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New Measurements of Solar Particle Events Enriched in Heavy Ions

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Abstract

The four most heavy-ion-rich of the nine largest solar energetic particle events detected by the Solar Isotope Spectrometer on the ACE, are the focus of this paper. We have used isotopic measurements of Ne to determine the degree of charge/mass fractionation and infer the charge states of C - Ni in these events. The results indicate a source temperature of ~ 4×10^6 K; this and the measured abundances suggest that these four events more similar to impulsive events than gradual. Although the ^{3}He/^{4}He ratios are not enhanced to the level typical of impulsive events, there are measurable enhancements over typical solar wind values in three of the events.

1 Introduction:

For some time, measurements of charge states in solar energetic particle (SEP) events were limited to those determined at ~ 1 MeV/nucleon in a series of events in 1978-1979 by Luhn et al. (1985, 1987). Although these values were assumed to be representative of charge states at higher energies, recent observations suggest this is not always the case; the mean charge state can be a strong function of energy within a given event and can differ from one event to another (Oetliker et al., 1997; Mazur et al., 1999; Möbius et al., 1999). At energies above 10 MeV/nucleon direct charge-state measurements using electrostatic deflection have, thus far, not been possible, but geomagnetic techniques (Leske et al., 1995) or knowledge of the elemental and isotopic composition of SEP events (Cohen et al., 1999a) allows mean charge states to be inferred.

In a study of ten large SEP events, Breneman and Stone (1985) found that while elemental composition varied from event to event, the compositional deviation from the SEP average was well fit by a power law in the mean charge to mass ratio (Q/M) of the elements. The composition determined from the average of many SEP events is consistent with that of the slow solar wind and the corona (Reames, 1995) since the event averaging substantially reduces the observed Q/M fractionation (Garrard and Stone, 1994).

Since isotopes of a given species have the same charge state distribution, the Q/M fractionation becomes a mass fractionation when examining isotope ratios. Thus, the degree of Q/M fractionation can be estimated from isotope ratios such as ^{22}Ne/^{20}Ne. Using the fractionation to infer the charge states of the elements is essentially an inversion of the Breneman and Stone (1985) analysis. Knowledge of the first ionization potential (FIP) fractionation is also required and can be estimated from various elemental ratios, such as Mg/Ne.

Using the approach outlined above, we infer the charge states of elements in four SEP events that are substantially enriched in heavy elements and speculate on the nature of the acceleration processes involved.

2 Data Analysis and Observations:

The data presented in this paper were obtained with the Solar Isotope Spectrometer (SIS), a dE/dx versus residual energy sensor which allows elemental and isotopic composition to be determined over the energy range of 10-100 MeV/nucleon (Stone et al., 1998). The geometry factor of SIS is ~38 cm^2-sr and the mass resolution is ~ 0.15 to > 0.3 amu, depending on total kinetic energy and nuclear charge.

From launch through the end of 1998, SIS has observed nine large SEP events, some Fe-rich and some Fe-poor. The two Fe-poor events are gradual events, typically characterized by composition similar to the solar wind, charge states representative of ~ 2 x 10^6 K, and large proton fluxes (Reames et al., 1994). In contrast, impulsive events are usually enhanced in the heavy elements (especially Fe), exhibit charge states implying temperatures ≥ 3 x 10^6 K, and frequently have ^{3}He/^{4}He ratios greatly enhanced over solar wind values (Reames et al., 1994 and references therein).

Four events, 6 November (day 310) 1997, 2 May (day 122) 1998, 6 May (day 126) 1998, and 14 November (day 318) 1998, with the largest ^{22}Ne/^{20}Ne (Leske et al., 1999) and Fe/C enhancements are the focus of this paper. These events are quite similar in their elemental composition over the energy range examined. The ^{3}He/^{4}He ratios (0.007, < 0.002, 0.04, 0.005) are significantly enhanced over the solar wind value, but less than the lower limit often used to identify impulsive events (Reames et al., 1994).

The elemental composition of the selected events is plotted in Figure 1, along with abundances typical of gradual and impulsive events (Reames, 1995). The elemental abundances were calculated by summing the measured intensities integrated over the entire event from 12 to 60 MeV/nucleon. It was found that the spectra of C to Fe in a given event were well represented by power laws.

Table 1 and Figure 2 present the charge state results we have obtained for the four events by following the technique described in Cohen et al. (1999a). Also plotted in Figure 2 are the charge states expected from applying a $(Q/M)^\gamma$ fractionation to the distributions given in Arnaud and Rothenflug (1985) and Arnaud and Raymond (1992). The shaded regions correspond to 2, 4, and 10 x 10^6 K and result from the range of γ's observed in the four events. Below Z = 26, 4 x 10^6 K fits the data well, while Fe and Ni are better represented by ≥ 10^7 K.

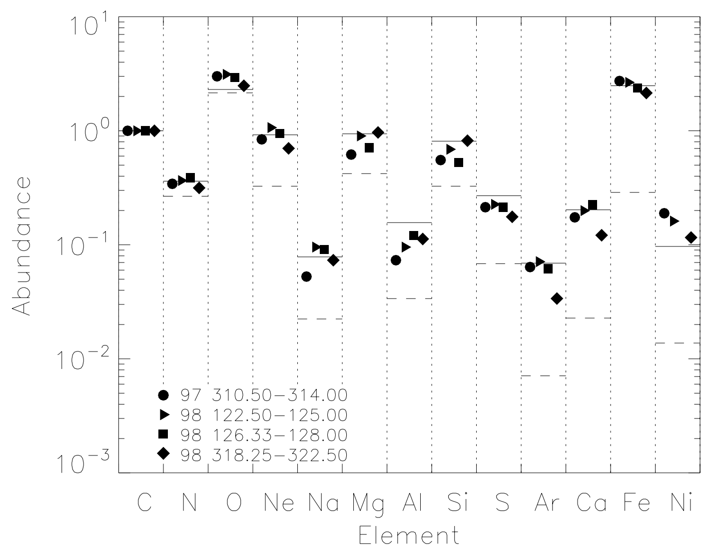

Figure 1: Abundances normalized to C for the four events. Solid (dashed) lines indicate average values for impulsive (gradual) values from Reames (1995).

3 Discussion:

The charge states inferred in these four events are higher than those expected to have originated from typical coronal temperatures (Ko et al., 1999). When compared to the results (at similar energies) from SAMPEX in two large gradual events in 1992 (Leske et al., 1995), the charge states of Z > 14 are found to be significantly higher in the ACE events. The charge states in Table 1 are more representative of the 3 – 5 x 10^6 K expected at the source of impulsive SEP events as deduced by Reames et al. (1994) from the heavy element enhancement patterns observed in impulsive events.

Z	97 310.5-314.0	98 122.5-125.0	98 126.3-128.0	98 318.25-322.5
6	5.90*	5.90*	5.90*	5.90*
7	6.59 ± 0.02	6.53 ± 0.11	6.60 ± 0.09	6.64 ± 0.03
8	7.47 ± 0.02	7.40 ± 0.15	7.59 ± 0.09	7.70 ± 0.02
10	8.89 ± 0.06	8.54 ± 0.43	9.07 ± 0.28	9.01 ± 0.12
11	9.13 ± 0.75	8.41 ± 1.26	9.28 ± 1.10	9.32 ± 0.80
12	10.27 ± 0.81	9.87 ± 1.19	10.47 ± 1.06	10.41 ± 0.84
13	10.84 ± 0.88	10.39 ± 1.40	11.03 ± 1.27	10.91 ± 0.94
14	11.95 ± 0.93	11.71 ± 1.30	12.37 ± 1.15	12.21 ± 0.96
16	13.15 ± 1.05	13.16 ± 1.53	13.69 ± 1.41	14.69 ± 1.07
18	13.56 ± 0.24	13.00 ± 1.35	14.65 ± 0.95	14.71 ± 0.39
20	13.77 ± 1.25	13.55 ± 2.35	14.85 ± 2.15	15.46 ± 1.43
26	18.97 ± 1.73	18.89 ± 3.26	21.61 ± 2.85	20.98 ± 1.99
28	19.61 ± 1.82	20.03 ± 3.42		22.32 ± 2.09

* assumed for normalization

However, our Fe and Ni results are indicative of even higher temperatures; they are more consistent with those measured at ~ 1 MeV/ nucleon by Luhn et al. (1987) in a sum over 22 impulsive events (~ 10^7 K for Fe based on a mean Q of 20.5 ± 1.2). One way of producing Fe charge states as high as ~ +19 is ionization by the electrons which form the electron-beam-generated waves (which are possibly responsible for the ion enhancements) (Miller and Viñas, 1993). However, the same process would fully strip Ne, Mg, and Si, inconsistent with our inferred charge states.

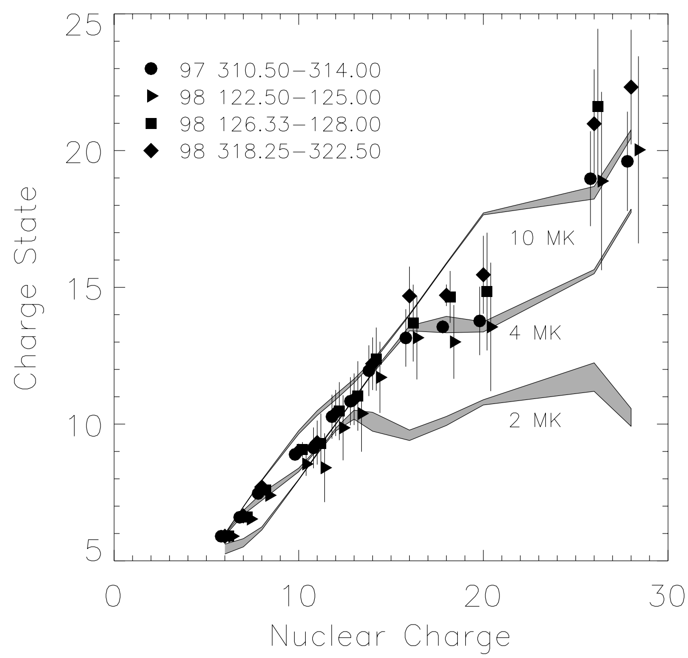

Figure 2: Inferred charge states for the four events. The shaded regions correspond to expected values for different coronal temperatures (see text).

If the heavier elements were to originate in a higher temperature (10^7 K) region, as a result of a non-equilibrium source plasma, they could have higher charge states than the lighter elements. Alternatively, the functional form of the fractionation (a power-law in Q/M) that we deduced from the isotopes (over a limited range near Q/M values of ~ 0.4) may not extend to the Q/M range of 0.2 - 0.3, resulting in an inferred charge state for Fe that is too high. Recent results from SAMPEX from the 6 November 1997 (Mazur et al., 1999) and 14 November 1998 (Larson et al., 1999) events, however, indicate charge states near +19 for iron, consistent with our results in the same events. Cliver (1995) has suggested some events may be a superposition of particles energized by separate impulsive and gradual acceleration phases. It is possible that the four ACE events are of this type and most of the Fe and Ni are from the Fe-rich impulsive phase, although the lack of an observed time dependence in the composition (and the similarity between the four events) suggests that this is not the case.

One difficulty in identifying the four events reported here as impulsive is the relatively low abundance of ^{3}He. Typically a minimum value of 0.1 for the ratio has used to classify an event as impulsive (e.g., Reames, 1995 and references therein). This value is substantially higher than those found here, although all four events have ^{3}He/^{4}He ratios which are enhanced over solar wind values. In addition, Reames et al. (1994) found a clear distinction between impulsive and gradual events in the Ne/C and Fe/C ratios. The ACE events all have Ne/C and the Fe/C ratios which fall among the impulsive events studied by Reames et al. and are greater than those of all 36 gradual events in that study. The authors also reported 18 events which were associated with impulsive flares and yet had $^{3}He/^{4}He$ ratios < 0.1. Two other such events (seemingly impulsive yet lacking strong $^{3}He/^{4}He$ enhancements) were studied by Van Hollebeke et al. (1990) indicating that these types of events are probably not rare but, until recently, have been largely ignored since identifying them has been difficult due to instrumental limitations.

As the solar activity increases over the next few years there will be additional opportunities to study such events with improved instrumentation, which should contribute to a better understanding of the characteristics of impulsive and gradual SEP events and of the different plasma processes involved. Using precise measurements of the isotopic abundances to determine Q/M fractionation and thereby infer charge states appears to be a useful tool in this effort especially at energies ≥ 10 MeV/nucleon where charge states are not currently being directly measured.

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