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Inferred charge states of high energy solar particles from the Solar Isotope Spectrometer on ACE

C. M. S. Cohen, A. C. Cummings, R. A. Leske, R. A. Mewaldt, E. C. Stone
California Institute of Technology, Pasadena, CA

B. L. Dougherty, M. E. Wiedenbeck
Jet Propulsion Laboratory, Pasadena, CA

E. R. Christian, T. T. von Rosenvinge
Code 661, NASA Goddard Space Flight Center, Greenbelt, MD

Abstract. The large solar event on November 6, 1997, was enriched in heavy elements (Fe/O ~ 1) with very hard energy spectra (power law index of -2). There was also a large enrichment in heavier isotopes, suggesting unusually strong charge to mass (Q/M) fractionation ($\sim(Q/M)^{-7}$). Assuming that the fractionation is dominated by Q/M and first ionization potential (FIP) related processes, we have inferred the charge states of twelve elements with energies of 12-60 MeV/nucleon. These results suggest a source temperature of 3 - 6 x 10^6 K, significantly higher than deduced at lower energies.

Introduction

Solar energetic particle (SEP) events have been classified into two broad categories, impulsive and gradual [e.g., *Reames*, 1995]. Impulsive events are typically smaller in intensity and duration (of the order of a few hours or a day), exhibit large enhancements of ^{3}He and heavy elements such as Fe, and the ions have charge states typical of a source region of ~10^7 K. Gradual events often last for days, have compositions that are similar to those found in the corona and solar wind and have charge states reflecting a source temperature of ~2 x 10^6 K. It is thought that impulsive events are dominated by particles accelerated out of flare associated material, while gradual events are dominated by particles accelerated out of the ambient corona and solar wind by a shock which forms in the corona and subsequently propagates into the interplanetary medium. *Cliver* [1995] also describes two classes of hybrid events that have mixtures of impulsive and gradual characteristics. Ionic charge states of energetic particles are an important indicator of the source region.

Direct charge state measurements of SEPs with ~0.5 to 2.5 MeV/nucleon were made on ISEE-3 [*Luhn et al.*, 1985, 1987]. More recently, indirect determinations were made up to ~70 MeV/nucleon by measuring the geomagnetic latitude distribution of particles observed by the polar-orbiting SAMPEX spacecraft [*Leske et al.*, 1995; *Mason et al.*, 1995; *Oetliker et al.*, 1997]. Other measurements based on geomagnetic filtering have resulted in charge state determinations of iron at ~200 - 600 MeV/nucleon [*Tylka et al.*, 1995].

Charge states from the large solar event on November 6, 1997, at ~ 1 MeV/nucleon have been determined directly by *Möbius et al.* [1998] and indirectly by *Mazur et al.* [1998]. In this paper we use element and isotope composition data to infer charge states at energies above 12 MeV/nucleon using data from the Solar Isotope Spectrometer on the Advanced Composition Explorer [*Stone et al.*, 1998a].

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Data Analysis

The Solar Isotope Spectrometer (SIS) has two telescopes composed of silicon solid-state detectors allowing the nuclear charge (Z), mass (M), and kinetic energy (E) to be measured using standard dE/dx versus residual energy techniques for particles with ~10 to ~100 MeV/nucleon [*Stone et al.*, 1998b]. The ~40 cm^2 sr geometry factor and ~0.15 - 0.3 amu mass resolution (depending on Z and E) allow elemental and isotopic abundances to be accurately determined on relatively short timescales.

Hourly-average particle intensities for ~10 days of November 1997 are presented in Figure 1 of *Mason et al.* [1998]. Two events, on November 4 and 6, are clearly identified in the SIS data. The intensities averaged over the second event (1200 November 6 to 0000 November 10) are shown as a function of energy for Z = 6 - 28 in Figure 1. Within statistical uncertainties, a single power law of index -2.11 fits the spectra for all species over a common energy interval of 12 - 60 MeV/nucleon, resulting in relative abundances (Si ≡ 1) given in Table 1.

These abundances are compared to photospheric values [*Grevesse, Noels, and Sauval,* 1996] in Figure 2. It is clear that the abundances in this event have a strong dependence on nuclear charge with enhancements that increase with increasing Z. Two fractionation processes that alter SEP composition relative to the photosphere have been well documented. The first occurs in the chromosphere or lower transition region of the Sun where elements with high first ionization potential (FIP) are still present as neutrals and those with low FIP are singly ionized. The ions are more efficiently transported to the corona than the neutrals, resulting in an overabundance of elements with FIP less than ~10 eV in the corona. This effect has been observed in SEP data [e.g., *Cook, Stone, and Vogt,* 1984], solar wind measurements [e.g., *Gloeckler and Geiss,* 1989], optical observations of the corona [e.g., *Sheeley,* 1996], solar gamma rays [e.g., *Ramaty et al.*, 1995], and also modeled [*von Steiger and Geiss,* 1989]. Typically this fractionation is characterized as a step function in the measured relative abundances normalized to those of the photosphere as a function of FIP. The step height is usually a factor of 3-5, although variations have been observed in both energetic particle and solar wind data [*Garrard and Stone,* 1994; *Williams,* 1998; *von Steiger, Geiss, and Gloeckler,* 1997].

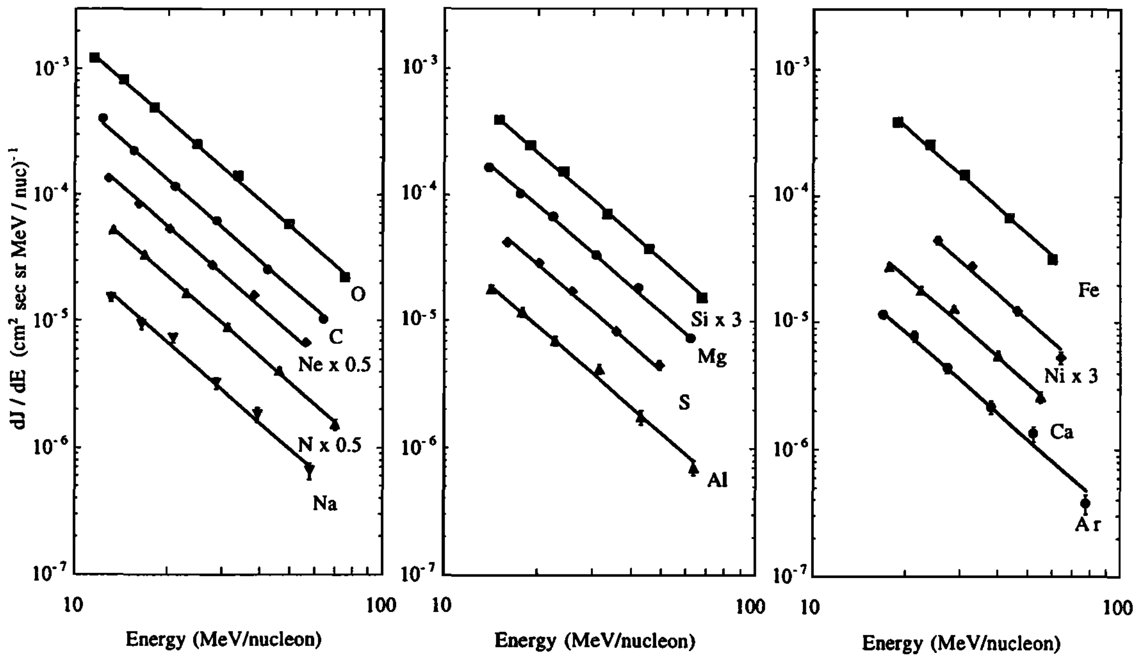

Figure 1. Intensities of elements C - Fe averaged over 1200 November 6 - 0000 November 10. Power law fits with a common spectral index of -2.11 were made over the energy range 12 - 60 MeV/nucleon.

The second fractionation process has been empirically determined from SEP measurements during many large solar events. It has been found that the measured abundances in any single event as compared to coronal values are enhanced or depleted by an amount that is well correlated with the element's charge to mass ratio (Q/M). It is presumed that this fractionation, typically expressed as a power law in Q/M, results from acceleration and propagation processes that depend on the particles' rigidity [*Breneman and Stone*, 1985].

Taking these two processes to be the dominant ones affecting relative abundances, we relate the observed SEP abundances to the photospheric abundances (ph) in the following manner:

$$\frac{R_{SEP}(Z)}{R_{ph}(Z)}=\frac{F(Z)}{F(Z_0)}\left[\frac{Q(Z)}{M(Z)}\frac{M(Z_0)}{Q(Z_0)}\right]^{\gamma} \qquad (1)$$

where Z is the nuclear charge of the element of interest and Z_0 is the nuclear charge of a 'baseline' element. For a given element: F is the value of the step function; Q is the mean ionic charge; M is the mean mass; and R is the ratio of the integrated intensity, J, to that of the baseline element, or, $R(Z) = J(Z) / J(Z_0)$.

In the past, variations of relation (1) has been used to derive coronal abundances for a wide range of elements from the measured SEP composition ≥ 5 MeV/nucleon and charge states measured at ~1 MeV/nucleon [e.g., *Breneman and Stone*, 1985]. Assuming that (1) also applies to the November 6 event, we can use the SIS composition data to calculate the mean charge state of any element by choosing an appropriate reference element and by estimating γ from the SIS isotope data (see below). Thus,

$$Q(Z)=Q(Z_0)\frac{M(Z)}{M(Z_0)}\left[\frac{F(Z_0)}{F(Z)}\frac{R_{SEP}}{R_{ph}}\right]^{\frac{1}{\gamma}}. \qquad (2)$$

To obtain an estimate of γ, we compared magnesium isotope data (^{24}Mg, ^{25}Mg, and ^{26}Mg) obtained by SIS during this event with those typical of the solar system [*Anders and Grevesse*, 1989]. Note that solar wind observations of Mg isotopes [*Kallenbach et al.*, 1997] are consistent with those in *Anders and Grevesse*. Assuming different isotopes have the same ionic charge and the same FIP-related enhancement, the measured SEP isotope ratios should be enhanced by a factor $(M_1/M_2)^{\gamma}$, where M_1 and M_2 are the isotope masses. The observed enhancements of ^{25}Mg and ^{26}Mg yield a γ of -7.2 ± 0.4. A fit to the isotopic abundances of several elements from this event yields a similar value for γ [*Leske et al.*, 1998].

We have taken F(Z) to be a step function where elements with FIP < 10 eV are enhanced by a factor *s*, elements with FIP > 11 eV are not enhanced, and sulfur (FIP = 10.2 eV) is enhanced by *s*/2. We estimated *s* from the measured elemental ratio of Mg to Ne (corrected for Q/M fractionation) compared to that for the photosphere. The value of *s* is sensitive to the assumed charge states of Mg and Ne. Using a Q/M-dependent correction factor averaged over the range from 1.3 - 10 x 10^6 K, we obtain *s* = 1.7. This value is lower than is typically observed in SEP data, although *Garrard and Stone* [1994] also report events with *s* less than 2.

Lastly, a baseline element must be chosen. We have used C with the assumption that $Q(Z_0)$ is 5.9 and $F(Z_0)$ is 1. While our results are not very sensitive to this choice, C provides well constrained values of Q and F. Over a wide range of coronal temperatures carbon is nearly fully stripped. Direct and indirect measurements of C at ~1 MeV/nucleon in this event indicate charge states of ~5.7 to 5.8 with the mean charge state of all elements increasing with increasing energy [*Möbius et al.*, 1998; *Mazur et al.*, 1998]. Previous SEP data indicate F(Z) for C is well defined [e.g., *Cook, Stone, and Vogt*, 1984].

Results and Discussion

The results of the charge state analysis are given in Table 1. The reported uncertainties reflect those of the photospheric abundances [*Grevesse, Noels, and Sauval*, 1996] and the statistical uncertainties of the SEP abundance measurements. The data are plotted as a function of nuclear charge in Figure 3 along with curves corresponding to several different ionization

Table 1. Abundances (12 - 60 MeV/nucleon) and Resulting Charge States for Elements Carbon - Nickel

Element	Nuclear Charge	Abundance	Inferred Charge State
Carbon	6	1.081 ± 0.040	5.9 ± 0.1*
Nitrogen	7	0.628 ± 0.005	6.6 ± 0.2
Oxygen	8	5.450 ± 0.107	7.5 ± 0.2
Neon	10	1.547 ± 0.036	8.7 ± 0.2
Sodium	11	0.092 ± 0.005	9.0 ± 0.1
Magnesium	12	1.140 ± 0.026	10.1 ± 0.2
Aluminum	13	0.126 ± 0.005	10.6 ± 0.3
Silicon	14	≡ 1	11.7 ± 0.2
Sulfur	16	0.389 ± 0.012	12.9 ± 0.5
Argon	18	0.116 ± 0.005	13.7 ± 0.5
Calcium	20	0.322 ± 0.005	13.4 ± 0.1
Iron	26	4.886 ± 0.081	18.4 ± 0.3
Nickel	28	0.339 ± 0.014	18.8 ± 0.1

* value assumed in calculations

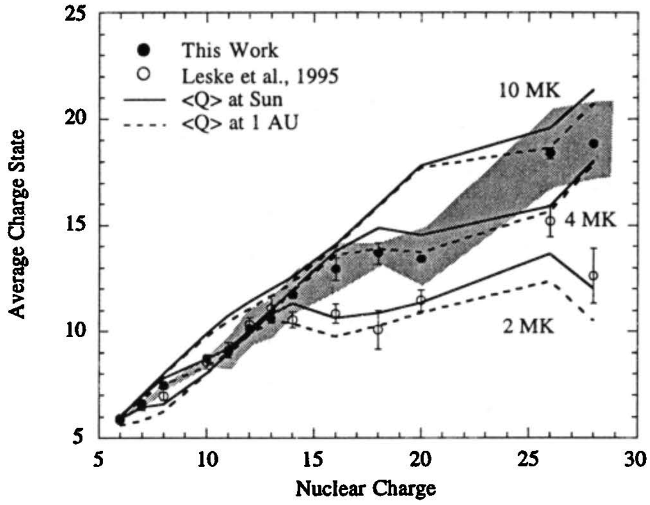

Figure 3. Average charge state results from SEP measurements, compared with calculated values from *Arnaud and Rothenflug* [1985] and *Arnaud and Raymond* [1992] (solid lines) at the indicated temperatures. Dashed lines are average charge states at 1 AU, after a $(Q/M)^{-7}$ fractionation of source distribution (not appropriate for comparison with *Leske et al.* data where such large fractionation was not observed). The shaded region indicates the maximum variation of the present results due to the alteration of input parameters.

temperatures assuming thermal equilibrium of the electron distribution in the source region [*Arnaud and Rothenflug*, 1985; *Arnaud and Raymond*, 1992]. Plotted for comparison are charge states at similar energy/nucleon from two gradual SEP events in 1992 obtained by *Leske et al.* [1995] using the geomagnetic technique.

The inferred charge states are not very sensitive to the values of the input parameters $Q(Z_0)$, γ, and s, as indicated by the shaded region in Figure 3. The variations due to a change in a single parameter are largest for Fe but always less than 1.5 charge units: $Q(Z_0) = 5.9 \pm 0.1$ results in $Q_{Fe} = 18.40 \pm 0.32$; $\gamma = -7.2 \pm 0.4$ yields $Q_{Fe} = 18.40 \pm 0.47$; $s = 1.7 + 1.1 - 0.5$ gives $Q_{Fe} = 18.40 + 1.35 - 0.89$. Using the extreme parameter values yields a maximum Q_{Fe} of 20.9 and a minimum of 17.2.

It is apparent from Figure 3 that the mean charge states deduced for elements with $Z > 13$ (and the source temperature inferred from them) are significantly higher in the November 6 event than those in the 1992 events. Since these charge states are the means of the accelerated/propagated charge state distribution at 1 AU rather than of the source distribution in the corona, inferring a coronal temperature is most appropriately done by comparing our results to the dashed curves in Figure 3. These curves are the mean charge states expected at 1 AU assuming the original distribution (as given for each temperature by *Arnaud and Rothenflug* [1985] and *Arnaud and Raymond* [1992]) is altered by a $(Q/M)^{-7.2}$ fractionation. In all cases the mean charge state of the source distribution is greater than that of the propagated distribution because low charge states are enhanced when γ is negative.

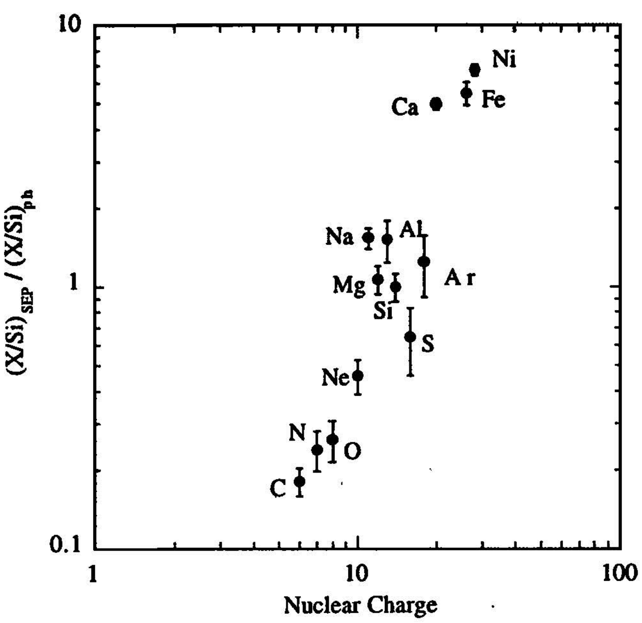

Figure 2. Measured abundances (SEP) of elements (X) from 12 - 60 MeV/nucleon (normalized to Si) as compared to photospheric abundances (ph).

Attempting to characterize the calculated charge states with a single ionization temperature results in temperatures of ~2 x 10^6 K for the events of *Leske et al.* and ~3 - 6 x 10^6 K for the November 6 event. However, there are element-to-element variations in both data sets and it is clear the charge states of Ca, Fe, and Ni deduced from the SIS data are not all consistent with a common temperature.

If one assumes a common temperature for all species, the elemental composition data can be represented by $T \approx 2.5 \times 10^6$ K if $s = 2.6$ and $\gamma = -4$. However, this value of γ is in conflict with that determined from the isotope data. Thus, either the element and isotope fractionation processes differ or the source is not isothermal. Since the charge states in the solar wind often do not correspond to a common temperature [*Ko et al.*, 1998], it seems reasonable to assume a non-isothermal state, such as might be present in the higher-temperature flare-associated plasma that may be the source of high charge state SEPs.

As previously discussed, particles accelerated out of flare-associated material reflect the higher temperatures near the flare site (~10^7 K), with a charge state of ~20 reported for Fe [*Luhn et al.*, 1987]. Those originating from the ambient corona and solar wind exhibit charge states of ~12 for Fe, typical of coronal temperatures (~2 x 10^6 K). The derived charge state of Fe and other heavy elements in this event indicate a hot source. This is unusual for an SEP event of this size; however, this event was atypical in many ways. In particular, the energy spectra are very hard, with the Fe spectrum extending to > 200 MeV/nucleon, and there is a large enhancement of heavy elements (Fe/O ~ 1). The Q/M fractionation deduced from the isotopic composition [*Leske et al.*, 1998] is much stronger than reported previously: power law exponents reported by *Garrard and Stone* [1994] range from -4 to +5 while we find $\gamma \sim -7$. We are not aware of any theoretical models that would predict this degree of fractionation.

Only recently has it been possible to measure SEP charge states at several different energies, as was done for two events in 1992 using several instruments on SAMPEX. The results suggested a surprising increase in the charge state of Fe with energy (most evident above 8 MeV/nucleon [*Oetliker et al.*, 1997]). There is evidence that this energy dependence starts at lower energies in the November 6 event. SAMPEX and ACE measurements show that the mean charge state of Fe increases strongly with increasing energy from ~0.2 to ~2 MeV/nucleon [*Mazur et al.*, 1998; *Möbius et al.*, 1998]. At >30 MeV/nucleon, the charge state of Fe found by SAMPEX [*Mazur et al.*, 1998] is consistent with the value of +18 deduced here. The combination of these results indicate that the Fe charge state in the November 6 event has a stronger energy dependence than found in the 1992 events.

While explanations based on non-thermal processes (e.g., x-ray ionization, post-acceleration stripping) cannot be ruled out for the high charge states inferred at high energies, many characteristics of this event (including the range of Q_{Fe} deduced) are well described by the definition of a 'mixed-gradual hybrid' event (an event which temporally evolves from characteristically impulsive to gradual) given in *Cliver* [1995]. While Cliver suggests a time dependent superposition of impulsive and gradual characteristics, the SAMPEX and ACE data suggest an energy dependent superposition. As is evident in *Mason et al.* [1998], the time profile of this event varies with energy, being more gradual-like at lower energies. This is true of the charge state and spectral features as well. Indeed, the measured distribution of Fe charge states at ~0.2 - 1.0 MeV/nucleon in this event is broader than expected from a single, isothermal source, possibly indicating a mixture of different SEP populations [*Möbius et al.*, 1998]

In summary, we have used the isotope data from SIS to determine the Q/M fractionation during a large SEP event on November 6, 1997. Assuming the composition of this event can be related to that of the photosphere through FIP and Q/M based fractionation, we have inferred the mean charge states of elements with $6 \leq Z \leq 28$. These charge states indicate a high temperature source which is probably not isothermal. The deduced FIP fractionation was low, s=1.7, while the Q/M fractionation was the largest ever deduced, $\sim(Q/M)^{-7}$. The high Fe/O ratio (~1) and hard, power-law energy spectrum (index of -2.11) are also unusual for an event of this size.

If the energy dependence of the mean charge states in the November 6 event (and the 1992 events) are common, and high energy charge states such as Fe^{+18} are typical, then the dependence of SEP fractionation effects on Q/M and the magnitude of the associated isotopic fractionation effects may have been significantly underestimated in earlier studies. Energy dependent charge states will have implications for the origin and acceleration of SEPs.

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C. M. S. Cohen, A. C. Cummings, R. A. Leske, R. A. Mewaldt, E. C. Stone, California Institute of Technology, MC 220-47, Pasadena, CA 91125, (email: cohen@srl.caltech.edu)

B. L. Dougherty, M. E. Wiedenbeck, JPL, 4800 Oak Grove Dr., M/S 169-327, Pasadena, CA 91109

E. R. Christian, T. T. von Rosenvinge, Code 661, NASA Goddard Space Flight Center, Greenbelt, MD 20771

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