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Event-to-event variations in the isotopic composition of neon in solar energetic particle events

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Abstract. Using the Solar Isotope Spectrometer on the Advanced Composition Explorer, we have measured the isotopic composition of neon at 24–72 MeV/nucleon in nine solar energetic particle events between 4 November 1997 and 16 November 1998. The ^{22}Ne/^{20}Ne ratio varies from $\sim$ 0.7 to $\sim$2 times the solar wind value from event to event, indicating significant mass fractionation in the acceleration and/or transport of these particles. The mass fractionation is strongly correlated with the Fe/O and Na/Mg element abundance ratios, suggesting that elemental and isotopic fractionation are both governed by the ionic charge to mass ratio.

Introduction

Solar energetic particles (SEPs) provide a direct sample of solar material that can be used to study the composition of the solar atmosphere, as well as particle acceleration and transport processes which may alter the composition. Two types of SEP events, impulsive and gradual, are generally recognized [*e.g., Reames,* 1995a]. In impulsive events, the ^{3}He abundance is often greatly enhanced, possibly by ion cyclotron wave resonances [*Fisk,* 1978; *Temerin and Roth,* 1992] or cascading Alfvén waves [*Miller,* 1998], which may also influence heavy ion composition. The heavy element abundances in large, gradual SEP events are known to differ from event to event, and these variations are found to be correlated with the ionic charge to mass ratio, Q/M [*Breneman and Stone,* 1985]. When corrected for this fractionation, SEP abundances can reveal the elemental composition of the corona [*Breneman and Stone,* 1985; *Garrard and Stone,* 1993; *Reames,* 1995b] independently of spectroscopic and *in-situ* solar wind measurements [*von Steiger et al.,* 1997]. Similarly, the isotopic composition of the corona, which could not be determined spectroscopically for most elements, can in principle be deduced from SEP studies [*Mewaldt and Stone,* 1989; *Williams et al.,* 1998], to complement *in-situ* solar wind measurements [*Kallenbach et al.,* 1998].

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Most earlier SEP isotope measurements [*e.g., Dietrich and Simpson,* 1979; *Mewaldt et al.,* 1979, 1984; *Simpson et al.,* 1983; *Williams et al.,* 1998] appeared to be consistent with terrestrial or meteoritic abundances within large uncertainties. Isolated differences were found for gradual events [*Mewaldt and Stone,* 1989; *Williams et al.,* 1998], and there were indications of significant enrichments of ^{22}Ne in ^{3}He-rich periods [*Mason et al.,* 1994].

The isotopic composition of Ne is particularly interesting, as both the meteoritic component Neon-A, with ^{22}Ne/^{20}Ne=0.122 [*Cameron,* 1982], and the solar wind value of 0.073 [*Geiss et al.,* 1972; *Kallenbach et al.,* 1997] have been suggested as being representative of the solar composition. Earlier SEP measurements [*e.g., Dietrich and Simpson,* 1979] tend to agree more closely with Neon-A, while more recent measurements [*Williams et al.,* 1998] agree better with the solar wind value. In new studies by the Advanced Composition Explorer (ACE), large enhancements were found in the 6 November 1997 SEP event for many heavy isotopes from ^{13}C to ^{60}Ni, with the ^{22}Ne/^{20}Ne ratio enhanced by a factor of 2 over the solar wind value [*Leske et al.,* 1999]. In this present work, we examine the ^{22}Ne/^{20}Ne abundance ratio in 9 SEP events observed by the Solar Isotope Spectrometer (SIS) on ACE, and find that the ratio varies widely from event to event.

Data Analysis

The SIS instrument consists of two identical silicon solid-state detector telescopes with a combined geometry factor of 38 cm^{2}sr [*Stone et al.,* 1998]. Using the dE/dx versus residual energy technique, the nuclear charge, Z, mass, M, and total kinetic energy, E, can be determined for particles with energies of $\sim$ 10 to $\sim$ 100 MeV/nucleon, with a mass resolution of $\sim$ 0.15 to $>$ 0.3 amu, depending on E and Z.

Time profiles of the nine largest SEP events observed by SIS to date are illustrated for 24 – 72 MeV/nucleon Ne nuclei in Figure 1, and mass histograms of Ne at the same energies in these time periods are shown in Figure 2. Consistency requirements among multiple determinations of Z and M were used to reject events that underwent nuclear interactions in the instrument or involved chance coincidences. Also, the measured trajec-

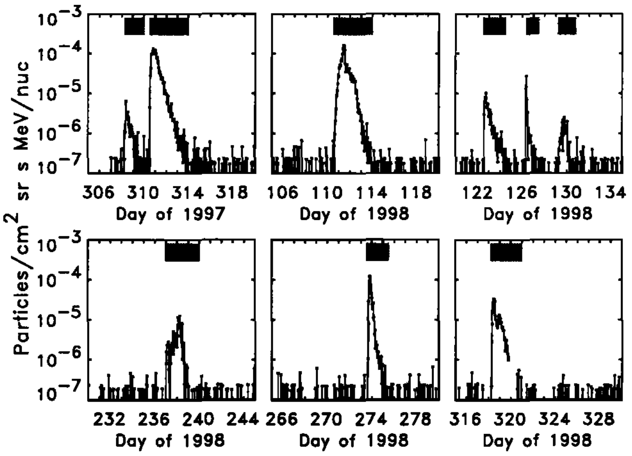

Figure 1. Time profiles of hourly-averaged fluxes of Ne nuclei with 24 – 72 MeV/nucleon measured by SIS, illustrating the SEP events and time periods (*shaded boxes*) used in this analysis.

Table 1. SEP ^{22}Ne/^{20}Ne Ratios, 24–72 MeV/nucleon

Time Period	SEP value (%)	SEP/SS[a]
1997 308 06:00 - 310 00:00	5.8 ± 2.2	0.79 ± 0.30
1997 310 12:00 - 314 00:00	15.07 ± 0.69	2.06 ± 0.09
1998 110 12:00 - 114 00:00	4.63 ± 0.37	0.64 ± 0.05
1998 122 12:00 - 124 12:00	14.9 ± 2.2	2.04 ± 0.31
1998 126 08:00 - 127 12:00	21.2 ± 4.4	2.90 ± 0.60
1998 129 04:48 - 130 19:12	7.9 ± 3.5	1.08 ± 0.49
1998 236 22:00 - 240 00:00	5.6 ± 1.4	0.77 ± 0.19
1998 273 12:00 - 275 12:00	11.2 ± 1.2	1.54 ± 0.17
1998 318 05:00 - 321 00:00	14.3 ± 1.1	1.96 ± 0.15

[a]"Solar system" value of 7.3% [*Anders and Grevesse,* 1989]

tory of each particle was used to reject those particles which could have exited through the sides of the instrument without stopping.

The abundances in Table 1 were obtained by counting events in the peaks in Figure 2, ignoring the effects of small tails in the distributions and any contributions from ^{21}Ne, expected to be $\sim 2 \times 10^{-3}$ of ^{20}Ne [*Anders and Grevesse,* 1989]. Using measured quiet-time intensities in SIS through November 1998, the background counts expected due to galactic cosmic rays and anomalous cosmic rays (ranging from 0.41% to 6.4% of the SEP Ne, depending on the intensity of the SEP event) have been subtracted from these data. Small corrections of $\lesssim$5% were applied to correct relative isotopic abundances to equal energy per nucleon intervals.

In all cases, the ^{22}Ne peak is clearly separated from the ^{20}Ne peak, with a typical mass resolution of $\sim$ 0.19 amu. The ^{20}Ne peak is shown with the same height in each panel of Figure 2, and the relative height of the ^{22}Ne peak is clearly seen to vary significantly from event to event. The isotopic composition of other species, such as Mg and O, has been found to vary dramatically in these events as well [*Leske et al.,* 1998].

Results and Discussion

In the 6 November 1997 event, which has been examined in more detail than the others [*Leske et al.,* 1999], we find no indication that the ^{22}Ne/^{20}Ne ratio varies significantly during the course of the event, nor does it vary appreciably with energy from $\sim$ 20 to 100 MeV/nucleon. Preliminary analysis of the other events also shows no significant changes with time in the Ne isotopic composition, while results in the first seven of these events from the Ultra Low Energy Isotope Spectrometer (ULEIS) on ACE find similar ^{22}Ne/^{20}Ne ratios as SIS at the much lower energies of $\sim$ 1 MeV/nucleon [*Dwyer et al.,* 1998]. Thus, in each case, it appears that the observed abundance anomaly is characteristic of the event as a whole, rather than the result of a mixture of

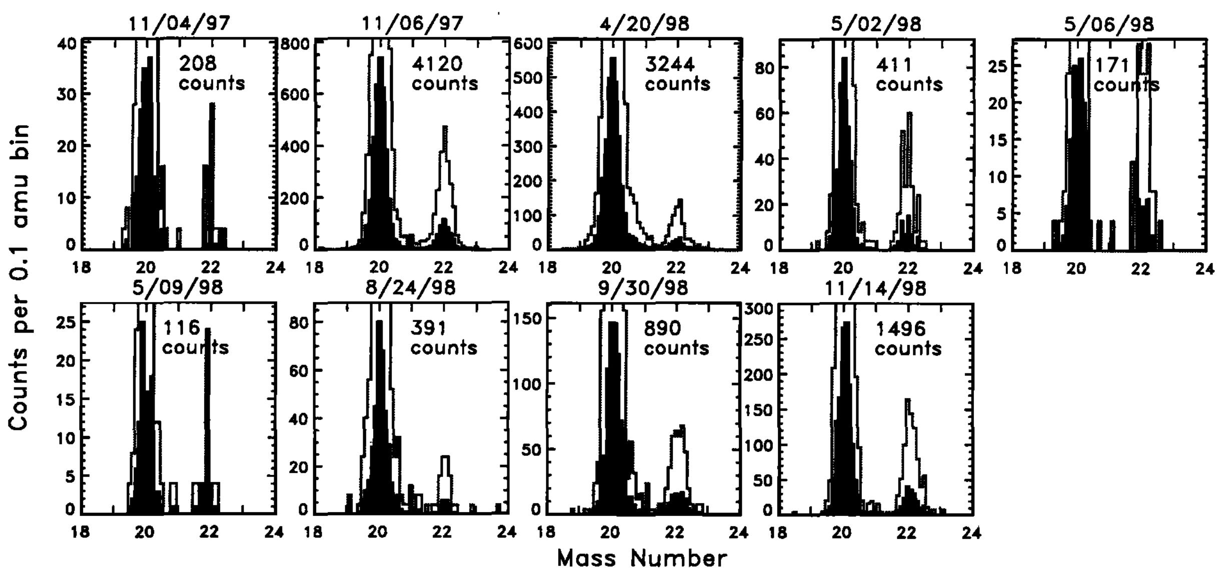

Figure 2. Mass histograms (*shaded*) of Ne with 24 – 72 MeV/nucleon from SIS, accumulated during the time periods indicated in Table 1. Views expanded by a factor of 4 (*solid lines*) are also shown.

source populations with different compositions, spectral indices, or time histories.

The abundances of heavy elements with $6 \leq Z \leq 28$ in these nine events also vary considerably, with Fe/O ranging from 0.016 in the 24 August 1998 event to 0.90 in the 6 November 1997 event at energies of 12-60 MeV/nucleon [*Cohen et al.*, 1999b]. Elemental abundance variations in gradual events have been shown to scale reasonably well as a power law in the ionic charge to mass ratio, Q/M, with a different power law index, γ, for each SEP event [*Breneman and Stone*, 1985], and similar correlations may apply in impulsive events. If these variations arise from rigidity-dependent acceleration and/or transport processes, there should be mass fractionation as well, since two isotopes of the same element and same velocity have different rigidities. Thus, it seems reasonable to ask whether the isotopic abundance variations and elemental abundance variations are correlated.

The first panel of Figure 3 shows the ^{22}Ne/^{20}Ne ratio measured in SEP events compared with the Fe/O ratio measured in the same events. Large, statistically significant differences from the solar wind ^{22}Ne/^{20}Ne ratio are evident. In general, the deviations from the solar wind composition seem reasonably well correlated with the Fe/O ratio. Note that some of the earlier measurements are actually averages over several solar events, and given the event-to-event variability, this may contribute to some of the scatter.

If one assumes that the elemental abundance variations scale as $(Q/M)^\gamma$ [*Breneman and Stone*, 1985], and that the Fe/O ratio is representative of the elemental fractionation, then an estimate for the index γ is given by [*Mewaldt and Stone*, 1989]:

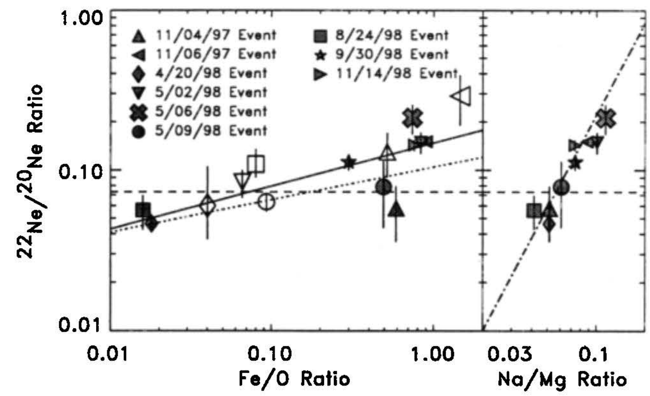

Figure 3. ^{22}Ne/^{20}Ne abundances plotted vs. the observed Fe/O (*left*) and Na/Mg ratios (*right*). ACE/SIS data (*filled symbols*) are from the indicated SEP events. Other data for Fe/O (*open symbols*) are from *Simpson et al.*, [1983] (*diamond*, 15-32 MeV/nucleon, 4 SEP event average); *Williams et al.*, [1998] (*circle* and *inverted triangle*, 19-70 MeV/nucleon, 2 individual SEP events); *Mewaldt et al.*, [1984] (*square*, 8-51 MeV/nucleon, 1 SEP event); *Dietrich and Simpson*, [1979] (*triangle*, 28-49 MeV/nucleon, 7 SEP event average); and *Mason et al.*, [1994] (*left-pointing triangle*, 0.6-4 MeV/nucleon, 3-day ^{3}He-rich period). Dotted, solid, and dashed-dotted lines show possible expected correlations for the ratios (see text). The dashed line indicates the solar wind ^{22}Ne/^{20}Ne value [*Geiss et al.*, 1972].

$$\gamma_{est} = \frac{\ln[(\mathrm{Fe/O})_{SEP}/(\mathrm{Fe/O})_{corona}]}{\ln[(Q/M)_{\mathrm{Fe}}/(Q/M)_{\mathrm{O}}]}, \qquad (1)$$

assuming that the coronal Fe/O ratio represents the average SEP value. The expected SEP ^{22}Ne/^{20}Ne ratio would then be $(20/22)^\gamma \times (^{22}\mathrm{Ne}/^{20}\mathrm{Ne})_{corona}$. (Note that $\gamma < 0$ for Fe-rich events.)

For most of the events in Figure 3, the Q/M values for Fe and O are not measured at the energies of the Ne isotope measurements. Using the charge states measured at 15-70 MeV/nucleon in earlier gradual events [*Leske et al.*, 1995] (which are very similar to the average values found in gradual events at ~ 1 MeV/nucleon [*Luhn et al.*, 1985]), equation (1) yields the predicted ^{22}Ne/^{20}Ne ratio given by the dotted line in Figure 3. However, for impulsive events in the figure, the ionic charge states are expected to be greater than in gradual events [*Luhn et al.*, 1987]. Also, equation (1) implicitly assumes that the elemental fractionation associated with the first ionization potential (FIP) effect is the same magnitude in the SEP event as it is between the photosphere and corona. While this may be true on average, the size of the FIP fractionation is known to vary from event to event [*Garrard and Stone*, 1994]. The $(\mathrm{Fe/O})_{SEP}$ value used in equation (1) must therefore be corrected to represent only the Q/M fractionation, not any contribution from atypical FIP fractionation.

As an example, when the charge states (which were similar to those measured in impulsive events [*Luhn et al.*, 1987]) and FIP fractionation determined at 12-60 MeV/nucleon in the 6 November 1997 event [*Cohen et al.*, 1999a] are used in equation (1), the correlation shown by the solid line in Figure 3 is expected. The solid and dotted lines thus serve to illustrate the degree of variation that might be attributed to charge state and FIP fractionation differences among the events.

Although the Fe/O ratio is commonly measured in SEPs and is therefore convenient to use for comparing different events, its variability due to the effects discussed above contributes greatly to the scatter seen in Figure 3. By comparing the ^{22}Ne/^{20}Ne ratio to an element ratio where both elements have either high FIP or low FIP, scatter due to differences in the degree of FIP fractionation is eliminated. Also, by choosing elements whose mean charge states are not expected to vary much over a broad temperature interval, scatter due to charge state differences may be greatly reduced. As discussed in more detail by *Cohen et al.* [1999b], Na and Mg fit both these requirements. These elements are likely to be similar to Ne in their Q/M values, and so sensitivity to the functional form of the Q/M dependence is also lessened. As shown in the second panel of Figure 3, the ^{22}Ne/^{20}Ne ratio is much better correlated with the Na/Mg ratio than with Fe/O, with a correlation coefficient of 0.94 (compared with 0.75 for the SIS Fe/O data). The dotted-dashed line shows the correlation expected using the coronal Na/Mg ratio [*Anders and Grevesse*, 1989] in place of the Fe/O ratio in equation (1), assuming both Na and Mg have 2 electrons attached (for reasons discussed in *Cohen et al.* [1999b]). Subject to the FIP and charge state variations discussed above, both the isotopic and elemental fractionation appear to be governed by the same Q/M-dependent process.

Although the sample of SEP events is still small, it is interesting to note that during the one year period sampled here, the total solar particle fluence of ^{22}Ne relative to ^{20}Ne at energies $\gtrsim$25 MeV/nucleon was ~ 0.12, a factor of 1.6 above that of the solar wind value. If this is typical of the long term trend, and not merely a statistical fluctuation or something unique to this phase of the solar cycle, it may help to account for the enriched isotopic composition of Ne (^{22}Ne/^{20}Ne$\sim$ 0.089) found implanted in lunar materials [*Wieler*, 1998], which had been originally attributed to SEPs on the basis of the required implantation energy.

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