis digitized microscope stage system connected to an on-line computer. This device controlled the driving from one viewing field to the next and recorded onto a disk storage the coordinates of all events that were flagged by the operator. A visual scan threshold was established to detect all nuclei heavier than He. A total rescan was made to insure that all events were recorded.

Identification of the charge number of individual events was accomplished by means of a television-microscope system in which the image of the emulsion track was scanned by the television camera. The resulting picture was digitized and then analyzed by an on-line computer to produce an average track width or "blackness" measure of the track. Since the track width depends on the primary and secondary energy loss effects in the emulsion, which in turn depend on the nuclear charge and velocity, plots of "blackness" versus range produce profiles that could be identified for each charge. More details of the technique can be found in a thesis by Pellerin (1974) and in Pellerin (1975).

III. RESULTS AND DISCUSSION

Differential spectra of oxygen and iron-group elements derived from the 4 July 1974 observation are shown in Figure 1. For purposes of comparison with earlier measurements, it should be noted that the absolute fluxes of solar oxygen observed here are approximately two orders of magnitude smaller than any previous observations in the SPICE program (Bertsch et al., 1973a, 1974) at corresponding energies.

Solar particles are seen to dominate the observed oxygen fluxes up to an energy of about 50 MeV/nucleon. Above this energy the observed oxygen fluxes are in agreement with those of quiet-time galactic cosmic rays. The solid line traversing the oxygen points in Figure 1 is a weighted least-squares fit of the measurements below 50 MeV/nucleon to a spectrum of the form $\exp(-E/E_0)$ with the resultant value of $E_0 = 5.75 \pm 0.45$ MeV/nucleon.

The solid line traversing the iron group ($22 \leq Z \leq 30$) fluxes in Figure 1 was obtained by renormalizing the fitted oxygen spectrum to the iron-group measurements (using the same E_0 above). The Fe/O ratio determined in this manner is 39 ±9%. This ratio is clearly inconsistent with a ratio of 3 to 6% found in earlier (Bertsch et al., 1973a, 1973b, 1974) solar particle events. Had the latter ratio prevailed on 4 July 1974, the expected iron-group spectrum would be that shown by the dashed line in Figure 1.

More complete element abundance measurements obtained in this work are shown in Table I together with the results for earlier events. In obtaining these abundances, data were confined to the 15 to 30 MeV/nucleon interval where all reported species were observed in order to avoid the uncertainties of special extrapolation sometimes employed in abundance determination.

The 4 July abundances shown in Table I exhibit a systematic enhancement in the relative abundances of heavier nuclei when compared with most of the earlier measurements at comparable energies (Crawford et al., 1972; Teegarden et al., 1973; Bertsch et al., 1974). These enhancements are somewhat less pronounced, however, than those observed by Mogro-Campero and Simpson (1972a, b).

The magnitude and trend of the enhancements is more graphically displayed in Figure 2 which shows the results in the last two columns of Table I divided by the corresponding solar-system abundances (Cameron, 1973). The enhancement appears to be best characterized by an exponential rise with atomic number from carbon through silicon with a constant or more slowly rising behavior above silicon. Possible departures from the monotonically increasing trend may exist for sulphur, for example, although the statistics of the measurements do not permit an adequate examination of such detailed structure.

It should be clearly understood that the significance of the results shown in Figure 2 does not lie in the mere existence of heavy-nucleon enhancements in solar cosmic rays but rather in their existence at energies well above 10 MeV/nucleon. At energies below a few MeV/nucleon, heavy-nucleus enhancements are commonly observed as was noted above. The magnitude of these observed enhancements decreases dramatically with increasing energy, however, and it has been generally, though not universally, believed that heavy-element enhancements are a low-energy phenomenon. In fact some of the most promising recent studies of the low-energy region are those that associate the particle fluxes and composition with macroscopic spatial structures such as high-speed solar-wind streams and magnetic sector structure (Roelof and Krimigis, 1973; Gloeckler et al., 1975). In contrast, energetic particles above ~ 10 MeV/nucleon are more commonly associated with spatially and temporally discrete solar flares where a much different environment for particle acceleration would be expected to prevail.

Before pursuing this comparison of particle-energy regimes, the following features of the 4 July high-energy enhancements are noted: 1) the particles are not clearly associated with a particular solar flare; 2) the absolute particle fluxes are small in comparison with observations at comparable times (relative to the time of maximum flux for 10 MeV protons, for example) during earlier events; 3) the energy spectra are steeper than those observed at the same energy during comparable times during earlier events. Typical values of E_o in earlier events (see Bertsch et al., 1974 and references therein) are factors of 2 to 3 larger than those found here.

These observations lead us to associate the particles observed on 4 July with the particle population at energies ~ 1 MeV/nucleon where heavy-nucleus enhancements and small values of E_o (Armstrong and Krimigis, 1971) are common (at times when the observed spectra are not flattened by velocity dispersions). This population has been associated with the macrostructure of the corona (Roelof and Krimigis, 1973; Gloeckler et al., 1975) and may well represent acceleration in a large spatial region. For example, Gloeckler et al. (1975) observe relative enhancements of iron nuclei lasting for a period of ten days, occupying an entire solar sector. It is, in fact, this same solar sector, observed two rotations later, in which the present 4 July observations were made.

In contrast, the intense fluxes of energetic particles more clearly associated with large solar flares might emerge directly from the flaring region where temperatures are adequate to strip nuclei of all orbital electrons and where the intense spatially-compact magnetic fields lead to flat energy spectra with element abundances that are representative of those of the photosphere or corona. In such circumstances this flare-associated population might dominate the high-energy "tail" of the low-energy population that we believe to be observed on 4 July 1974.

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FIGURE CAPTIONS

FIGURE 1: Differential energy spectra for oxygen (circles) and iron-group ($22 \leq Z \leq 30$) nuclei (squares) observed at 0804 UT on 4 July 1974. Oxygen points are fitted by an exponential spectrum, $\exp(-E/E_0)$, where $E_0 = 5.75$ MeV/nucleon for energies below 50 MeV/nucleon. At higher energies, the galactic flux becomes significant. The iron data are fitted by a line of the same slope at a level of 39% oxygen. The dashed line represents a 6% Fe/O abundance which is the upper range of observation seen in more typical solar events (e.g., Bertsch et al., 1973a). The low intensity of this event is emphasized by spectral points for oxygen, reduced by a factor of 100 for the April 1969 (plus) and the September 1971 (star) events.

FIGURE 2: Ratio of energetic ($\geq$ 15 MeV/nucleon) nuclei abundances to solar system abundances (Cameron, 1973), normalized to one at oxygen, as a function of nuclear charge. Data for the 4 July 1972 event is shown by circles and for comparison, results of Mogro-Campero and Simpson (1972b) are shown by the X's. In the case of iron, a range of charges are included in the group, shown by the horizontal bar, but the main contributor is expected to be iron.

TABLE I

ABUNDANCES RELATIVE TO OXYGEN

ELEMENT	BERTSCH et al., 1973a	TEEGARDEN et al., 1973	CRAWFORD et al., 1972	MOGRO-CAMPERO AND SIMPSON, 1972b	PRESENT WORK (15 ≤ E ≤ 30 MeV/N)
He	101 ± 10	42.0 ± 2.5	—	—	—
Li	—	<.003	—	—	—
Be	<.02	<.003	—	—	—
B	<.02	<.008	—	—	
C	.56 ± .06	.49 ± .03	—	.42 ± .13	.35 ± .10
N	$.19^{+.03}_{-.07}$	.116 ± .011	—	.23 ± .10	$.15^{+.09}_{-.15}$
O	≡1.0	≡1.0	~1.0	≡1.0	≡1.0
F	—	<.006	—	—	—
Ne	.16 ± .03	.127 ± .011	$.10^{+.10}_{-.05}$	.20 ± .10	.43 ± .09
Mg	.078 ± .018	.182 ± .014	.125 ± .030	.22 ± .11	.20 ± .06
Si	.031 ± .010	.107 ± .011	≡0.1	.58 ± .21	.29 ± .08
S	.021 ± .007	.025 ± .005	.015 ± .006	.13 ± .09	.03 ± .02
A	<.017	<.004	<.004	.08 ± .07	.06 ± .03
Ca	<.010	<.011	.008 ± .005	.10 ± .09	
Cr – Ni	.03 – .06	.028 ± .005	.094 ± .033	.79 ± .29	.37 ± .09

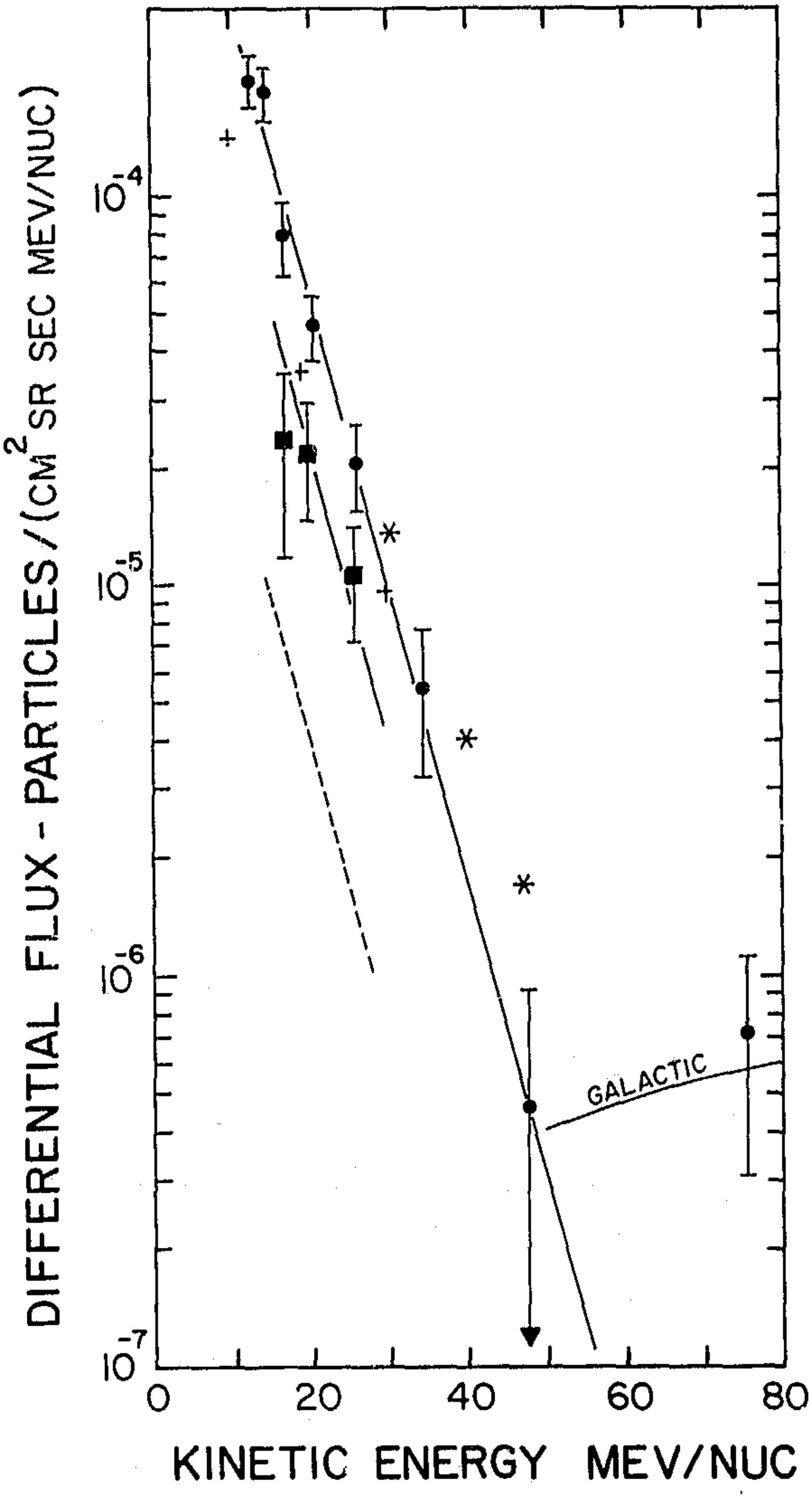
DIFFERENTIAL FLUX - PARTICLES/(CM^2 SR SEC MEV/NUC)
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0
20
40
60
80
KINETIC ENERGY MEV/NUC
GALACTIC

Fig. 1

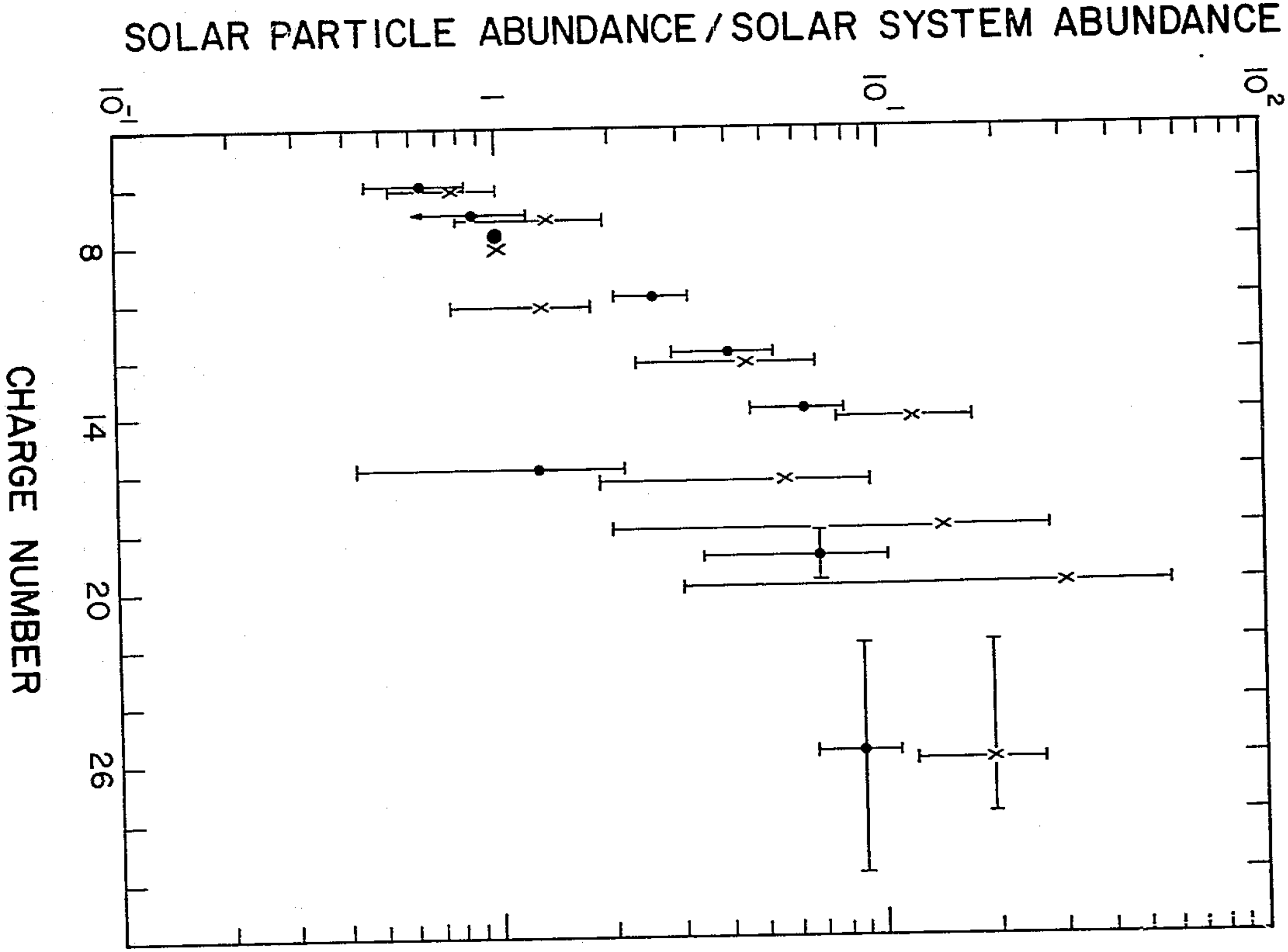
SOLAR PARTICLE ABUNDANCE / SOLAR SYSTEM ABUNDANCE
10^{-1}
1
10^{1}
10^{2}
8
14
20
26
CHARGE NUMBER

Fig. 2