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New observations of heavy-ion-rich solar particle events from ACE

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Abstract. Following launch of the Advanced Composition Explorer in August 1997, the Solar Isotope Spectrometer measured the composition of nine solar energetic particle events. We have used isotopic measurements of Ne to determine the degree of charge-to-mass-dependent fractionation and infer the charge states of C - Ni in the four most heavy-ion-rich of the nine events. The results indicate a source temperature of $\sim 4 \times 10^6$ K; this and the measured abundances suggest that these four events are more characteristic of impulsive events than gradual. Although the $^3He/^4He$ ratios are not enhanced to the level commonly ascribed to impulsive events, there are sizable enhancements over typical solar wind values measured in three of the events.

1. Introduction

Solar energetic particle (SEP) events are typically classified into one of two categories, gradual or impulsive. In gradual events particles are accelerated at interplanetary shocks driven by coronal mass ejections, while impulsive events are associated with impulsive flares and active regions. Heavy elements (Ne - Fe) and ^{3}He are significantly enhanced over coronal values in impulsive events but not in gradual events (*Reames et al.* 1994), and the mean charge states of the heavy ions are higher in impulsive events than in gradual events (*Luhn et al.* 1987).

The elemental composition of gradual SEP events varies from event to event, differing systematically from that of the photosphere (e.g., *Cook et al.* 1984). The first ionization potential (FIP) is an organizing parameter for both SEP events and the solar wind (*Geiss* 1998), with individual SEP events exhibiting evidence of additional fractionation effects. A study of 10 gradual SEP events by *Breneman and Stone* [1985] found that the degree to which the elemental composition of an individual event deviated from the average SEP composition was well organized by the mean charge-to-mass ratio of the elements. The abundances normalized to average abundances versus Q/M were well fit by a power law with a slope that differed for each event. When the SEP composition is averaged over many events, the Q/M-dependent fractionation is small (*Garrard and Stone* 1994, *Reames* 1995a) and the resulting abundances are consistent with those measured in the solar wind and spectroscopically in the corona (*Reames* 1995a).

Knowledge of the ionic charge states of SEPs at relevant energies is critical to such studies. Typically the charge states have been assumed to equal those determined at ~ 1 MeV/nuc in a series of events in 1978-1979 by *Luhn et al.* [1985, 1987]. However, recently it has been observed that the mean charge state can be a strong function of energy within a given event (*Oetliker et al.* 1997; *Mazur et al.* 1999; *Möbius et al.* 1999) as well as differing from event to event. In the absence of direct measurements of Q, the degree of Q/M fractionation can be estimated from the enhancement of heavier isotopes, such as ^{22}Ne relative to ^{20}Ne, both of which should have the same Q distribution.

In this paper we concentrate on four events that are substantially enriched in heavy elements as well as exhibiting $^{22}Ne/^{20}Ne$ ratios well above solar wind values (*Leske et al.* 1999). We present the characteristics that these events have in common, use the Ne isotope measurements to determine the degree of Q/M fractionation and thereby infer the charge states of the elements from their enhancements over coronal values, 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 E and Z.

The 9 largest SEP events observed by SIS through the end of 1998 are listed in Table 1. The individual event composition as compared to the unweighted 9-event average is shown as a function of nuclear charge in Figure 1. SIS has observed both Fe-rich and Fe-poor events; for this paper we concentrate on the four most Fe-rich events: November 6, 1997; May 2, 1998; May 6, 1998 and November 14, 1998. These events, all magnetically well connected, also have the largest enhancements of $^{22}Ne/^{20}Ne$ (*Leske et al.* 1999) and similar elemental composition over the energy range 12-60 MeV/nucleon.

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Table 1. Characteristics of Observed SEP Events

Event Time Year Start End	$^3He/^4He$ (8-14 MeV/nuc)	Fe/O (12-60 MeV/nuc)
1997 306 0600 - 310 1200	0.008	0.588 ± 0.011
1997 310 1200 - 314 0000	0.007	0.900 ± 0.006
1998 110 1200 - 117 0000	< 0.06	0.018 ± 0.001*
1998 122 1200 - 125 0000	< 0.002	0.833 ± 0.016
1998 126 0800 - 128 0000	0.04	0.740 ± 0.014
1998 129 0450 - 131 1200	< 0.002	0.492 ± 0.015
1998 237 0000 - 244 0000	< 0.002	0.016 ± 0.001
1998 273 1200 - 278 0000	< 0.003	0.299 ± 0.003
1998 318 0600 - 322 1200	0.005	0.761 ± 0.006

* measured over 12 to 40 MeV/nucleon

The elemental composition of the selected events given in Table 2 was 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 are well represented by power laws.

Using the $^{22}Ne/^{20}Ne$ enhancement as a measure of the Q/M fractionation and the observed Mg/Ne ratio as a measure of the FIP enhancement, we can infer the charge states of the individual elements by following the technique of *Cohen et al.* [1999]. The results for the four events are given in Figure 2. For ionization temperatures of 2, 4, and 10 x 10^6 K we have taken the charge state distributions in *Arnaud and Rothenflug* [1985] and *Arnaud and Raymond* [1992] and calculated a new distribution assuming each charge state abundance was enhanced by a factor of $(Q/M)^\gamma$, where γ is obtained from the $^{22}Ne/^{20}Ne$ ratio for each event. Average charge states were then calculated from these new distributions and are presented as shaded regions in Figure 2. A temperature of 4 x 10^6 K does a remarkable job of fitting the inferred charge states of the elements below Z = 26. However, in all four events the deduced charge states for Fe and Ni are more consistent with temperatures ≥ 10^7 K.

If, as assumed by *Cohen et al.* [1999], the $^{22}Ne/^{20}Ne$ enhancements result from varying degrees of Q/M-dependent fractionation, elemental abundance enhancements should be correlated with $^{22}Ne/^{20}Ne$ if there is little change in mean

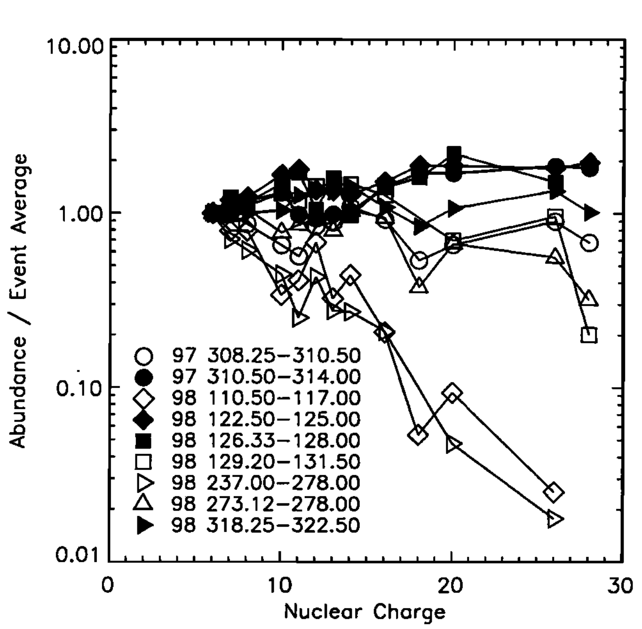

Figure 1. Individual event composition as compared to the average composition of all 9 SIS events, normalized to C.

charge states from event to event. For example, over the temperature range of 1.5 to 4 x 10^6 K, the mean charge states of $_{11}Na$ and $_{12}Mg$ do not vary significantly from +9 and +10, respectively, because of their He-like electron configuration. Thus, the abundance of ^{23}Na (Q/M = 0.39) relative to Mg (mean Q/M = 0.41 taking into account isotopic composition) should be correlated with $^{22}Ne/^{20}Ne$. Figure 3 shows that the correlation for these nine events is in good agreement with that calculated for 2.5 x 10^6 K, assuming all charge states in the distribution are enhanced by $(Q/M)^\gamma$. Similar agreement is found for 4 x 10^6 K. The correlation in Figure 3 is consistent with the assumption of a common Q/M fractionation process affecting elemental and isotopic enhancements.

3. Discussion

The composition of four events analyzed here suggests source temperatures higher than expected from the ambient corona (*Ko et al.,* 1999). The inferred charge states for Z ≥ 14 are also significantly greater than those measured at similar energies by SAMPEX during two large gradual events in 1992 (*Leske et al.* 1995). However, our results are not inconsistent with temperatures 3 to 5 x 10^6 K previously derived from the enhancement patterns of heavy elements in impulsive events (*Reames et al.* 1994).

The composition of these four events is more typical of impulsive events than gradual. The measured abundances divided by average gradual and impulsive event abundances are plotted versus nuclear charge (Z) in Figure 4 for all four events. These four events are much better represented by the average impulsive-event abundances than the gradual-event abundances. *Reames et al.* [1994] also found a clear distinction between 36 gradual events and 139 impulsive events in the distribution of both the Ne/C and Fe/C ratios. The four events analyzed here resemble impulsive events, with Ne/C and the Fe/C ratios greater than those of all 36 gradual events in *Reames et al.* [1994].

Reames [1995b] suggested the high Fe abundance in some gradual events is due to Fe-rich material predominantly confined to the initial stages of the event. We examined the time dependence of the composition of the four events and found little variation in the Fe abundance. The temporal variation of the Fe/O ratio is largest for the November 6, 1998 event (see *Mason et al.* 1999), but the Fe abundance through-out that event is significantly greater than is typical of gradual events.

Although the composition of these events is typical of impulsive events and the temperatures inferred for Z≤20 agree well with the range suggested by *Reames et al.* [1994] for impulsive events, the deduced charge states of Fe and Ni indicate much higher temperatures. The charge state measurements of *Luhn et al.* [1987], summed over 22 impulsive events during 1978-1980, suggest a temperature of > 5 x 10^6 K for Si (based on a mean of Q = 14 ± 2) and ~ 10^7 K for Fe (based on a mean of Q = 20.5 ± 1.2). In an effort to explain this, *Miller and Viñas* [1993] suggested that the electrons forming the electron-beam-generated waves that might be responsible for the ion enhancements could also ionize Fe to ~ +19. However, in this case Ne, Mg, and Si should be fully stripped, in disagreement with the inferred charge states in Figure 2.

Another possibility is non-equilibrium source plasma, with the heavier elements originating in a higher temperature (10^7 K) region. Alternatively, the Q/M-dependence of the fractionation deduced from the isotopes (corresponding to

Table 2. Observed Element Composition (12 to 60 MeV/nucleon)

Z	Nov 6 1997 310.5 - 314.0	May 2 1998 122.5 - 125.0	May 6 1998 126.3 - 128.0	Nov 14 1998 318.25 - 322.5	Phot.*	Gradual†	Impulsive†
6	1000 ± 12	1000 ± 38	1000 ± 39	1000 ± 15	1000	1000	1000
7	347 ± 6	371 ± 19	385 ± 20	309 ± 7	251	267	362
8	3058 ± 29	3218 ± 99	3010 ± 95	2602 ± 33	2042	2151	2304
10	848 ± 10	1077 ± 40	955 ± 37	672 ± 11	363	327	922
11	54 ± 2	98 ± 8	94 ± 6	69 ± 2	6	22	78
12	625 ± 8	913 ± 35	706 ± 29	915 ± 14	115	422	940
13	74 ± 2	102 ± 7	120 ± 7	101 ± 3	9	34	157
14	558 ± 7	700 ± 28	532 ± 23	776 ± 12	110	327	811
16	216 ± 4	230 ± 13	214 ± 12	164 ± 4	65	68	270
18	66 ± 2	73 ± 6	62 ± 50	32 ± 2	8	7	69
20	177 ± 3	196 ± 11	230 ± 11	112 ± 3	7	23	203
26	2752 ± 26	2680 ± 79	2228 ± 66	1980 ± 24	95	288	2484
28	191 ± 3	207 ± 8		106 ± 2	5	14	97

* Photospheric abundances from Grevesse and Sauval [1998]

† Average solar energetic particle abundances for gradual and impulsive events from Reames [1995a]

Q/M values of ~ 0.4) may not extend to the Q/M range of 0.2 - 0.3, resulting in inferred charge states that are too high. However, the inferred Fe charge state of +19 for the November 6, 1997 event is consistent with the mean value of 19.5 ± 2 obtained at similar energies during this event by SAMPEX (*Mazur et al.* 1999). The high mean charge states of Fe and Ni could also be the result of preferential acceleration in the same manner that $^3He^{+2}$ is enhanced in many impulsive events (*Bochsler and Kallenbach* 1994). Since the second harmonic of the ion cyclotron frequencies of $Fe^{+18\text{-}20}$ and $Ni^{+19\text{-}21}$ are very close to the $^3He^{+2}$ cyclotron frequency, wave-particle resonance could enhance the abundance of these ions resulting in measured <Q> values higher than those at the source region.

It is also possible that the composition of these four events includes a superposition of particles energized by separate impulsive and gradual acceleration phases (see, e.g., *Cliver* 1995), in which most of the Fe and Ni are from the Fe-rich impulsive phase. However, if this is the case, it is somewhat surprising that all four events have such a similar composition, with little or no time dependence.

The four events reported here also differ from previously identified impulsive events in having much smaller ^3He abundances. While the $^3He/^4He$ ratio appears to be enhanced in three of the four events (November 6, 1997, May 6, 1998, and November 14, 1998 [see Table 1]), all have ratios smaller than 0.1, the minimum value adopted by *Reames* [1990; 1995a,b] for an event to be considered impulsive. However, the four events reported here are similar to 18 events reported by *Reames et al.* [1994] which were associated with impulsive

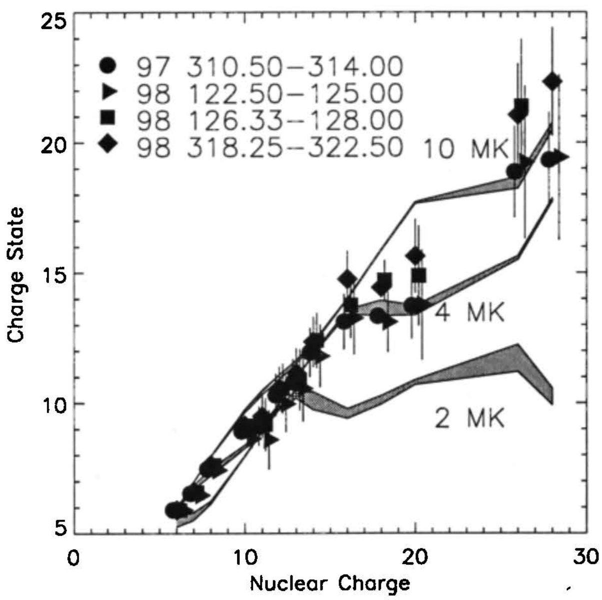

Figure 2. Inferred average charge states as a function of nuclear charge for the four selected events. The three shaded regions correspond to expected values for 2, 4, and 10 x 10^6 K assuming *Arnaud and Rothenflug* [1985] and *Arnaud and Raymond* [1992] charge state distributions and the range of Q/M-fractionation indicated by the measured $^{22}Ne/^{20}Ne$ ratios.

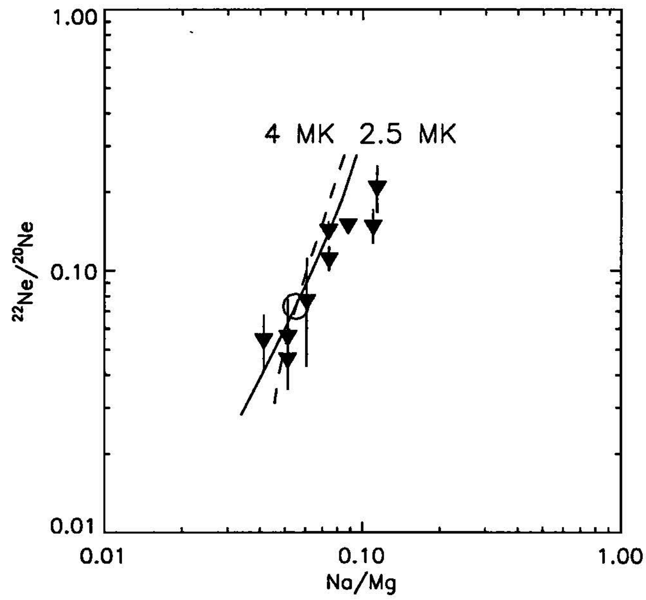

Figure 3. Measured $^{22}Ne/^{20}Ne$ ratios as a function of Na/Mg for all nine events (solid points). The open circle corresponds to the solar system abundance of $^{22}Ne/^{20}Ne$ (*Anders and Grevesse* 1989) and the photospheric abundance of Na/Mg (*Grevesse and Sauval* 1998). The two curves indicate the expected correlation if both the elemental and isotopic abundances are affected by a common Q/M-fractionation, showing little expected difference for 2.5 and 4 x 10^6 K.

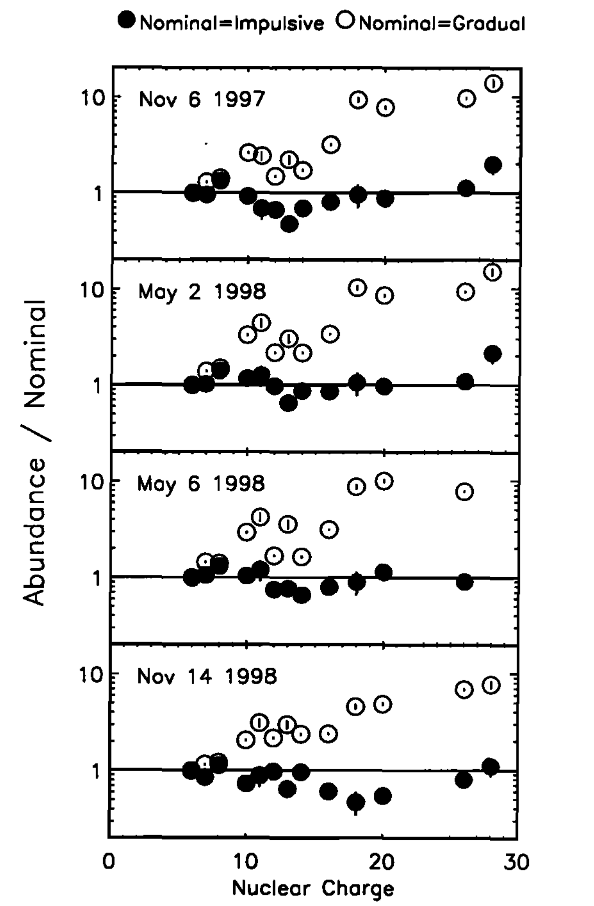

Figure 4. Measured abundances in four Fe-rich SEP events compared to average values for impulsive (solid points) and gradual events (open points) as given in *Reames* [1995a].

flares and had ^{3}He/^{4}He ratios < 0.1. *van Hollebeke et al.* [1990] studied two other examples of this type of event. Because of instrumental limitations, until recently events with small ^{3}He enhancements have been difficult to identify and have been largely ignored.

Increasing solar activity should provide opportunities to study additional events similar to the four selected here. As these first results indicate, precise observations of elemental and isotopic abundances can contribute to a better understanding of the characteristics of impulsive and gradual SEP events and of the different plasma processes involved.

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