Ionic Charge States Inferred from Elemental and Isotopic Composition in ^{3}He-rich Solar Energetic Particle Events

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***Abstract*. Data from the ACE Solar Isotope Spectrometer have been used to study heavy ion elemental and isotopic abundances at energies above 10 MeV/nuc in a number of ^{3}He-rich solar energetic particle events. The isotopic composition observations have revealed a fractionation pattern in which heavy isotopes are enhanced relative to lighter isotopes of the same element as a power law in the ratio of the masses. Adopting the assumption that this represents a special case of a general fractionation law in which different ion species are fractionated as a power law in Q/M, we infer ionic charge state values (Q) for a number of elements and compare them with direct measurements, when available. The relationship between these Q values and the observed elemental fractionation patterns are discussed.**

***Keywords*: ^{3}He-rich solar energetic particles, composition, ionic charge states**

I. Introduction

Solar energetic particle (SEP) events with large enhancements of ^{3}He relative to ^{4}He are thought to have an intimate association with magnetic reconnection in solar flares. Although the detailed mechanisms are still a subject of active study and debate, it is widely believed that the energy released in magnetic reconnection drives plasma processes that lead to interactions with the ambient charged particle population and cause preferential acceleration of some species. The large ^{3}He enhancement is typically accompanied by elemental enhancements that increase approximately monotonically with atomic number, Z, resulting in Fe being enhanced relative to O by a factor ~ 10 and the heaviest elements by factors $\sim 10^2$–10^3 [1], [2]. These commonly-cited composition characteristics of ^{3}He-rich SEP events are accompanied by a relatively robust pattern of non-monotonic elemental enhancement variations [1], [3], [4] throughout the range of elements that has been well studied, $6 \leq Z \leq 28$. In addition, investigations of isotope ratios such as ^{22}Ne/^{20}Ne and ^{26}Mg/^{24}Mg [5], [6] have found that large (factors >3) enhancements of these ratios are common in ^{3}He-rich events.

Observed values of Q_{Fe} below $\sim$0.1 MeV/nuc in ^{3}He-rich events are found to be comparable to those in the solar wind and correspond to quiescent coronal temperatures. At higher energies, $\sim$0.5 MeV/nuc, Q_{Fe} typically increases by several charge units, indicating that significant stripping takes place during acceleration and implying that the acceleration must take place relatively low in the corona where ambient densities are sufficient to produce the Coulomb collisions needed to cause this stripping [7], [8]. To date, available space instruments have not been capable of measuring ionic charge states much above 1 MeV/nuc in ^{3}He-rich events.

Energy spectra in ^{3}He-rich events tend to be relatively soft and often steepen at energies $\gtrsim$ 1 MeV/nuc [9], [10] and events having measurable intensities of heavy elements above 10 MeV/nuc are relatively rare. Over the course of solar cycle 23, a number a ^{3}He-rich SEP events that did extend to high energies were observed using the Solar Isotope Spectrometer (SIS [11]) on NASA's Advanced Composition Explorer (ACE) spacecraft. In this paper we report elemental and isotopic composition measurements from several of these events and discuss the observed fractionation patterns in terms of possible mechanisms that depend on the ionic charge, Q, and the mass, M, of the particles.

II. Observations

Figure 1 shows measurements of heavy element abundances in the 7 most intense ^{3}He-rich events observed with SIS. These abundances are expressed in terms of enhancement factors relative to slow solar wind values [12] and normalized to yield an oxygen enhancement of 1 for each event. For comparison, the average elemental composition in ^{3}He-rich SEP events compiled by Reames [4] is presented in the same form (rectangles). In addition to the well known enhancement of Fe/O by about an order of magnitude, there are a variety of other features common among these events as well as in the Reames average composition. These include a larger enhancement for N than for either of its neighboring elements, C and O, enhancement peaks at Ne and Al, an enhancement dip in the Si–S region, and a plateau in the enhancement value from Ar to Ni.

Figure 2 shows the correlation between the isotope ratios ^{22}Ne/^{20}Ne and ^{26}Mg/^{24}Mg. The circles show data from ^{3}He-rich events, with the area of the points inversely proportional to the relative uncertainty in the measurements in order to emphasize events with higher

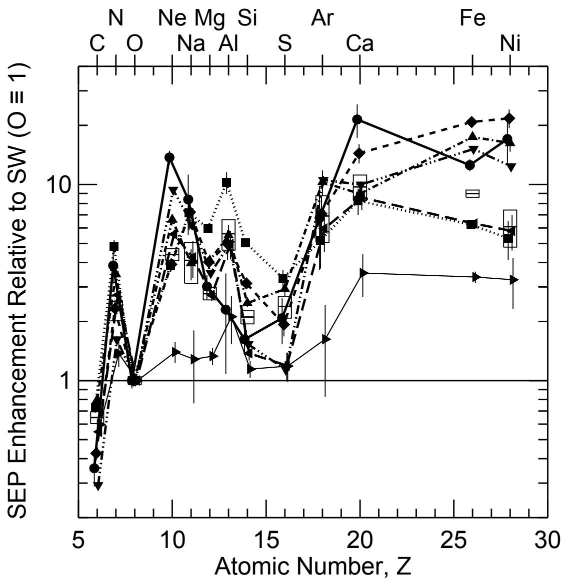

Fig. 1: Elemental abundance enhancements relative to solar wind values [12] in 7 ^{3}He-rich SEP events. Rectangles show enhancements calculated from the average ^{3}He-rich SEP event composition of Reames [4].

statistical significance. The × symbols correspond to gradual (shock-accelerated) SEP events reported in [13]. These gradual events are typically much more intense than the ^{3}He-events being considered here. The dashed lines indicate the solar wind values for the two isotope ratios. As pointed out in [13], the observed correlation of the two isotope ratios is consistent with that expected assuming that the isotope fractionation is a consequence of a general fractionation pattern that has the form of a power law in Q/M. The ^{3}He-rich events with the smallest statistical uncertainties cluster close to this same correlation line, but with larger enhancements of the two ratios.

In most of the ^{3}He-rich events measured with SIS, counting statistics do not permit the measurement of additional isotope ratios. An exception is the event of 20 Aug 2002, which is indicated by the largest circle in Figure 2. In this event, which provided more than 2/3 of all the heavy nuclei collected by SIS from ^{3}He-rich events, it has been possible to measure a number of additional isotope ratios. Figure 3 contains a plot comparing enhancements of isotope ratios in the 20 Aug 2002 event relative to solar wind ratios. The diagonal solid line is a weighted fit to these enhancement factors assuming that they go as a power law in the ratio of the masses of the two isotopes. The best-measured isotope ratios appear to have such a dependence, and the slope of the fitted line gives the "fractionation exponent", $-\alpha$, in this case yielding $\alpha \approx -14$. It should be noted that there is a single fit parameter; the fitted line must pass through the origin. Thus the slope can be obtained from a single isotope ratio such as ^{22}Ne/^{20}Ne.

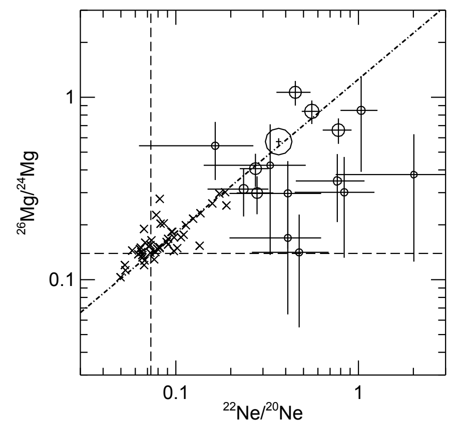

Fig. 2: Measured correlation between Ne and Mg isotopic abundance ratios. Circles show ^{3}He-rich events, × symbols indicate gradual events [13]. Dashed lines show solar wind values of the isotope ratios. The dot-dash line is the correlation expected assuming fractionation as a power law in Q/M.

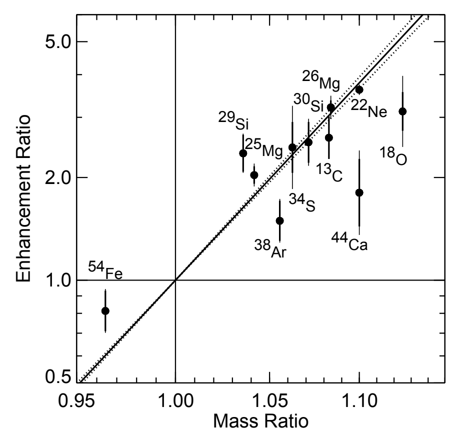

Fig. 3: Log-log plot of enhancement factor for various isotope ratios relative to solar wind values (ordinate) versus the ratio of the isotope masses. SEP data are from SIS measurements in the 20 Aug 2002 ^{3}He-rich event. Solar wind values are from [12]. Points are labeled by the isotope in the numerator of the ratio. The denominator is the most-abundant isotope of the same element.

III. Fractionation Model

As discussed by Cohen et al. [14], [15], if SEP fractionation goes as $(Q/M)^\alpha$, then measurements of isotope ratio enhancements should provide a direct measure of α because it is expected that different isotopes of the same element should normally have the same ionic charge state, Q. Having obtained the fractionation exponent by this means, one can then use measured elemental abundance ratio enhancements to derive the ratio of ionic charge states of the two elements being considered. Fractionation as a power-law in Q/M in gradual events was originally proposed in [16]. Recent work on ^{3}He-rich events [1], [2] also suggests a fractionation law of this kind. All of these studies have suffered from the lack of direct measurements of ionic charge states in the events being studied, making it necessary to use average values from a number of events or values expected in a thermal source population of an appropriate temperature. This uncertainty about the actual charge states relevant to an event may be responsible for observed deviations from the fitted power-law dependence on Q/M. The SIS isotope observations shown in Figures 2 and 3, while consistent with fractionation as a power-law in Q/M, do not prove that the fractionation law has this form. The same isotope fractionation would be obtained from a power-law in $f(Q)/M$ for any function, f, of the charge states since the dependence on Q would cancel when considering ratios between isotopes of the same element.

For our analysis we adopt the hypothesis that fractionation in ^{3}He-rich events goes as a power law in Q/M and use the method of Cohen et al. to derive ionic charge states. Figure 4 shows the enhancements of ^{22}Ne/^{20}Ne and Fe/C in a single plot. The fractionation exponents derived from the ^{22}Ne/^{20}Ne enhancements are indicated on the right hand axis of the plot. Combining this exponent with the Fe/C enhancement, one can calculate Q_{Fe}/Q_C. With the additional assumption that C is fully stripped ($Q_C = 6.0$), one obtains the values of Q_{Fe} that are indicated (dotted lines). As a test of the validity of the assumptions, one can check that the analysis yields $Q_{Fe} \le 26$, the charge of a fully-stripped Fe ion. For all except one event, which has a large uncertainty in the ^{22}Ne/^{20}Ne measurement, this condition is satisfied by the SIS events shown.

In Figure 4 we have labeled three events for which there is some ionic charge state information available from other sources. Figure 5 compares our inferred values of Q_{Fe} in the 9 Sep 1998 and 1 May 2000 events

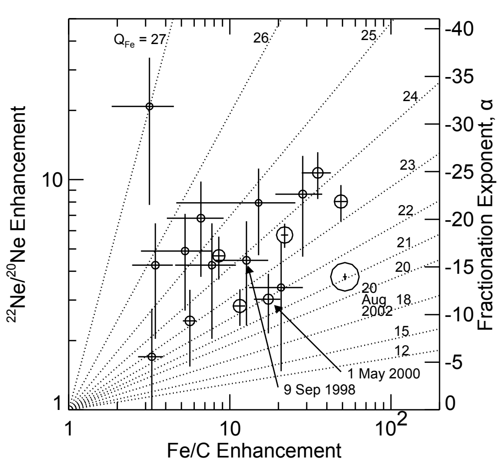

Fig. 4: Enhancement of the ^{22}Ne/^{20}Ne isotope ratio plotted versus the enhancement of Fe/C in a number of ^{3}He-rich events. The fractionation exponent and the value of Q_{Fe} are derived from these two enhancements (see text).

with direct measurements made using the ACE/SEPICA instrument at energies below 1 MeV/nuc [7]. As noted above, the Q_{Fe} values are increasing with energy in the sub-MeV range. The higher values of Q_{Fe} that we infer are not inconsistent with this trend, although the energy gap from ~ 1 to ~ 10 MeV/nuc between the two data sets prevents a precise comparison. Also shown in Figure 5 are preliminary values of Q_{Fe} for the 20 Aug 2002 event obtained from the LICA instrument on SAMPEX using the geomagnetic cutoff method (J. Mazur, private communication; see [17] for a description of the method). Although, in addition to the error bars that are shown, there may be a significant systematic uncertainty (due to the relatively low event intensity compared to the gradual events usually studied with the cutoff method and to the fact that at SAMPEX energies there may be a contribution from another large ^{3}He-rich event that occurred on the preceding day), the SAMPEX data are consistent with the SIS result that indicates a high-energy Q_{Fe} value > 20 in this event.

The indirect technique we are using allows the determination of Q values from measured elemental abundance enhancements for a wide range of elements. Because of the large fractionation exponents found in ^{3}He-rich events, high-precision measurements of the enhancements are not required to obtain useful estimates of Q. In Figure 6 we show the ionic charge states derived from measured enhancements relative to carbon for 12 elements in the 20 Aug 2002 event. These are expressed in the form $Z - Q_Z$, which is the mean number of attached electrons. To obtain values of Q_Z from the charge state ratios Q_Z/Q_C we have assumed that carbon is fully stripped. The inferred numbers of attached electrons follow a simple pattern of step increases (between $Z = 6$ & 7, 8 & 10, and 16 & 18.) with relatively constant values in between. The plateau with 2 attached electrons (He-like ions) between Ne and S was previously inferred [18] based on elemental abundances in this region together with the fact that these elements should have two attached electrons in a thermal

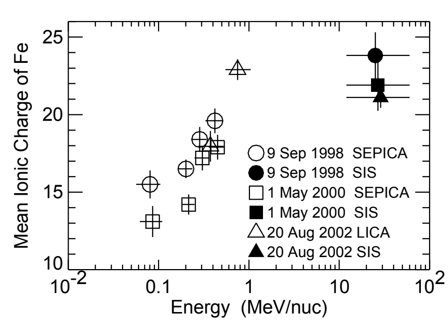

Fig. 5: Comparison of Q_{Fe} values inferred from our SIS analysis with measurements in the same events by ACE/SEPICA and SAMPEX/LICA at lower energies. Points for different events have been displaced slightly in energy to improve legibility.

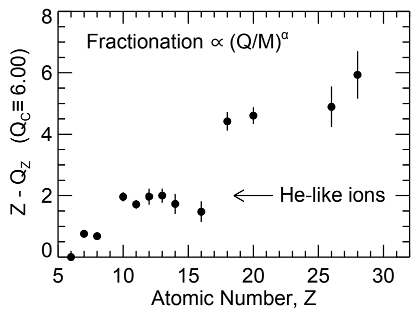

Fig. 6: Inferred ionic charge states for a number of elements in the 20 Aug 2002 event. Charge states are expressed in the form $Z - Q_Z$, the mean number of attached electrons.

population of material over a wide range of temperatures between 1 and 10 MK.

IV. Discussion

Adopting the inferred pattern of charge states shown in Figure 6, one can account for much of the structure seen in the elemental enhancements (Fig. 1). For a fractionation law of the form $(Q/M)^{\alpha}$ with a negative value of α, increases in Q lead to decreases in the abundance enhancement and increases in M cause enhancement increases. Thus going from C to N we find that Q remains unchanged (because the unit increase in Z is balanced by the addition of one orbital electron) while M increases by 2, causing N to have a larger enhancement than C. From N to O, Q increases by a factor 7/6 and M by a smaller factor of 16/14, so the enhancement decreases. Between O and Ne, Q increases by 8/7 and M by a larger factor of 20/16, causing the enhancement peak at Ne. Going from Ne to Mg to Si to S, Q increases by 2 with each step (constant number of attached electrons) while M increases by 4 per step. Since $Q/M < 1/2$ for these ions (because they are not fully stripped), each successive step makes a modest increase in Q/M causing a gradual downward slope in the enhancement versus Z. An exception to this smooth variation occurs for Al, which has $M = 2Z + 1$ rather than having $M = 2Z$ as do the dominant isotopes of Ne, Mg, Si, and S. This extra mass unit leads to the peak in the enhancement pattern at Al. (A similar effect that would be expected for Na, another element with $M = 2Z + 1$ is not evident, possibly because the neutron-rich isotopes of Ne and Mg have large enough abundances to obscure it.) The step up in the number of attached electrons by ~2 units between S and Ar leaves Q unchanged while M increases by 36/32, producing the sizeable step up in the enhancement factor. Going from Ar to Fe, the increase in the number of attached electrons and the increase in the neutron excess ($M \approx 2Z + 4$ for Fe) cause Q/M to remain relatively constant, thereby creating the plateau in the abundance pattern.

The fact that most of the ^{3}He-rich SEP events shown in Figure 1 have enhancement patterns with the same qualitative features suggests that the charge state pattern shown in Figure 6 is a common characteristic of ^{3}He-rich SEP events, or at least of that subset of events with hard enough heavy ion energy spectra to be measurable above 10 MeV/nuc.

It should be recognized that the ionic charge states inferred in this type of analysis correspond to the state of the material when the fractionation is taking place. They need not correspond to charge states in the SEPs detected in interplanetary space. The fact that the inferred values of Q are comparable to or larger than those obtained by direct measurements below 1 MeV/nuc (Fig. 5) indicate a fractionation process taking place after the acceleration and stripping in the sub-MeV range.

As mentioned above, fractionation as a power-law in $f(Q)/M$ for any function of the charge states, $f(Q)$, would be consistent with the isotopic fractionation we observe. We have considered the alternative possibility that the fractionation may go as a power law in Q^2/M [19], since this parameter determines the rate of energy losses to Coulomb collisions during stochastic acceleration. This assumption leads to the very different conclusion that the fractionation takes place when charge states are essentially identical to those characteristic of the quiescent corona, requiring that fractionation occur before acceleration and stripping. It may be possible to distinguish between these two fractionation scenarios by applying the technique discussed here for inferring charge states from isotopic and elemental composition to observations at energies below 1 MeV/nuc where the results can be compared with direct charge state measurements.

Acknowledgments

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