CHARGE COMPOSITION OF SOLAR COSMIC RAYS

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ABSTRACT

The composition of energetic solar particles is reviewed for all solar events in which measurements on helium and heavier nuclei have been made simultaneously in the same detector during a given particle event. For nuclei of equal charge-to-mass ratio, the relative abundances have been the same within uncertainties in every measurement, and consistent with spectroscopic photospheric estimates. Iron has a slightly different charge-to-mass ratio but is still of considerable interest. An observation of the Fe/O in the January 24, 1971 solar event has provided a second determination of this value.

1. Introduction

The existence of heavy nuclei among the energetic solar particles has been known for about a decade, and they have now been seen by many observers in several different solar particle events. However, because of the low abundances of nuclei with charges greater than two, only the most intense solar particle events have intensity levels sufficiently high to study details of the particle composition. Before the most recent event to be reported here, namely that on Jan. 24, 1971 there were only six events in which such measurements were made. The Jan. 24, 1971 event is also only the second event in which Fe group nuclei have not only been detected, but in which the flux of Fe nuclei can be compared directly to the abundance of medium nuclei (C,N,O, & F). The first was the September 2, 1966 event (Bertsch, et al., 1969). In the other events when detectors capable of distinguishing Fe group nuclei were flown, either the intensity of the event was too small to expect to see Fe group nuclei at the energy/nucleon threshold for the detector (Fichtel and Guss, 1961; Biswas et al., 1962; Biswas et al., 1963; Biswas et al., 1966; Bertsch et al., 1971) or it was not possible to compare directly the Fe group flux to medium or helium nuclei measured in the same instrument because of the nature of the detector (Fleischer et al., 1970; Crozaz and Walker, 1971; Price et al., 1971).

One outstanding feature of the energetic solar particle composition, which has been seen in an examination of the experimental results, is the constancy of the relative abundances of particles with the same charge-to-mass ratio within experimental errors in all events where a comparison could be made at energies where the nuclei are fully ionized. Moreover, the observed abundances show a strong similarity to photospheric and coronal values measured by spectroscopic techniques.

2. Experimental Technique

The most recent data presented here were obtained from nuclear emulsion stacks flown on sounding rockets during the solar particle event which began at about 2309Z on January 24, 1971. The payloads and their Nike-Apache vehicles were kept on standby at the Fort Churchill Research Range in Manitoba, Canada prior to the event as part of a continuing SPICE (Solar Particle Intensity and Composition Experiment) Program. There were two sounding rockets flights which reached apogee at about 0819Z and 1512Z on January 25, 1971, i.e. about nine and 16 hours respectively after the event began.

Each payload had two nuclear emulsions stacks consisting of 24 pellicles with lateral dimensions 2.5 in. x 2.8 in. A thin cover of stainless steel and lexan, having a total thickness equivalent to 72 microns of emulsion, separated the outermost pellicle from the particle radiation. This first pellicle was 200 microns thick. It was followed by three 300-micron and twenty 600-micron pellicles. Experience has shown that this arrangement of thicknesses is advantageous since the high density of solar proton tracks in the outer pellicles of the stack makes it difficult to analyze tracks in a 600-micron plate. The two stacks had different sensitivites: one was made from Ilford K.5 material sensitive to minimum ionizing events, and the other was made from Ilford K.2 emulsion sensitive to protons of energy less than 40 MeV.

During the flight, the nosecone of the payload was opened while the payload was above about sixty kilometers yielding an exposure time of 245 sec. By means of spin stabilization, the emulsion plates were held in a vertical plane. The zenith angle of arrival of each particle in the stacks can therefore be determined during the analysis. Those events that entered the stacks from directions below the horizon are excluded from the analysis because of their unknown energy loss and possible interactions in the atmosphere.

An area scan is made in the top plate of the K.5 emulsion stack to locate nuclei heavier than helium, and heavy nuclei tracks with entrance angles from 10° to 60° with respect to the surface are accepted. In addition, a minimum projected length of 78 microns is demanded to ensure a sufficient track length for analysis. Identification of multiply-charged particles is accomplished by measuring the total obscuration as a function of range using the Goddard digitized T.V. microscope system. Helium nuclei are resolved from protons in the less sensitive K.2 emulsion stack by measuring the grain density of each track near the point where the particle enters the emulsion plate. More details on the general type of data analysis used in the SPICE program including figures are given by Bertsch et al. (1971).

3. Results and Discussion

As mentioned in the Introduction, composition measurements on energetic solar particles have now been reported for six solar particle events. These include ten independent measurements at different times during the events ranging from a few hours to several days after the onset of the flare associated with an event. In all but one case (18 July 1961), the time associated with a measurement is approximately 4 min. so that one would expect temporal variations in the flux or spectral shapes to be small during each measurement period. All particle species are, of course, recorded during the same time interval.

One striking feature of the results obtained has been the constancy of the composition of the multiply-charged nuclei (as measured by the helium-to-medium-nuclei ratio) with energy, with time during an event, and from one event to the next. This constancy prevails within the 15 to 20% statistical uncertainty of the individual measurements despite large variations in the intensity, changes in the spectral shape, and large differences in the proton-to-helium ratio. The weighted average of the He/M ratio is 58 ± 5. The energy region spanned by the measurements is from 10 to 200 MeV/nucleon.

The spectra of helium and medium nuclei from the most recent event (12 April 1969) in which the measurements for both have been completed are shown in Fig. 1.

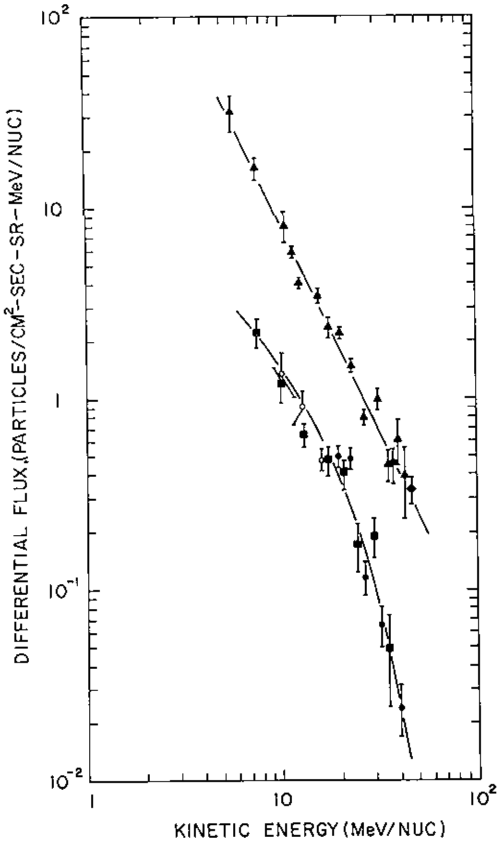

FIG. I

Fig. 1. Differential energy spectra for protons, helium, and medium group nuclei ($6 \leq Z \leq 9$). Proton fluxes shown here are divided by 10 for ease of representation. Proton fluxes determined from ionization and range measurements on individual events are shown by triangles whereas fluxes determined by taking the difference of integral particle counts at different depths in the stack are labeled by diamonds, Helium nuclei are represented by squares. Medium nuclei are multiplied by 58 the best estimate of the helium-to-medium ratio, and are shown by circles. Solid circles are used for energy regions where charges could be assigned to individual members of the medium group. Open circles refer to medium nuclei which are resolved from helium, but are not individually identified. (Bertsch et al., 1971).

The fluxes of the medium nuclei shown in the figure have been multipled by 58 to allow direct comparison with the helium fluxes. Proton fluxes multiplied by 0.1 for convenience in plotting are also shown in Fig. 1.

In several events it has been possible to observe more detailed abundances of individual elements. Where comparisons are possible, these abundances also appear to be independent of time and energy. The average abundances relative to that of oxygen are shown in Fig. 2 together with the corresponding photospheric and coronal abundances that have been obtained from spectroscopic measurements. Error bars on the points corresponding to spectroscopic measurements in Fig. 2 indicate the range of values quoted in the literature and not statistical errors.

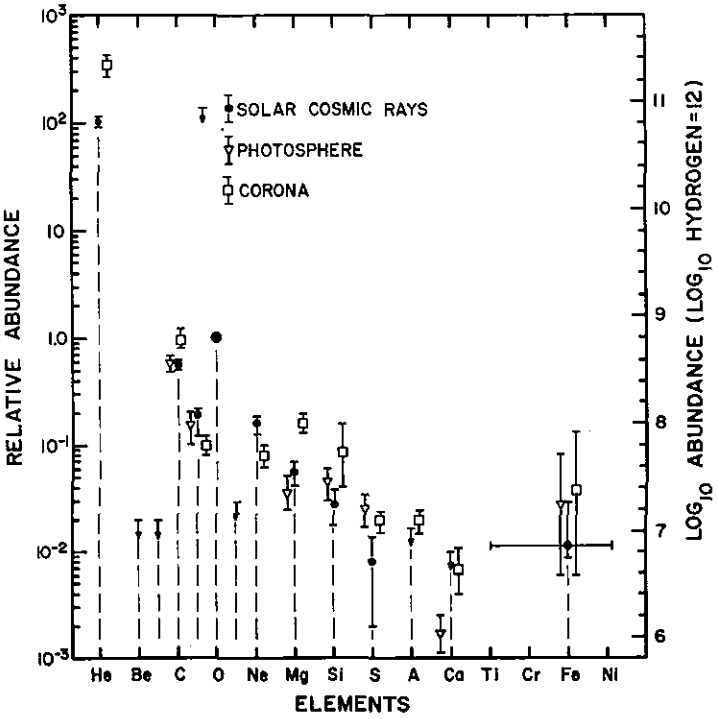

FIG. 2

Fig. 2. Solar abundances relative to oxygen determined from solar cosmic ray measurements and from spectroscopic measurements of the solar corona and photosphere. The uncertainties in the results from solar cosmic ray abundances represent experimental uncertainties in abundance ratios relative to oxygen. For both spectroscopic studies, the error bar symbol is used to denote a range of values quoted by different authors. The horizontal bars on the iron point denote a group of charges for both cosmic ray and spectroscopic data. For the general coronal abundances, see Dupree and Goldberg (1967) and Pottash (1964a and 1964b). For the iron abundance in the corona see Jordan (1966), Nikolsky (1969), Pottash (1967), and Wilding and Sandlin (1968). General photospheric abundances are from Goldberg, Muller, and Aller (1960); and Lambert and Warner (1968). For the iron abundance in the photosphere see Garz and Koch (1969), Garz et al. (1969), Goldberg, Kopp, and Dupree (1964), Grevesse and Swings (1969), Rogerson (1969), and Warner (1968). The energetic solar particle abundances are compiled from Fichtel and Guss (1961), Biswas et al. (1962), Biswas, et al. (1963), Biswas et al. (1966), Durgaprasad et al. (1968), Bertsch et al. (1969), and Bertsch et al. (1971).

From Fig. 2, the solar-particle composition is seen to be in better agreement with the spectroscopic photospheric abundance estimates than with those of the corona. This is seen particularly in the C and Mg abundances. If the solar-particle abundances do reflect those of the photosphere, then we may use the particle measurements to obtain abundances of elements such as

He and Ne for which no measurements exist in the photosphere. These abundances relative to that of oxygen are shown in Fig. 2. Combining the photospheric H/O ratio and the solar-particle He/O ratio, we find H/He = 16 ± 2 for the sun.

The relative constancy of the abundances of the multiply-charged solar particles presumably arises from the constancy of their charge-to-mass ratio. Stripped of all orbital electrons (at the energies of observation), two nuclear species of the same velocity will have the same magnetic rigidity and will behave similarly in electromagnetic fields during their acceleration and propagation. In this connection, special attention must be paid to the measured abundance of Fe whose charge-to-mass ratio differs by 7% (for Fe^{56}) from that of the lighter nuclei measured. Owing to this difference, a larger error has been assigned to the solar-particle Fe-group abundance shown in Fig. 2 (see Bertsch et al., 1969 and 1971). The determination of the solar Fe abundance from measurements in solar-particle events requires that any time or energy dependent effects resulting from the different charge-to-mass ratio must be understood. The Fe abundance shown in Fig. 2 comes from a single measurement on 2 Sept. 1966, the only measurement prior to the one to be reported here for which there is a direct comparison to the medium nuclei intensity determined at the same time in the same detector.

Preliminary data are now available from the sounding rocket flights on 25 Jan. 1971. Particle fluxes were sufficiently great on both flights into this event to allow measurements on Fe-group nuclei. These were located by scanning the entire outermost plate of each stack, selecting only very heavy events ($Z \geqslant 18$). Preliminary identification of the iron-group nuclei has been made in these scans. More detailed scans of ~ 10% of the outer plate in each flight have also been completed in order to locate all medium and heavier events. While measurements have not been made to resolve each of the species in this sample, previously observed abundances can be used to correct for tracks formed by nuclei above the medium group (~ 8% correction). Then by assuming the oxygen-to-medium ratio that has been observed in all the earlier measurements, the Fe/O ratio given in Table I is determined for the second flight in the Jan. 1971 event.

TABLE I

SUMMARY OF SOLAR IRON-GROUP MEASUREMENTS

$(\mathrm{Log})_{10}$ Solar Cosmic Rays		$(\mathrm{Log})_{10}$ Spectroscopic Values	
		Photosphere	Corona
Nov. 12, 1960	< 7.2*	6.6 - 7.7	6.6 - 7.9
Sept. 2, 1966	6.89-7.26*		
April 12, 1969	< 7.0*		
Jan. 24, 1971	6.91-7.54*		

*Values are relative to oxygen assumed to be $(\mathrm{Log})_{10}(\mathrm{Oxygen}) = 8.8$

The range of uncertainty in the most recent measurement is in part due to the still uncertain medium flux in the energy region where iron is detected (> 22 MeV/nucleon). Iron has been observed in the first flight as well, but the medium nuclei flux measurements have not progressed to the point where an Fe/O ratio can be quoted.

In conclusion, the Fe/O ratio observed in Jan. 1971 at the present time appears to be similar to the previous measurement, and consistent with the 85% confidence upper limits set in the two other events given in Table I. It should be pointed out, however, that the possibility for a higher abundance exists here, perhaps reflecting a propagation effect. More detailed measurements are being made.

4. References

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