A Possible Mechanism for Enriching Heavy Ions in \(^3\)He-rich Solar Energetic Particle Events

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Abstract

We investigate a mechanism to produce a seed population enriched in heavy ions, such as those observed in \(^3\)He-rich solar energetic particle events. It is shown that if an initial particle population following a power law in energy nucleon\(^{-1}\) passes through a small amount of material, at energies below the \(dE/dx\) Bragg peak, the greater affinity of heavier ions for electron pick-up results in their penetrating the material more easily. This results in an enhancement of heavy ions in the particle population that just barely penetrates the material. The bulk of the seed particles fall in the energy range of 10 s of keV nucleon\(^{-1}\). It is supposed that some further process then energizes this seed population to produce the particles observed in interplanetary space. We find a broad range of parameters that produces enhancements comparable to Fe/O ~ 8 commonly observed.

Key words: Sun: flares – Sun: magnetic fields – Sun: particle emission

1. Introduction

Solar energetic particle (SEP) events with enormous (>1000 ×) enhancements of \(^3\)He have long been studied because their unique composition pointed to an acceleration mechanism distinct from that operating in large solar particle events whose ion composition more nearly resembles the solar corona and solar wind (see reviews by Kocharov & Kocharov 1984; Klecker et al. 2006a; Mason 2007; Reames 2017). Early spacecraft instrumentation observed only occasional \(^3\)He-rich SEP events, but with improved sensitivity and lower energy thresholds, experiments on the Advanced Composition Explorer found that \(^3\)He enrichments in the range of \(\sim 0.5-\)several MeV nucleon\(^{-1}\) were in fact present in the interplanetary medium up to 90% of the days during solar active periods (Wiedenbeck & Mason 2014). Individual \(^3\)He-rich SEP events have been associated with solar jets and the eruption of narrow CMEs (Wang et al. 2006; Nitta et al. 2008), pointing to an origin associated with active regions. This view is reinforced by a close statistical association with the occurrence of these events and sunspot number over the solar cycle (Reames et al. 1994; Wang et al. 2012; Wiedenbeck & Mason 2014).

Early studies also showed that \(^3\)He-rich SEP events were enriched in heavy ions up to Fe (Gloeckler et al. 1975; Hurford et al. 1975; Zwicky et al. 1978; Möbius et al. 1982). Later studies showed that this enhancement continues beyond Fe to masses as high as 200 amu; though, the extreme rarity of such ultra-heavy (UH, 78–220 amu) nuclei limits the ability for us to study events in the detail obtained for Fe and lighter elements (Reames 2000; Mason et al. 2004). Compared to oxygen, the enrichment of heavy elements increases with mass, such that Fe is \(\sim 8\) times larger than for large SEP events or other source populations, such as the solar wind, and so, although clearly associated with the \(^3\)He-rich SEPs, the Fe enhancement is relatively modest, and it does not correlate with the \(^3\)He/\(^4\)He ratio on an event by event basis (Mason et al. 1986; Reames et al. 1994). For elements with mass > 100 amu the enrichment factor is \(\sim 100-200\) (Mason et al. 2004; Reames & Ng 2004).

Although a number of explanations for the extreme enhancement of \(^3\)He have been published, the most widely accepted mechanism is based on its unique charge-to-mass ratio, which could preferentially interact with plasma waves much more strongly than other ions (e.g., Fisk 1978; Möbius et al. 1982; Kocharov & Orischenko 1983; Temerin & Roth 1992; Zhang 1995; Miller & Reames 1996; Drake et al. 2009; Petrosian 2012; Eichler 2014). This could pre-heat a population enriched in \(^3\)He that is then accelerated by an additional process associated with a narrow CME or jet, leading to the multi-MeV nucleon\(^{-1}\) population observed in interplanetary space.

Fisk (1978) and others proposed that the plasma frequencies that preferentially heat the \(^3\)He could have a second harmonic that could interact with partially stripped heavy ions whose gyrofrequencies fell in the favored range. It was therefore surprising when experiments observed \(^3\)He-rich SEP heavy ionization states and found these ions to be nearly or fully stripped (Klecker et al. 1984; Luhn et al. 1987). More recently, it was shown that Fe ionization states strongly decreased in the range below \(\sim 0.5\) MeV nucleon\(^{-1}\) (Möbius et al. 2003; Klecker et al. 2006b), so that the very high temperatures inferred from the earlier higher energy measurements could not represent the original population. Instead, this energy dependence was taken as evidence of another process, namely stripping of the Fe as it passed through a hot plasma. In this case, at low energies the Fe charge state reflects the plasma temperature, while at higher energies the increased charge state is due to stripping interactions with the plasma (Klecker et al. 2006b).

This mechanism addresses the Fe charge states, it does not address the enhanced abundance of Fe observed in \(^3\)He-rich SEPs.

Most of the models for heavy ion enrichment were developed before the enrichment of UH nuclei was known, and so they do not address this feature. Nevertheless, the range of charge-to-mass ratios for the UH nuclei lies well outside that
for Fe and lighter elements, and so their enrichment does not have an obvious explanation regarding the kinds of resonance conditions proposed in many of the models. Kartavykh et al. (2011a, 2011b) have explored another mechanism where the enrichment of heavy ions is due to an interplay between Coulomb loss rates and acceleration rates, assuming stochastic acceleration with simultaneous charge stripping. However, in these models, the enrichment factors depend sensitively on the plasma parameters, acceleration timescales, and the frequency spectrum of the Alfvénic wave turbulence, and the observed enrichment factors can only be reproduced for a limited range of these parameters. In summary, while much progress has been made, there is still no satisfactory model for the heavy ion enrichments observed in ³He-rich SEP events.

The Fisk (1978) mechanism for ³He enrichment was a heating mechanism that produced a seed population enriched in ³He but did not specify an acceleration mechanism that energized the particles to the energies observed in the SEP event. In this paper, we similarly propose a mechanism that produces heavy ion enrichments in a seed population that is then further accelerated by an unspecified mechanism. The scenario in our model is as follows:

1. A particle population of normal SEP abundances is produced up to ∼1 MeV nucleon⁻¹ by an unspecified stochastic or shock-associated process; the particle energy spectra are a power law that is the same for all elements.
2. The particles then pass through a small amount of material.
3. The heavier ions have lower charge-to-mass ratios than the lighter ones at the same energy nucleon⁻¹, and so their ionization energy loss rate, per nucleon, is less. This allows the heavy ions to pass through the material more easily.
4. The resulting population is enriched in heavy ions, which are then further accelerated to the energies observed in the SEP event.

There is a great deal of uncertainty regarding the specification of the stopping power in a coronal plasma, so below we first illustrate the effect on a gas of H at ambient, and then sketch out the case at higher temperatures.

2. Model Calculations

2.1. Hydrogen Gas

Figure 1 shows the total (nuclear + electronic) dE/dx for O and Fe in H gas, using tables from the 2013 version of Stopping and Range of Ions in Matter (SRIM; Ziegler et al. 2008, 2010). At high energies, the dE/dx depends on the square of the ion charge, so the dE/dx for Fe is about 10 times higher than for O. Below the Bragg peak near 1 MeV nucleon⁻¹, however, the more highly charged Fe picks up electrons from the gas more easily than O, and the separation of the Fe and O curves decreases. Per unit mass, this allows the Fe to move more easily through gas. Generally, ions with masses intermediate between O and Fe fall between the two curves, while ions heavier than Fe lie above it.

Using these dE/dx values, we assume an initial particle population following a differential intensity that is a power law in energy nucleon⁻¹, dJ/dE ∝ E⁻³. This population then passed through a thickness of H gas, producing spectra such as those shown in Figure 2. In the figure, the O and Fe abundances are set to the same value at high energy, so that the spectra after passing through the material show relative changes in abundance at a given MeV nucleon⁻¹. Note that at energies above a few MeV nucleon⁻¹ there is no substantial change in either the shape or relative abundances, but at energies near the Bragg peak and below large changes occur. Each point on the original spectrum is moved to lower energies by the amount of energy loss in the H gas, with a correction for width of each ΔE energy window.

The 200 µg cm⁻² of H gas in this example stops O below about 230 keV nucleon⁻¹, and Fe below about 85 keV nucleon⁻¹ (red and blue arrows in Figure 2). For the E⁻³ spectrum, the
number of particles at energies above the blue arrow are about 7.3 times greater than above the red arrow, and this results in the enhanced abundance of Fe at lower energies. The figure shows that this enhancement reaches large values for slowed particles that have lost most of their original energy.

We now examine the dependence of enhancements on the thickness of the H target and the original power-law spectral index. To characterize the enhancement in each case, the spectra are integrated from the threshold energies for each ion. Thus, in Figure 2, the Fe/O enrichment is proportional to \( \left( \frac{E_{0,Fe}}{E_{0,O}} \right)^{-2} = \left( \frac{0.085}{0.230} \right)^{-2} = 7.3 \). Figure 3 shows the Fe/O enhancement for \( E^{-3} \) original spectra passing through different thicknesses of H gas. At both low and high grammages of H there is little effect, but the enhancement grows as the energy approaches the Bragg peak and then declines again. The small effect at low grammages arises simply from the fact that in those cases the original spectra are little affected by the material. The small effect at high grammages is due to the fact that the critical differences between the \( dE/dx \) of O and Fe are operating over only a relatively small energy range and thus do not affect the result a great deal if the particles have large ranges in H.

The figure shows a peak in the Fe/O ratio of about 8 at 200–250 \( \mu \text{g cm}^{-2} \) with a FWHM covering the range from about 110 to 380 \( \mu \text{g cm}^{-2} \).

Figure 4 shows the dependence of the Fe/O ratio for the case of different original power laws passing through 250 \( \mu \text{g cm}^{-2} \) of H. The enhancement increases as the original power law becomes steeper, which is due to the fact that with the steeper power law the different threshold energies for which Fe and O penetrate the H will have a stronger effect on the relative numbers of particles that make it through. For example, for a spectral index of \(-3\) in Figure 2, about 8 times as many Fe penetrate the H as do O ions, but for a spectral index of \(-5\), over 60 times the number of Fe make it through the H compared to O.

Figure 3. Enhancement in Fe/O after passing through different grammages of H gas. Original spectra were an \( E^{-3} \) power law. Upper x-axis shows the energy of O that is stopped by the gas.

Figure 4. Enhancement in Fe/O after passing through 250 \( \mu \text{g cm}^{-2} \) of H gas vs. power-law spectral index of the original population.

Figure 5. Blue points: calculated enhancement of different ions after passing through 200 \( \mu \text{g cm}^{-2} \) of H gas for original spectra with indices of \(-3\) and \(-4\). Red points: observed enhancements in \(^3\text{He}\)-rich SEP events (Mason et al. 2004). The figure shows that spectral indices between about \(-3\) and \(-4\) yield Fe/O enhancements of \( \sim 10 \times \).

The figure shows that the differences between the enhancements for Fe and below are not very sensitive to the original spectral index, but at the very high masses the sensitivity is quite strong. The outlier ion below 100 amu is Ni, whose calculated
enhancement is much larger than nearby elements. This is due to the SRIM \( \frac{dE}{dx} \) curve for Ni falling below Fe between \( \sim 20 \)–200 keV nucleon\(^{-1}\).

2.2. High Temperature Plasma

Although the calculations above, using an H gas target, illustrate the basic mechanism, it is desirable to describe the process in a high temperature plasma more nearly resembling the corona. This is necessarily very approximate because the corona has a wide range of temperatures and densities, and it is not known which would be appropriate for \(^3\)He-rich SEPs. Kartavykh et al. (2008) have modeled ionization of heavy ions at coronal temperatures, and Figure 3 of their paper shows that equilibrium is obtained for \( \tau N \) values of \( \sim 10^{10}\) s cm\(^{-3}\), where \( \tau \) is time and \( N \) is the electron density. For 10 keV nucleon\(^{-1}\) protons in a H gas, this corresponds to a traversed grammage of about 2.5 \( \mu \)g cm\(^{-2}\), and so in the calculation above the value of 200 \( \mu \)g cm\(^{-2}\) is well above the limit expected to achieve ionization equilibrium. We therefore approximate the electronic stopping power \( \frac{dE}{dx} \) of an ion by

\[
\frac{dE}{dx}(Z, v) = \frac{dE}{dx}(p, v)Q^2, \tag{1}
\]

where \( Z \) = nuclear charge, \( p \) denotes protons, \( v \) = ion velocity, and \( Q \) is the mean charge state of the ion in a hot plasma. We used the SRIM \( \frac{dE}{dx} \) table for H gas, and extended it to energies below 100 keV nucleon\(^{-1}\) using the NIST online proton table. The charge state \( Q \) was calculated using ionization and recombination cross sections for ions moving in a plasma characterized by a Maxwellian distribution function with electron temperature \( T_e \) (Luhn & Hovestadt 1987; Luhn et al. 1987; Kocharov et al. 2000; Kovarstev et al. 2001). Ionization and recombination rates were from Arnaud & Raymond (1992), Mazzotta et al. (1998), and Mattioli et al. (2007).

Figure 1 shows \( \frac{dE}{dx} \) in a 300,000 K H plasma calculated in this manner for O and Fe (dashed lines). At the highest energies, the H gas and high temperature curves meet, as expected from Equation (1) because at high energies the ions are fully stripped. At low energies the \( \frac{dE}{dx} \) in the hot plasma is much higher because the plasma electrons strip electrons from the O and Fe that would otherwise have been captured, lowering their \( Q \) state. Nevertheless, below 100 keV nucleon\(^{-1}\) the O and Fe \( \frac{dE}{dx} \) slope in the plasma is negative, and the two \( \frac{dE}{dx} \) curves are considerably closer to each other than at high energies. This will lead to the same sort of Fe enrichment compared to O seen in the H gas, though, at different energies. At intermediate energies of a few hundred keV nucleon\(^{-1}\), the high temperature O and Fe curves diverge, and there is also structure that is caused by various shell effects. This behavior is qualitatively different from the H gas \( \frac{dE}{dx} \) curves and can introduce effects not seen in the H gas.

Figure 6 plots the enhancement of Fe/O for different plasma temperatures and grammages assuming an original power-law spectral index of \(-2.5\). Note that as the temperature rises, the peak enhancement moves to lower and lower grammages. This arises directly from the higher \( \frac{dE}{dx} \) at low energies shown in Figure 1, which increase with temperature. The peak Fe/O enhancement decreases above 500,000 K because the hotter plasma maintains Fe in a higher charge state down to low energies, so the spacing between the Fe and O \( \frac{dE}{dx} \) curves remains larger than that seen in Figure 1. If the original spectral index is \(-2.0\) or \(-3.0\), the enhancements shown in Figure 6 change by a factor of \( \sim 2\), while peaking at virtually the same grammage.

From Figure 6, we choose a case that has Fe/O \( \sim 8\), namely, 20 \( \mu \)g cm\(^{-2}\), temperature of 200,000 K, and a spectral index of \(-2.5\). Figure 7 shows enhancements in this case for He, C, O, Ne, Mg, Si, S, Ar, Ca, Fe, Ni, and Kr. The error bars in the figure show the variation in the result if the original spectrum is \(-2.0\) (lower bound) or \(-3.0\) (upper bound). For the elements
above 100 amu, we do not have the ionization cross sections so there are no points there.

The elements from C through Fe show a rise similar to the observed data, but with more structure and outliers. These features arise from the different shell structure details of different elements compared to O, a behavior not seen in the data for H gas.

3. Discussion

We have shown that a seed population in the range of 10 s of keV nucleon\(^{-1}\) with enhanced abundances of heavy ions can result if an initial population with a power-law spectral form passes through H gas or plasma. The enhanced abundance seed particles come from that part of the original population that is almost, but not quite, stopped by the material traversed. This behavior is restricted to the range below the Bragg peak in the \(dE/dx\) curves, and arises from the greater pick-up of electrons in heavier ions as they slow down. This basic atomic property assures that the enhancement should increase with mass throughout the periodic table. This feature is qualitatively similar to the heavy ion enhancements observed in \(^3\)He-rich SEP events. The calculated Fe/O enhancements of \(\sim 8\) occur for original spectral indices in the range around \(-2\) to \(-4\), which are not unreasonable for an accelerated particle spectrum (e.g., see Figure 9 in Mason et al. 2002). Although the calculations used a power law that extends to very high energy, the resulting seed population arises from the low energy portion, so there is no requirement for the original population to contain particles above \(\sim 0.5\) MeV nucleon\(^{-1}\). We believe it is significant that with these typical parameters, the calculated Fe/O enhancement in the population is a factor of \(8-10\), agreeing closely with observations of hundreds of \(^3\)He-rich SEP events. Although many papers cited above have modeled processes that might produce enhancements in some heavy ions, we are not aware of any that would work over the entire mass range, nor have any predicted a specific Fe/O enhancement. The model of Kartavykh et al. (2011b) can produce enhancements at \(\sim 0.3-0.5\) MeV nucleon\(^{-1}\), ranging for Fe/O from \(<1\) to \(\sim 10\) and for Kr/O from \(<1\) to \(\sim 100\), with predictions also for higher masses (their Figure 7). Like the model we describe here, Coulomb energy losses are a key feature, but in the Kartavykh model the Coulomb losses compete with a stochastic acceleration process, and the deduced enhancements depend very much on the assumption for the spectral index of the Alfvén turbulence (via \(M/Q\) dependence of the acceleration) and on the parameter \(\tau N\).

The calculation presented here is intended to illustrate the enhancement effect arising from low energy \(dE/dx\), and has many deficiencies. The most important is the lack of precision in \(dE/dx\) curves, especially for heavy ions at low energies. The calculation using a H gas target, though artificial, has the advantage that the deduced energy loss curves are based on a great deal of laboratory data. The deduction of high temperature plasma energy loss curves has many unknowns, and is further hampered by the fact that the actual temperature is not known; rather, we have merely explored temperatures that produced the enhancements. The effect of atomic shells in the high temperature data is also a source of concern because it can introduce features that are not seen in the H gas case. There are many other deficiencies in the model, for example, the assumption of a single target thickness. However, this problem is somewhat mitigated by the fact that similar enhancements are seen over a fairly broad range of target thicknesses. We note that the 20 \(\mu\)g cm\(^{-2}\) case shown in Figure 7 implies \(\tau N\sim 10^{11}\) s cm\(^{-3}\). Coronal jets associated with \(^3\)He-rich impulsive events have \(N\sim 10^6\) cm\(^{-3}\) (e.g., Shimojo & Shibata 2000), so a residence time of \(\sim 100\) s would be required. While the residence time does not affect the calculations here, nevertheless, the implied total grammage traversed appears easy to obtain in the low corona.

The temperatures of 200,000–300,000 K that yield the enhancements could be occurring in cool coronal loops (Foukal 1976; Brekke et al. 1997) or perhaps in cool material that has been associated with a \(^3\)He-rich SEP event (Mason et al. 2016). Because the charge states of the ions directly affect the \(dE/dx\) relation (Equation (1)), the assumption here of equilibrium is an important component of the high temperature behavior. Although the grammages traversed are well above the threshold for equilibrium, there still could be coronal conditions under which this is not the case and that could change the \(dE/dx\) relations substantially. For example, in a scenario with simultaneous acceleration and coulomb losses not considered here, the effective charge will depend on the model parameters and will generally be somewhat below the equilibrium charge states (e.g., Kartavykh et al. 2008). Regardless, though, the basic mechanism by which the heavier ions pass through the material more easily at energies below the Bragg peak, indicates that such changes in the \(Q\) states might not change the overall enhancement pattern.

The enhancements calculated here most nearly resemble the observed Fe/O enhancement for temperatures in the range of \(\sim 100,000–500,000\) K. This is considerably lower than derived from approaches that examined the mass-to-charge ratios of elements in the range Ne–O in order to identify a range where preferential acceleration based on \(Q/M\) could take place. For example, Reames et al. (1994) estimated this temperature range to be at \(\sim 3–5\) MK. There is no direct contradiction here because the mechanism for producing the enhancements is different. However, at higher energies the observed ionization states in \(^3\)He-rich events are higher than those predicted for \(\sim 3–5\) MK, suggesting that the ions observed in interplanetary space have undergone additional stripping after acceleration. Reames et al. (1994) have suggested several possible mechanisms that might be responsible.

Direct observations of Fe ionization states in impulsive \(^3\)He-rich SEP events have found that the charge state can increase from \(\sim 13–15\) at 0.1 MeV nucleon\(^{-1}\) to \(\sim 18–20\) at \(\sim 0.55\) MeV nucleon\(^{-1}\) (Möbius et al. 2003; Klecker et al. 2006a, 2006b; DiFabio et al. 2008; Guo et al. 2014). Ionization states of Fe at 0.1 MeV nucleon\(^{-1}\) are more nearly consistent with a plasma temperature of \((1.2–1.8)\times 10^6\) K (Klecker et al. 2006b), but the energy dependence observed at higher energies occurs at energies significantly below those expected for an equilibrium model. Kartavykh et al. (2005, 2007, 2008) have suggested additional mechanisms that could explain the observed energy dependence. These considerations show that the ionization states observed in interplanetary space do not fit a simple temperature origin at the Sun.

The upcoming Parker Solar Probe and Solar Orbiter missions to the inner heliosphere will greatly improve the observational knowledge of \(^3\)He-rich SEP events, thereby more tightly constraining possible models. For example, intensities of these events will be much higher in the inner heliosphere, making it possible to improve the precision of the heavy ion data. Thus,
observations at 1 au have shown the presence of UH nuclei only by summing over many events, whereas closer to the Sun they may be observable by summing over just a few events or even in single events. In the model described here, the UH enrichments would be expected to be routinely present. Additionally, proximity to the Sun will improve the constraints on the timing and location of $^3$He-rich SEP events, and this may provide key information on details of the acceleration.

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