Correlated Elemental and Isotopic Variations in Solar Energetic Particles


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Abstract

We consider whether the observed fractionation of Ne isotopes recently reported in solar energetic particle (SEP) events is due to the same charge-to-mass dependent fractionation processes that apparently cause SEP elemental composition variations. We find that the observed correlation of the $^{22}\text{Ne}/^{20}\text{Ne}$ and Na/Mg ratios in nine large SEP events is consistent with a common fractionation process if the charge states of these ions are characteristic of a source temperature of ~1.5 to ~4 million degrees.

1 Introduction:

Measurements of the nine largest solar energetic particle (SEP) events observed since the launch of ACE in August 1997 have shown that a number of isotope abundance ratios, including $^{22}\text{Ne}/^{20}\text{Ne}$, can vary by a factor of ~3 to ~4 from event to event (Leske et al. 1999a, 1999b) – considerably more than had been expected based on measurements of the elemental composition of SEPs. Variations in the elemental composition are commonly assumed to indicate that the acceleration and/or transport of SEPs depends on particle rigidity, and therefore on the charge-to-mass ratio (Q/M) of the ions in the source plasma. Note that existing measurements show that in most large events SEP ions with $Z>6$ are not fully stripped, with the mean Q/M ratio of Fe in SEPs typically ~1/2 that of O. Measured SEP charge states in gradual SEP events are generally characteristic of a source temperature of ~2 MK, similar to coronal temperatures (see, e.g., Luhn et al. 1985, Leske et al. 1995), while in impulsive events the temperatures are somewhat higher (Luhn et al. 1987, Reames et al. 1995, Cohen et al. 1999a, b).

Breneman and Stone (1985) showed that the abundances of the elements from C to Ni in a given event, relative to SEP abundances averaged over many solar events, were ordered by the mean charge-to-mass ratio, $\langle Q/M \rangle$ measured at ~1 MeV/nuc (Luhn et al. 1985). Following them we represent the measured abundance ratio of two species $N_i/N_j$ in a given event as a power-law in $\langle Q/M \rangle$:

$$N_i/N_j = (S_i/S_j)[\langle Q/M \rangle / \langle Q/M \rangle_i]^{\gamma}$$

Where $S_i/S_j$ is the coronal abundance ratio, and the index $\gamma$ varies from at least –10 to +5 (Garrard and Stone, 1994, Leske et al. 1999b). If the $^{22}\text{Ne}/^{20}\text{Ne}$ variations result from varying degrees of Q/M-dependent fractionation, elemental abundance enhancements should be correlated with $^{22}\text{Ne}/^{20}\text{Ne}$. In this paper we test the hypothesis that the elemental and isotopic variations result from the same Q/M-dependent process.

2 Solar Particle Data:

The nine solar events considered here were the largest observed by the Solar Isotope Spectrometer (SIS) on ACE during the period from launch (8/25/97) to the spring of 1999. The elemental and isotopic composition of these events has been reported by Cohen et al. (1999b) and Leske et al. (1999b). We can expect the $^{22}\text{Ne}/^{20}\text{Ne}$ variations to be correlated with variations in the abundances of neighboring elements if
we consider two elements that have $<Q/M>$ ratios that differ in the same manner under a broad range of conditions. For example, the mean charge-to-mass ratio for Fe is less than that for oxygen at all temperatures, even when these ions are fully stripped, and variations in $^{22}\text{Ne}/^{20}\text{Ne}$ are indeed correlated with those of Fe/O in these events (see Leske et al. 1999b). However, Fe charge states are very sensitive to temperature, and the mean Fe charge state is known to vary by as much as a factor of two with energy in a given event, and also to vary from event to event (e.g., Oetliker et al. 1997, Mazur et al. 1999, Moebius et al. 1999). As a result, the behavior of this correlation is difficult to predict. In addition, it may be more meaningful to compare the Ne isotope variations with those of elements having similar $<Q/M>$ values.

Although there are no available high-energy measurements of SEP charge states for most of these events, Arnaud and Rothenflug (1985) have calculated charge-state distributions for a number of elements in thermal equilibrium over a range of temperatures. Figure 1 shows the calculated mean charge states of Ne, Na, and Mg ($Z = 10, 11,$ and $12$) as a function of temperature, assuming isotope abundances given in Anders and Grevesse (1989). Over the temperature range from $\sim 1.5$ to $4$ MK the mean charge states of Na and Mg do not vary significantly from +9 and +10, respectively, because of their He-like electron configurations. Thus, the abundance of $^{23}\text{Na}

![Figure 1: Mean Q/M ratios as a function of temperature based on the calculations of Arnaud and Rothenflug (1985).](image1)

![Figure 2: (left) Expected Na/Mg ratio vs. source temperature taking into account a fractionation process assumed to be a power-law in Q/M, with index $\gamma$. (right) Same as above, but for $^{22}\text{Ne}/^{20}\text{Ne}$.](image2)
(Q/M = 0.39) relative to Mg (mean Q/M = 0.41 taking into account the isotopic composition) should be
correlated with 22Ne/20Ne (note that 23Na is neutron rich, as is 22Ne).

If all charge states are affected by the same Q/M-dependent fractionation process, we can calculate the
expected abundances for each charge state of the various isotopes of Ne, Na, and Mg. Figure 2 shows the
expected 22Ne/20Ne and Na/Mg ratios as a function of temperature for power-law fractionation indices
ranging from −10 to +10. Note that because 22Ne and 20Ne have the same charge state distribution, the
expected 22Ne/20Ne ratio depends only on γ, and not on temperature. From Figure 2 it is clear that the
22Ne/20Ne and Na/Mg ratios should be strongly correlated for 1.5≤T≤4 MK, but anticorrelated (or perhaps
weakly correlated for temperatures outside this range. There is also a region with T > 10 MK (where the
ions become fully stripped) where a positive correlation is also expected with a somewhat different slope.

The comparison in Figure 3 illustrates

that the data for these nine events show a
correlation which agrees reasonably well
with that expected for temperatures of ~1.5
to 4 MK, assuming that all charge states are
enhanced by the same Q/M-dependent
mechanism. There is no strong evidence that
either the elemental or isotopic composition
of the source material varies significantly
from event to event. Although the overall
agreement would improve if the coronal
Na/Mg ratio were greater or the 22Ne/20Ne
ratio less than the expected values, the
observations are consistent with the
assumption of a common Q/M-dependent
fractionation process affecting both
elemental and isotopic enhancements. It
remains for theoretical models to identify
appropriate acceleration/transport
mechanisms that might lead to this
fractionation.

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References