# PART IV

# ACCELERATION, CONTAINMENT AND EMISSION OF HIGH-ENERGY FLARE PARTICLES

# THE CHARGE AND ISOTOPIC COMPOSITION OF SOLAR COSMIC RAYS

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**Abstract.** The charge and isotopic composition of solar cosmic rays potentially contain a wealth of information on the acceleration and confinment of energetic particles at the Sun. As the experimental techniques have improved and with the increasing number of measurements, this potential is now being realized. It is convenient to divide the composition studies into three areas: (a) helium-iron, with energies $>10$ MeV nuc$^{-1}$; (b) helium-iron, and the trans-iron elements, with energies $<2$ MeV nuc$^{-1}$; (c) the isotopic composition. In the first area at energies above 10 MeV nuc$^{-1}$ the solar cosmic rays appear to provide a representative sample of the solar corona. At lower energies (b) complex enhancement effects are noted. These increase with $Z$ and decrease with energy. This result as well as the high abundance of $^3$He suggest that the acceleration process is not a simple one and probably several stages are required.

## 1. Introduction

The original title for this paper as defined by the Conference Organizing Committee was the 'Acceleration, Containment and Emission of High Energy Particles'. The question of acceleration remains one of the major unsolved problems in particle astrophysics. The idea of prolonged particle containment at the Sun has increasingly become part of the accepted picture of solar cosmic rays without having been clearly established experimentally. In part this evolved from the observation of energetic particles associated with an active center (Fan *et al.*, 1968; McDonald and Desai, 1971). These display almost no velocity dispersion and appear to be co-rotating with an active center. They often persist for up to 14 days and have steep ($E^{-3}$ to $E^{-6}$) energy spectra. On one occasion these persisted over 14 solar rotations. However, with increasing sensitivity it is observed (McDonald and Van Hollebeke, 1973) that there are frequently many small particle injections associated with these streams of MeV particles. Furthermore, the particle propagation is diffusive and it still has not been possible to untangle coronal and interplanetary diffusion processes or to determine the time profile of the particle injection from the active region. One channel that is beginning to reveal a significant amount of information on both the acceleration and storage processes is the charge and mass composition of solar cosmic rays. The charge composition will be a function of both the acceleration process and the properties of the source region. The isotopes such as $^3$He should also give information on the dynamics of particle acceleration and storage in this source region. At low energies (i.e. $\leqq 2$ MeV nuc$^{-1}$) and high charges ($Z>$ iron) the charge composition is strongly energy dependent. However, above $\sim 10$ MeV nuc$^{-1}$ a representative sample of the solar corona is accelerated in flare-associated events for the elements helium-iron. The numerous measurements of charge composition and isotopes can best be understood by dividing the data into three regions:

(A) Helium-iron with energies $>10$ MeV nuc$^{-1}$.

*Gordon Newkirk, Jr. (ed.), Coronal Disturbances,* 415–420. *All Rights Reserved.*

(B) Helium-iron with energies $<2$ MeV nuc$^{-1}$ and the trans-iron elements.
(C) The isotopic composition of solar cosmic rays.

## 2. The Charge Composition of Helium-Iron with Energies >10 MeV Nucleon

The pioneering work in this region was carried out by Fichtel and his co-workers at the Goddard Space Flight Center using rocket borne nuclear emulsion (Fichtel and Guss, 1961; Biswas *et al.*, 1963, 1965, 1966; Durgaprasad *et al.*, 1968). Over a period extending from September 1961 to August 1972 rockets were successfully recovered for 8 events. These studies indicated that the composition for $Z=2$–$26$ does not change markedly from event to event and is in strong agreement with the spectroscopically determined abundances in the solar atmosphere. Further observations in this range has been done with particle detectors on the OGO-V satellite by the University of Chicago group (Mogro-Campero and Simpson, 1972) and on IMP VI by the Goddard cosmic ray group (Teegarden *et al.*, 1973). In addition plastic track detectors on rocket flights and on Apollo missions have provided data for a wide variety of events. In general these data sets are in good agreement. The only notable exception to this are the University of Chicago results in the argon-iron regions.

As the measurements have become more precise it is found that the ratio of He/C–N–O can vary by a factor of ~2 from event to event. This was first noted at lower energies by Armstrong *et al.* (1971) and confirmed by Teegarden *et al.* (1973). In the iron region Bertsch *et al.*, find that when the He/C–N–O ratio is low then the He/Fe ratio is also systematically lower. However, these variations from event to event are still less than that encountered between different sets of coronal abundance

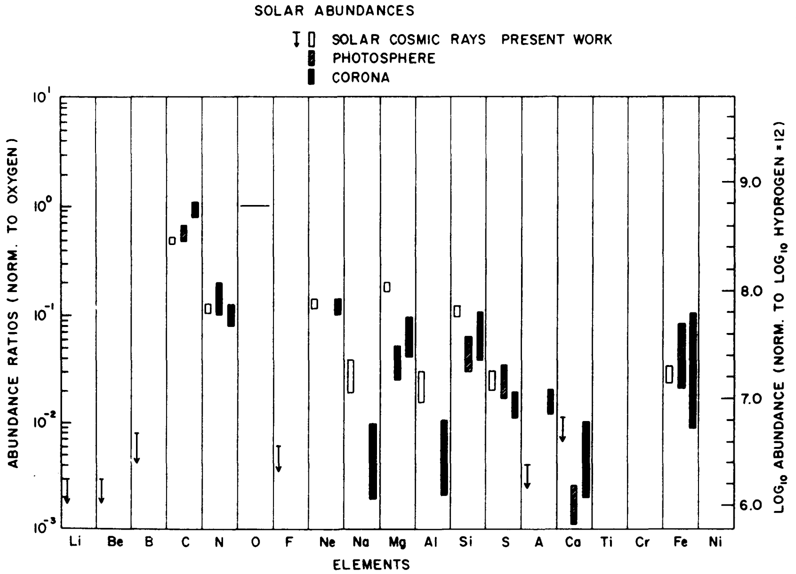

Fig. 1. A comparison of representative solar cosmic ray, coronal and photospheric abundances. All have been normalized at oxygen = 1.

data. A typical comparison between solar cosmic rays and coronal abundances is shown in Figure 1 (Teegarden *et al.*, 1973). The various measurements have all been normalized to oxygen. The spread in the particle and abundance data sets is an indication of the variation between various studies. Of particular note is the detection of Na and Al in the large flare events of August 1972 (Webber, 1973).

## 3. He–Fe, $E<2$ MeV nuc$^{-1}$ and the Trans-Iron Elements

The energy interval between 2 and 10 MeV is one of transition. Above 10 MeV, electron pick-up is not important except for iron. By 2 MeV, it has become important in the oxygen region. Up to the present time, most of the experimental work has been done using plastic track detectors on the Apollo missions or the 'Electrostatis Deflection Analyzer' flown on IMP VII by G. Gloeckler and his co-workers. All measurements show there is a systematic enhancement of heavy nuclei at low energies. This enhancement increases with $Z$ and decreases with energy. Following the example of Price (1973), it is useful to define an enrichment factor $Q(Z_1, Z_2)$ for the enrichment of $Z_1$, with respect to $Z_2$

$$Q = \frac{\dfrac{J(Z_1, E, t)\ \text{solar cosmic rays}}{J(Z_2, E, t)\ S.P.}}{\dfrac{\text{solar abundance of } Z_1}{\text{solar abundance of } Z_2}},$$

where $J(Z, E, t)$ is the flux of element $Z$, of energy $E$ at time $t$. Since at higher energies there is good agreement between the relative abundance of solar cosmic rays and coronal abundance, an equivalent definition of $Q$ would be to replace the ratio of solar abundances with the ratio of fluxes measured at higher energies.

The different measurements presently available in the low energy range are listed in Table I.

TABLE I

Measurements of energy dependent composition of solar heavy ions

| Event | Time interval studied | Detector | Reference |
|---|---|---|---|
| Strong flare | 1510 to 1514 UT, 25 Jan. 1971 | Lexan stack on rocket | Crawford *et al.* (1972) |
| Strong flare | 0756 to 0760 UT, 2 Sept. 1971 | Lexan stack on rocket | Price *et al.* (1973) |
| Small flare | Integrated over 17 to 19 Apr. 1972 | Lexan + $SiO_2$ glass on Apollo 16 | Braddy *et al.* (1973) |
| Very strong flare | 1914 to 1918 UT, 4 Aug. 1972 | Lexan stack on rocket | Price *et al.* (1973) |
| Almost quiet Sun | Integrated over 11 to 13 Dec. 1972 | Lexan on Apollo 17 | Price and Chan (1973b) |
| Small flare | Oct. 17–19, 1972 | Electrostatic deflection analyzer | Gloeckler *et al.* (1973) |

Price (1973) has summarized the systematics of heavy ion enhancement as measured by many different groups (Table I) as follows:

(1) At sufficiently low energies, the heavy elements in solar flare particles are always enriched relative to their abundance at high energies.

(2) The enhancement factor $Q$ is an increasing function of $Z$ from helium up to $Z \approx 44$ and probably higher. The available data is not adequate to determine any possible structure in $Q(Z, E)$.

(3) $Q$ decreases with energy. At higher energies ($\gtrsim 2$ MeV, it starts to approach a constant value.

An example of the systematic increase of $Q$ with $Z$ is shown in Figure 2 for a small event on 18 April 1972 using one of the Apollo 16 command module windows as the track detector. Oxygen, iron and the trans-iron elements have been normalized to helium above ~5 MeV nuc$^{-1}$. At lower energies the systematic enhancement of the heavier element is very evident. Shink *et al.* (1973) find that $Q(Z/\text{He}) \propto \exp Z/Z_1(E)$ where $Z_1(E)$ increases with energy.

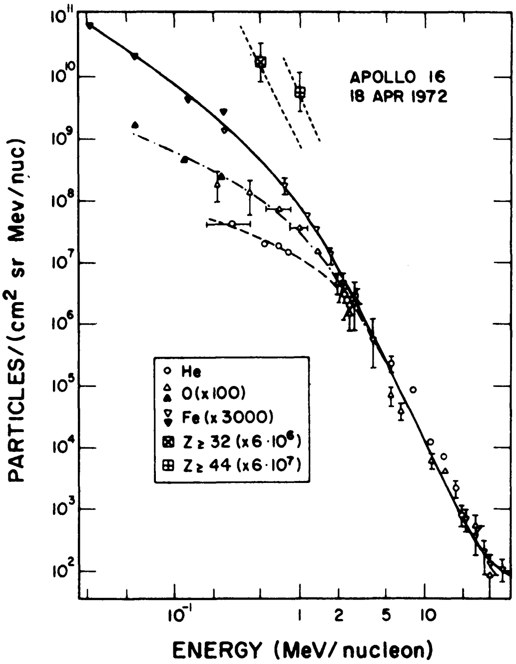

Fig. 2. Fe and heavier elements measured with Si–$O_2$ glass; O and He measured with Lexan stack for small event on 18 April 1972. The scaling factors are chosen so that the curves converge at higher energies (Price *et al.*, 1973).

Using the electrostatic deflection technique Gloeckler *et al.* (1973) have also been able to determine the charge states of oxygen and carbon. They find in average value at 100 keV nuc$^{-1}$ of 5.4 for carbon and 7.4 for oxygen. The expected equilibrium charge states are 2.5 and 2.9. This suggests these low energy particles may have traversed a hot coronal region after acceleration where they lose further electrons. The other possibility is that the ions have undergone considerable adiabatic deceleration during their interplanetary propagation.

This low energy enhancement when fully understood should give valuable insight into the acceleration process. One possible mechanism which involved two acceleration stages has been suggested by Cartwright and Mogro-Campero (1973). Initially the ions are fully stripped and are accelerated to suprathermal energies ($\sim 1$ MeV nuc$^{-1}$). They then pass through the relatively cool chromosphere where they reach charge equilibrium in their transport to the Fermi acceleration region. Since injection into Fermi acceleration is rigidity dependent, an enhancement of heavy nuclei can occur. This is probably indicative to the type of modification that will have to be made to conventional acceleration process.

## 4. Isotopic Composition of Solar Cosmic Rays

The satellite particle detector technology has now advanced to the point where it should be possible during the late '70's to resolve most of the individual isotopes region for C–Fe. This will be an important new tool in comparing coronal abundances with the 'Universal Abundances'. Webber *et al.* (1973) have measured the isotopes of Ne and Mg as well as $O^{18}$ during the large August 1972 events. These are in good agreement with the expected values.

It is possible with presently available systems to resolve the isotopes of hydrogen and helium. Thus far both the University of Chicago Group (Anglin *et al.*, 1973) and Caltech (Garrard *et al.*, 1973) have been able to measure $^3$He in a number of events. They find that the measured ratio of $He^3/He^4$ can be as large as 500 times the abundance ratio of $5 \times 10^{-4}$ measured in the solar wind (Geiss, 1972). Furthermore, the ratio of $He^3/He^4$ can vary by more than an order of magnitude from event to event. Since the ratio is so much greater than the expected value, the $He^3$ mist be produced by nuclear interaction. For example above 10 MeV nuc$^{-1}$ this results mainly from energetic $He^4$, C, N and O interacting with the nuclei in the coronal gas. The presence of these nuclear interactions products mean that solar $\gamma$-rays, neutrons and positrons would also be produced at the same time. There is a significant absence of deuterium which is not fully understood at this time.

The large values of $0.26 \pm 0.08$ reported for the $He^3$ rich event of October 13, 1969 (Gerrard *et al.*, 1973) would require the passage through at least 6 g cm$^{-2}$ of gas for a simple slab model. This is quite unrealistic and again indicates that the basic acceleration process must be re-examined. For example, the $He^3$ could be built up over a long period of time by particles stored in the active region. At this time there is no evidence for such storage. On the other hand, the $He^3$ could be produced by 'dumping' most of the protons onto the photosphere and reaccelerating the fragmentation products. The proton 'dumping' would actually be similiar to that experienced by the electrons.

While the origin of the $He^3$ is not understood at this time, its presence in such significant amounts indicates it is going to be a very important factor in understanding the source region dynamics.

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## DISCUSSION

*Athay:* What type of model is required to provide the 0.1 to 1 gm of matter that is needed for the $^3$He abundance. In a normal solar model this amount of matter is reached only for depths in the very low chromosphere or photosphere.

*McDonald:* We used a slab model.

*Sturrock:* Is it known whether the ions are all fully stripped?

*McDonald:* The carbon and oxygen ions at 0.1 MeV are almost completely stripped, e.g. we expect C III but measured C V. That implies that they were accelerated in a hot region or that they were originally in a hot region.