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Evidence for a Two-Stage Acceleration Process in Large Solar Energetic Particle Events

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Abstract Using high-resolution mass spectrometers on board the Advanced Composition Explorer (ACE), we surveyed the event-averaged ~0.1–60 MeV/nuc heavy ion elemental composition in 64 large solar energetic particle (LSEP) events of cycle 23. Our results show the following: (1) The Fe/O ratio decreases with increasing energy up to ~10 MeV/nuc in ~92% of the events and up to ~60 MeV/nuc in ~64% of the events. (2) The rare isotope ^{3}He is greatly enhanced over the corona or the solar wind values in 46% of the events. (3) The heavy ion abundances are not systematically organized by the ion's M/Q ratio when compared with the solar wind values. (4) Heavy ion abundances from C–Fe exhibit systematic M/Q-dependent enhancements that are remarkably similar to those seen in ^{3}He-rich SEP events and CME-driven interplanetary (IP) shock events. Taken together, these results confirm the role of shocks in energizing particles up to ~60 MeV/nuc in the majority of large SEP events of cycle 23, but also show that the seed population is not dominated by ions originating from the ambient corona or the thermal solar wind, as previously believed. Rather, it appears that the source material for CME-associated large SEP events originates predominantly from a suprathermal population with a heavy ion enrichment pattern that is organized according to the ion's mass-per-charge ratio. These new results indicate that current LSEP models must include the routine production of this dynamic suprathermal seed population as a critical pre-cursor to the CME shock acceleration process.

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1 Introduction

Early observations of solar energetic particle or SEP events extending up to GeV energies were made with ground-based ionization chambers and neutron monitors (Forbush 1946; Meyer et al. 1956). Such events, also known as ground level events or GLEs, were closely associated with the maximum of Hα flares on the Sun. Consequently, it was presumed that there was a causal relationship between the flare and the energetic particles observed at 1 AU.

Later, however, on the basis of a close association between SEP events and slow-drifting Type II and various kinds of Type IV radio bursts, Wild et al. (1963) proposed that the energetic particles might be accelerated at magnetohydrodynamic shock waves that typically accompanied the flares. In addition, Lin (1970) reported that the SEP events observed at 1 AU could essentially be grouped into two types. First, "pure" electron events that were closely associated with flares and metric Type III emission, and second, "mixed" events where protons, relativistic electrons, and flares were associated with Type II/IV radio events. Lin (1970) proposed two distinct acceleration processes for the pure and the mixed SEP events.

Using Skylab observations, Kahler et al. (1978) were the first to report a close association between coronal mass ejections (CMEs) and large solar proton events. They suggested that the CME could either create open field lines for flare particles to escape into the interplanetary medium or that the protons could be accelerated near a region above or around the outward moving ejecta far above the flare site. Subsequently, detailed analyses of flare durations, longitudinal distributions from multi-spacecraft observations, high resolution ionic charge state and elemental composition measurements, and clearer associations with radio bursts led most researchers in the 1990s to accept the view that the SEP events observed at 1 AU belong to two classes, namely impulsive and gradual (e.g., Kahler et al. 1978, 1984; Cliver et al. 1982; Kocharov 1983; Luhn et al. 1984; Mason et al. 1984; Cane et al. 1986; Reames 1988).

In this two-class picture the gradual events occurred as a result of diffusive acceleration of ambient coronal or solar wind material at CME-driven coronal and interplanetary (IP) shocks, while the impulsive events were attributed to stochastic acceleration of coronal material heated up to $\sim$10 MK during magnetic reconnection in solar flares (e.g., Reames 1999). The gradual or CME shock-accelerated events lasted several days and had larger fluences, while the impulsive or flare-accelerated events lasted a few hours and had smaller fluences. Impulsive events were observed when the observer was magnetically connected to the flare site, while ions accelerated at the expanding large-scale CME-driven shocks populate magnetic field lines over a broad range of longitudes (Cane et al. 1988).

The impulsive SEP events were electron-rich and associated with Type III radio bursts. These events also had ^{3}He/^{4}He ratios enhanced between factors of 10^3–10^4 and Fe/O ratios enhanced by up to a factor of 10 over the corresponding solar wind values, and had Fe with ionization states up to $\sim$20. In contrast, the gradual events were proton-rich, were associated with Type II bursts, had average Fe/O ratios of $\sim$0.1 with Fe ionization states of $\sim$14, and were assumed to have ^{3}He/^{4}He ratios similar to those measured in the solar wind (Reames 1999; Cliver 2000).

Since those earlier studies, instruments with greater sensitivity and resolution on board the Advanced Composition Explorer (ACE) (Stone et al. 1998a) have provided three major observational advances, making it possible to re-examine questions about the origin of the seed populations and probe details of the acceleration mechanisms for individual large SEP events. First, the newly developed capability of directly measuring the solar wind ion composition and its variations (Gloeckler et al. 1992; Geiss et al. 1996) has provided definitive solar wind abundances that can be compared with the SEPs. Second, improved ionization state measurements over a broader energy range have enabled us to investigate the energy dependence and the event-to-event variability of the ionic charge states (e.g., Oetliker et al. 1997; Mazur et al. 1999; Möbius et al. 1999, 2000; Klecker et al. 2006). And third, sophisticated mass spectrometers have enabled us to identify many SEP elements over a broad energy range, making it possible to quantify the affects of particle energy spectra on the average abundances.

2 Observations

In this paper we use data from the Ultra-Low-Energy Isotope Spectrometer (ULEIS: Mason et al. 1998) and the Solar Isotope Spectrometer (SIS: Stone et al. 1998b) on board ACE. We selected 64 large SEP events from NOAA's list of 85 solar proton events (SPEs) that affected Earth's environment between November 1997 and January 2005. Hereafter we refer to these 64 events as large SEP events or LSEP events. Details of the selection of events and their sampling intervals were provided by Desai et al. (2006a).

2.1 ^{3}He Enhancements

Figure 1a shows the 0.5–2.0 MeV/nuc ^{3}He and ^{4}He time-intensity profiles in a large SEP event that occurred on June 4, 1999 (from Mason et al. 1999). The temporal profiles of the two species are remarkably similar, which indicates that they probably have the same acceleration and transport history. In this event, the ^{3}He is enriched by a factor of 16 ± 3 while the Fe/O ratio (not shown) is enhanced by about a factor of 10 over the corresponding solar wind values.

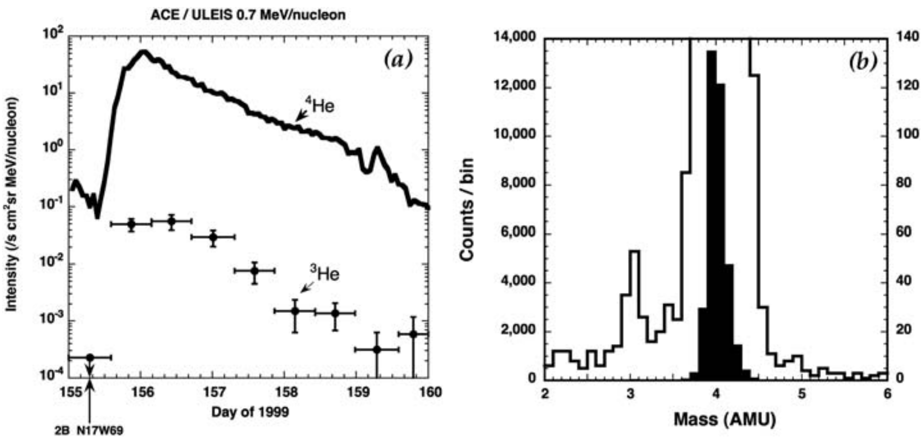


Fig. 1 (**a**) Temporal profiles of ~0.7 MeV/nuc ^{3}He and ^{4}He ions in a large SEP event. (**b**) 0.5–2.0 MeV/nuc He mass histogram obtained during several large SEP events. The *right scale* corresponds to the open histogram (taken from Mason et al. 1999)

In this survey, we find that the 0.5–2.0 MeV/nuc $^3He/^4He$ ratio in 29 of the 64 events (∼46%) is enhanced between factors ∼4–150 over the corresponding solar wind value. Large enrichments in the $^3He/^4He$ ratio are also observed above ∼10 MeV/nuc (e.g., Cohen et al. 1999; Wiedenbeck et al. 2000). Figure 1b shows the ∼1 MeV/nuc He mass histogram from several such events. Notice that the ^3He is clearly resolved from ^4He and the background. In summary, our results (see Desai et al. 2006a) indicate the presence of flare-accelerated material during a sizable fraction of large SEP events of cycle 23.

2.2 Heavy Ion Abundances

Table 1 provides the 0.32–0.45 MeV/nuc heavy ion abundances averaged over 64 large SEP (LSEP) events and those measured in a variety of heliospheric populations. The LSEP averages are the arithmetic mean values for the 64 event sample; the abundances for each event are obtained by taking ratios of the fluences integrated over the duration of the event. Figure 2 compares the large SEP abundances with the solar wind values (von Steiger et al. 2000), as a function of M/Q ratio. The charge states are average values measured in the slow solar wind (from von Steiger et al. 1997). These are: He^{2+}, $C^{5.38+}$, $N^{5.47+}$, $O^{6.05+}$, $Ne^{7.97+}$, $Mg^{9.5+}$, $Si^{8.57+}$, $S^{8.75+}$, $Ca^{9.02+}$, and $Fe^{9.84+}$.

From Fig. 2 we note the following: (1) The LSEP abundances are poorly correlated with the solar wind values. (2) C, N, O, Ne, and Mg have similar M/Q values but exhibit highly unsystematic enhancements and depletions relative to the solar wind values, with C in particular being depleted by about a factor of 2. (3) The abundances of Si, Ca, and Fe are enhanced relative to the solar wind values.

Figure 3 shows the energy-dependent behavior of Fe/O in 37 of the 64 large SEP events in this survey. The Fe/O ratios are 0.11–0.14 MeV/nuc from ULEIS (Desai et al. 2006a); 3.3–10 MeV/nuc from LEMT (Reames and Ng 2004); and 12–60 MeV/nuc from SIS (Desai et al. 2006a). Note that the Fe/O ratio either decreases or remains constant with increasing

Table 1 Heavy ion abundances in 64 Large SEP events at ACE, compared with those measured in other solar and heliospheric populations

Species	Large SEPs[a]	Slow SW[b]	ISEPs[c]	Photosphere[d]	Corona[e]
^4He	75.0±23.6	95.9±28.8	54±14	162±14	126±11
C	0.361±0.012	0.670±0.067	0.322±0.003	0.501±0.058	0.490±0.056
N	0.119±0.003	0.069±0.021	0.129±0.002	0.138±0.022	0.123±0.020
O	≡ 1.0±0.02	≡1	≡ 1.0±0.06	≡ 1.0±0.161	≡ 1.0±0.161
Ne	0.152±0.005	0.091±0.027	0.261±0.003	0.151±0.021	0.191±0.026
Mg	0.229±0.007	0.147±0.030	0.370±0.003	0.072±0.009	0.224±0.026
Si	0.235±0.011	0.167±0.034	0.409±0.004	0.071±0.007	0.214±0.022
S	0.059±0.004	0.049±0.010	0.118±0.015	0.032±0.008	0.032±0.008
Ca	0.022±0.002	0.017±0.003	0.060±0.003	0.005±0.0001	0.013±0.0002
Fe	0.404±0.047	0.120±0.024	0.950±0.005	0.061±0.006	0.186±0.017

[a] 0.32–0.45 MeV/nuc, from Desai et al. (2006a)

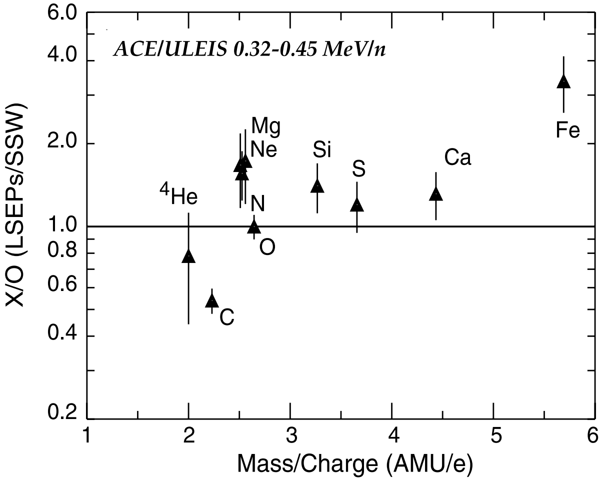
[b] From von Steiger et al. (2000); Ca/O ratio is from Wurz et al. (2003)

[c] ∼0.385 MeV/nuc, from Mason et al. (2004)

[d] From Lodders et al. (2003)

[e] ∼1.4 MK quiet corona, from Feldman and Widing (2003)

Fig. 2 Average abundances measured in 64 large SEP events between 0.32–0.45 MeV/nuc divided by the corresponding slow solar wind values, plotted versus the ion M/Q ratio



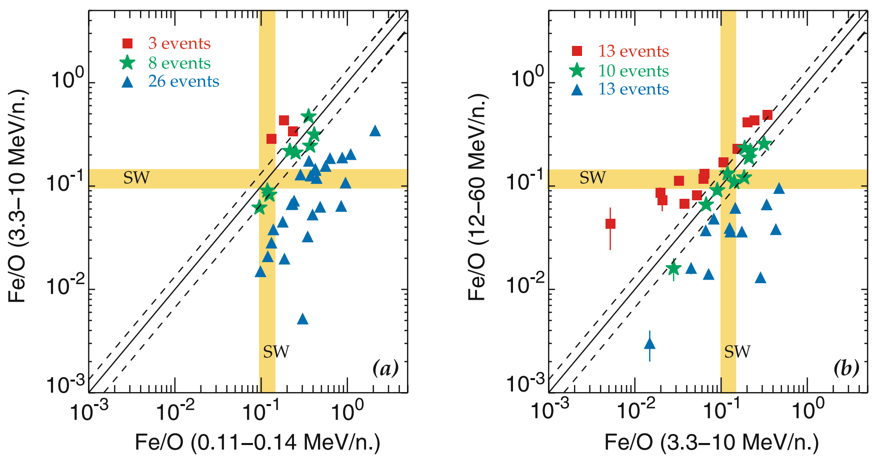


Fig. 3 (**a**) Fe/O ratio measured at 0.11–0.14 MeV/nuc versus that measured at 3.3–10 MeV/nuc for 37 large SEP events. (**b**) Fe/O ratio measured at 3.3–10 MeV/nuc versus that measured at 12–60 MeV/nuc for 36 SEP events. *Yellow bands* represent error limits for the Fe/O ratio measured in the slow solar wind (adapted from Desai et al. 2006a)

energy in 34 of the 37 events (∼92%) up to ∼10 MeV/nuc and in 26 of the 36 events (∼64%) up to ∼60 MeV/nuc. However, an unexpected and puzzling feature of Fig. 3a is that the low-energy Fe/O ratio between 0.11–0.14 MeV/nuc in most of the LSEP events (55 of the 64 events; see Desai et al. 2006a) is enhanced when compared with the average solar wind value.

2.3 Mass-per-Charge Dependent Fractionation

An important question arises: What mechanisms are responsible for the large enhancements and the event-to-event variability seen in the low-energy Fe/O during the LSEP events of cycle 23? This section investigates whether these enhancements are systematically organized by the ion's mass-per-charge (M/Q) ratio. Other surveys of large SEP abundances above

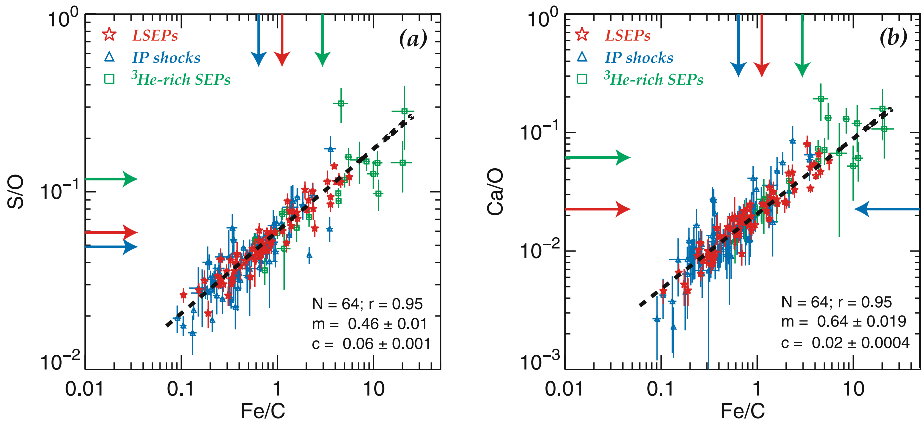


Fig. 4 (**a**) S/O and (**b**) Ca/O plotted versus Fe/C ratio at 0.38 MeV/nuc for three different types of events. *Blue triangles* = IP shock events of Desai et al. (2003); *red asterisks* = SEP events in this survey; and *green squares* = ^{3}He-rich SEP events of Mason et al. (2004). *Colored arrows along the axes* represent the average values of the respective populations. *Dashed black* line represents the linear fit to the large SEP data. The quantities N and r represent the number of SEP events and the correlation coefficient. The quantities m and c represent the slopes and intercepts of the linear fits (taken from Desai et al. 2006a)

~5 MeV/nuc (e.g., Mewaldt et al. 2007) have shown that the abundances of elements with First Ionization Potential or FIP $\lesssim$10 eV like Fe, Ca, and S are enhanced by about a factor of ~2.5 relative to those that have higher FIP values like C and O.

Thus, to examine the M/Q-dependent fractionation of ions with higher M/Q values compared to those with lower M/Q values, we first need to minimize the FIP fractionation effect discussed earlier. We do this in Fig. 4 by plotting the event-averaged abundances of S, Ca, and Fe (i.e., low FIP elements) relative to C and O (i.e., high FIP elements) and then plot (a) the S/O ratio and (b) the Ca/O ratio versus the Fe/C ratio at ~0.38 MeV/nuc for the 64 LSEP events in our survey.

Figure 4 also compares the LSEP abundances with those seen in IP shock events of Desai et al. (2003) and ^{3}He-rich SEP events of Mason et al. (2004). The dashed line represents a linear fit to the LSEP data with slope m and intercept c. We remark that the slopes and intercepts of the linear fits obtained independently by fitting the data for IP shocks (blue) and ^{3}He-rich events (green) are well within the respective 1σ error limits of the fit parameters for the three types of events.

Figure 4 shows the following: (1) Enhancements in the S/O and Ca/O ratios are accompanied by simultaneous enhancements in the Fe/C ratio. (2) The fits to the data provide an excellent representation of the event-to-event variations and the enhancement pattern of the heavy ion abundances in large SEP events. (3) For each element, the power-law dependence in large SEP events provides remarkably good fits to the corresponding event-to-event variations seen in IP shock events and in ^{3}He-rich SEP events.

3 Discussion

Our survey of the ~0.1–60 MeV/nuc heavy ion abundances in 64 large SEP events of cycle 23 shows the following:

- The Fe/O ratio decreases with increasing energy in ∼92% of the events up to ∼10 MeV/nuc and in ∼64% of the events up to ∼60 MeV/nuc.
- The rare isotope ^{3}He is greatly enhanced over the corona or the solar wind values in 46% of the events.
- The heavy ion abundances show large, variable, and unsystematic enhancements and depletions relative to the solar wind values.
- Event-to-event variations in the heavy ion abundances in LSEP events are organized according to the M/Q ratio and are remarkably similar to those seen in ^{3}He-rich SEP events and IP shock events.

3.1 Two-Stage Acceleration in Large SEP events

We now discuss the implications of these results for the acceleration mechanisms operating in large SEP events. Rigidity-dependent shock acceleration processes tend to deplete the abundances of heavier ions when compared with the lighter ions (e.g., Klecker et al. 1981; Cane et al. 1991; Desai et al. 2003, 2004). Figure 3 shows that the Fe/O ratio decreases with increasing energy in the majority of the LSEP events in our survey. Such systematic energy dependence of the SEP Fe/O ratios were also reported by a number of previous studies (e.g., Mazur et al. 1992; Tylka et al. 2005; Cohen et al. 2005; Mewaldt et al. 2006). Likewise, the Fe/O ratios in individual CME-driven IP shock events at ACE also exhibited similar spectral properties (see Desai et al. 2003, 2004), and are consistent with the behavior predicted by shock acceleration models (e.g., Lee 2005) in which ions with higher M/Q ratios are accelerated less efficiently than those with lower M/Q ratios.

However, the ^{3}He/^{4}He ratio (Fig. 1b) and the heavy ion abundances in large SEP events (Figs. 3a and 4) are significantly enhanced relative to the slow solar wind or the ambient coronal abundances (see Mason et al. 1999; Cohen et al. 1999; Desai et al. 2006a). Since ^{3}He has a smaller M/Q ratio than ^{4}He while ions such as Fe have a larger M/Q ratio than O, such large simultaneous enrichments are difficult to reconcile with rigidity-dependent shock acceleration of solar wind material. This implies that the dominant seed population for the majority of the large SEP events could not have originated either from the thermal or suprathermal solar wind or from the ambient corona (see also Mewaldt et al. 2002, 2006).

In fact, taken together Figs. 3 and 4 indicate the occurrence of *two* distinct M/Q-dependent fractionation processes in the same large SEP event. The first process results in producing M/Q-dependent enhancements, similar to those seen in the ^{3}He-rich SEP events, while the second process—probably due to shock acceleration—causes the Fe/O ratio to decrease with increasing energy.

Previously, Desai et al. (2003) found that the heavy ion abundances in CME-driven IP shocks were related to those measured in the ambient suprathermal population measured prior to the arrival of the shocks at 1 AU according to the simple relation $\log(\Gamma_X) = c + m[(M_X Q_O)/(M_O Q_X)]$, where $c = 0.59 \pm 0.06$, and $m = -0.62 \pm 0.06$, and (M_X/Q_X) is the M/Q ratio of element X. Here $\Gamma_X = (X/O)_S/(X/O)_A$ is the enhancement or depletion of the X/O ratio in IP shocks, $(X/O)_S$ relative to that in the suprathermal population, $(X/O)_A$ (see Fig. 12 of Desai et al. 2003).

We infer average abundances for the "source" population by applying this function to the survey-averaged large SEP abundances provided in Table 1. Since CME-driven IP shocks depleted the abundances of heavier ions more than those of the lighter ions, using this function results in the inferred source population for large SEP events to be even more abundant in heavier ions than the average abundances reported here (see Desai et al. 2006a).

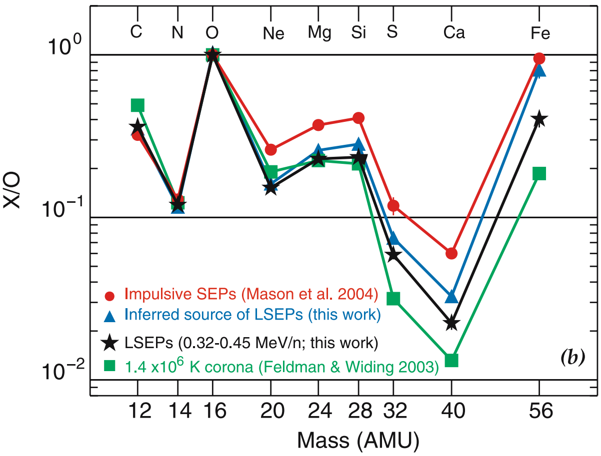


Fig. 5 Average abundances measured in 64 large SEP events, compared with those measured in ^{3}He-rich SEP events (from Mason et al. 2004) and in the ∼1.4 MK quiet corona (from Feldman and Widing 2003). Also shown are the inferred source abundances for large SEP events of cycle 23

Figure 5 compares the inferred source population with spectroscopic measurements of the ∼1.4 MK quiet corona (Feldman and Widing 2003), average values measured in ^{3}He-rich SEP events (Mason et al. 2004), and large SEP events as a function of atomic mass. Clearly, the heavy ions in the inferred source population are greatly enhanced over the quiet coronal values. Assuming that the inferred source abundances are a simple linear mixture of ambient coronal and heavy ion enriched impulsive flare-like material with no energy dependence, we find that more than 75% of the seed population must comprise material that is already enriched in heavy ions.

3.2 Role of Flares Versus CME-Driven Shocks

Figure 3 shows that the Fe/O decreases or remains constant with increasing energy up to ∼60 MeV/nuc in ∼64% of the events, and is therefore consistent with the rigidity-dependent effects of the CME-driven shock acceleration processes observed near 1 AU (e.g., Desai et al. 2004). This result taken together with observations of species-dependent spectral breaks (e.g., Cohen et al. 2005; Mewaldt et al. 2005) therefore points to acceleration at CME-driven shocks as the dominant process in the majority of LSEP events of cycle 23.

However, for ∼36% of the events there is a decrease in Fe/O around ∼3–10 MeV/nuc followed by an increase at the higher energies. This behavior is puzzling and could point to a separate mechanism operating at these high energies e.g., a direct Fe-rich acceleration event at or near the Sun (e.g., Cane et al. 2003, 2006), or perhaps the re-acceleration of a flare seed population with Fe/O ratios that increase with energy (e.g., Tylka et al. 2005). No doubt other possibilities exist as well, and we believe that there is insufficient data to resolve the issue at this time.

3.3 Origin of the Seed Population for Large SEP Events

An important question is what is the origin of the seed population for CME-driven shocks that produce large SEP events? Since tracer ion species like ^{3}He and interstellar pickup He^+ are extremely rare in the solar wind (Gloeckler and Geiss 1998), their mere presence during IP shock associated energetic particle events (see e.g., Desai et al. 2001; Kucharek et al. 2003) points to a seed population comprising suprathermal ions with speeds more than twice the bulk solar wind speed.

Such suprathermal ions probably have at least two advantages over the thermal solar wind ions. First, they have higher speeds that presumably exceed the injection threshold speeds typically associated with IP shocks. Second, they have broader velocity and nearly isotropic angular distributions when compared with the narrower velocity and anisotropic distributions of the thermal solar wind ions (Giacalone et al. 1994; Scholer et al. 1999).

In fact, Gloeckler (2003) reported the presence of a suprathermal ion population between ∼2–10 times the solar wind speed even in the absence of solar activity and interplanetary shocks. Presently, however, the origin of this suprathermal material is not clear. Indeed, many sources such as interstellar and inner source pickup ions, heated solar wind ions, and ions accelerated in prior solar and interplanetary activity are known to contribute to this energy regime (e.g., Mason 2000; Mewaldt et al. 2001; Mason et al. 2005).

One possibility is that flares provide much of the suprathermal seed population for CME-driven shocks near the Sun and in interplanetary space. Support for this is bolstered by the fact that ^{3}He enrichments are seen in the interplanetary medium for most of the time during solar active periods (e.g., Wiedenbeck et al. 2003; Desai et al. 2006b), perhaps indicating that a quasi-continuous mechanism (e.g., micro-flares) rather than short-lived episodes replenishes the solar corona and the interplanetary medium with suprathermal ions. Further evidence for this scenario was provided by Desai et al. (2006b) who found that the 80–100 keV/nucleon suprathermal heavy ion population during quiet times was remarkably similar to that measured in SEP events during solar maximum from 1998–2004, but similar to solar wind/CIR values during solar minimum conditions of 1994–1997, and 2005.

Another possibility is that the heavy ion enriched suprathermal seed population originates from flares that typically accompany the CMEs (e.g., Li and Zank 2005 and the references therein). However, even though the ^{3}He enrichments indicate the presence of impulsive-flare-accelerated material in the seed population, neither scenario can satisfactorily account for the relatively low ^{3}He/^{4}He ratios ($<10\%$) that are accompanied by the substantially large Fe/O ratios (∼1) in many of the large SEP events of cycle 23 (see Mewaldt et al. 2006; Desai et al. 2006a).

Other possibilities are (1) a common, unidentified mechanism produces the heavy-ion enriched suprathermal seed population, (2) heavy ions from the ambient corona or the solar wind are heated preferentially to produce a heavy-ion-enriched suprathermal tail, and (3) heavy ions are preferentially injected into the shock-acceleration process. New measurements from future missions like the Solar Orbiter and the Inner Heliospheric Sentinels will enable us to better understand the origin of this suprathermal seed population.

4 Conclusions

The new composition results obtained over solar cycle 23 can no longer be reconciled with the 1990s viewpoint that the large SEP events are produced by the acceleration of ambient coronal or solar wind material at CME-driven shocks near the Sun and in interplanetary space. Instead, any new comprehensive model for most of the large SEP events of cycle 23 must involve at least two steps: first, the routine production of a heavy-ion enriched suprathermal seed population, and second, CME shock acceleration of this material resulting in species-dependent spectral breaks and the decrease of Fe/O with increasing energy.

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