THE COMPOSITION OF HEAVY IONS IN
SOLAR ENERGETIC PARTICLE EVENTS

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Abstract. We review recent advances in determining the elemental, charge-state, and isotopic composition of \( \lesssim 1 \) to \( \lesssim 20 \) MeV per nucleon ions in solar energetic particle (SEP) events and outline our current understanding of the nature of solar and interplanetary processes which may explain the observations.

The composition within individual SEP events may vary both with time and energy, and will in general be different from that in other SEP events. Average values of relative abundances measured in a large number of SEP events, however, are found to be roughly energy independent in the \( \sim 1 \) to \( \sim 20 \) MeV per nucleon range, and show a systematic deviation from photospheric abundances which seems to be organized in terms of the first ionization potential of the ion.

Direct measurements of the charge states of SEPs have revealed the surprisingly common presence of energetic \( \text{He}^+ \) along with heavy ions with typically coronal ionization states. High-resolution measurements of isotopic abundance ratios in a small number of SEP events show these to be consistent with the universal composition except for the puzzling overabundance of the SEP \( ^{22}\text{Ne}/^{20}\text{Ne} \) relative to this isotope ratio in the solar wind. The broad spectrum of observed elemental abundance variations, which in their extreme result in composition anomalies characteristic of \( ^{3}\text{He}-\)rich, heavy-ion rich and carbon-poor SEP events, along with direct measurements of the ionization states of SEPs provide essential information on the physical characteristics of, and conditions in the source regions, as well as important constraints to possible models for SEP production.

It is concluded that SEP acceleration is a two-step process, beginning with plasma-wave heating of the ambient plasma in the lower corona, which may include pockets of cold material, and followed by acceleration to the observed energies by either flare-generated coronal shocks or Fermi-type processes in the corona. Interplanetary propagation as well as acceleration by interplanetary propagating shock will often further modify the composition of SEP events, especially at lower energies.

1. Introduction

Solar energetic particles (SEP), broadly defined as particles of energies greater than \( \sim 1 \) MeV, are commonly accelerated in association with solar flare eruptions. The study of these particles has important bearing on a number of problems in solar physics, heliospheric physics, and astrophysics. Knowledge of the elemental and isotopic abundances of the solar atmosphere, which can be inferred from composition measurements of SEP, is essential for constructing models of interior and atmospheres of the Sun and other stars as well as for a better understanding of nucleosynthesis and of the evolution and formation of the solar system. Solar particles observed in interplanetary space are
a direct sample of the solar material, which in principal can be measured in arbitrary
detail. Before relating the SEP composition measurements to solar abundances one
must, however, understand and correct biases which alter the composition of these
particles as they undergo heating, acceleration and propagation.

Comprehensive measurements of the elemental, charge state and isotopic composi-
tion of SEP over a wide energy range, in a large number of solar flare events, at various
phases during such events, and at different locations in the heliosphere give us the means
of understanding these compositional biases. Equally important, such detailed observa-
tions should also lead to refinements of models of particle acceleration and propagation
in astrophysical plasmas, and would allow us to determine what fraction of the energy
released in flares goes into acceleration of particles, and how this fraction depends on
the physical conditions at the flare site.

In this paper we review recent progress in the study of the composition of heavy ions
in SEP events. Results prior to 1974 were discussed in an earlier review on this subject
(Fan et al., 1975). Various aspects of SEP composition have also been addressed in a
number of review papers (e.g., Gloeckler, 1975, 1979; Mewaldt, 1980; Klecker, 1981;
McGuire, 1983). The material is divided into three major sections: (1) average element-
al, charge state and isotopic compositions of heavy ions in SEP events; (2) variabilities
in the composition of SEPs; and (3) $^3$He-rich, heavy-ion-rich and carbon-poor SEP
events.

2. Average Elemental, Charge State and Isotopic Compositions of Heavy Ions in
SEP Events

Since the discovery of nuclei heavier than He in SEP by Fichtel and Guss (1961)
numerous measurements of their composition have been made; the most recent ones
with high-resolution instruments flown on satellites and space probes. The introduction
of thin-window proportional counters (Hovestadt and Vollmer, 1971) and ~ 2 and 5 μ
thins solid state detectors (Krimigis et al., 1977) as $dE/dx$ elements in $dE/dx$ vs $E$
instruments reduced the low energy limit of the measurements by an order of magnitude to
several hundred keV nucl$^{-1}$. This and the use of large-geometry solid-state telescopes
(e.g. Cook et al., 1979) led to a large increase in the number of SEP events whose heavy
ion compositions could be determined, permitted studies of the time dependence of
elemental abundances during SEP events, and resulted in measurements of rare ele-
ments such as Na and Ni. At the same time, development of high-voltage electrostatic-
deflection techniques (Turns et al., 1974; Hovestadt et al., 1978) provided the first direct
measurements of the ionization or charge states of ≤1 MeV nucl$^{-1}$ ions in SEP events.
Use of position-sensitive solid-state detectors to determine individual particle trajec-
tories in $dE/dx$ vs range telescopes (Althouse et al., 1978) allowed for the first time
high-resolution measurements of the isotopic composition of SEPs.

Relative abundances are generally measured at equal energy per nucleon and extend
in energy from ≤0.5 MeV nucl$^{-1}$ (Mason et al., 1980, 1983; Hamilton and Gloeckler,
1981) to ≥100 MeV nucl$^{-1}$ (Dietrich and Simpson, 1978), although the majority of the