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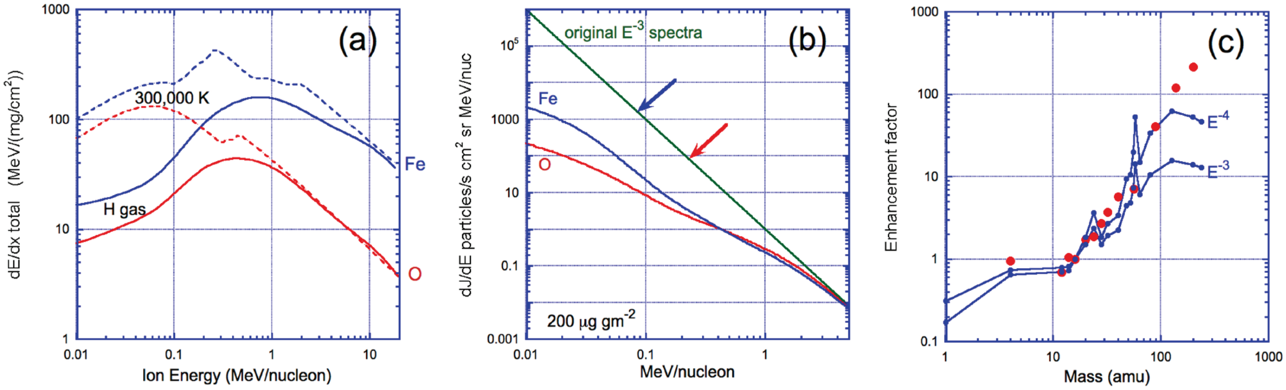
A Possible Mechanism for Enriching Heavy Ions in ^{3}He-rich Solar Energetic Particle Events



(a) dE/dx energy loss rates for O and Fe in hydrogen gas at ambient (solid lines) and 300,000 K (dashed lines). (b) E^{-3} differential energy spectra before (green line) and after passing through 200 micro-g/cm^2 of H; arrows show lowest incident energy that penetrates the gas for Fe (blue) and O (red). (c) blue points: ratios of elements normalized to O after passing through 200 micro-g/cm^2 of H gas for original spectral indices -3 and -4; red points are observed enhancements in ^{3}He-rich SEP events (Mason et al. 2004)

Extreme enrichments (>10,000x) of ^{3}He in small SEP events have long been taken as evidence of a process that favorably heats ^{3}He due to its unique charge-to-mass *(Q/M)* ratio. Heavy ions up through Fe are routinely also enhanced proportional to their mass, but at a relatively modest level (~8 for Fe) and, surprisingly, uncorrelated with the ^{3}He enhancement. The discovery by advanced instruments on *Wind* and *ACE* that the heavy ion enhancement extends into the ultra-heavy range (UH, 78-220 amu), and reaches factors of 100-200 above 100 amu, does not fit easily into models depending on *Q/M* since the wide UH mass range covers a very broad range of values for *Q/M*. So there is still no satisfactory model for heavy ion enrichments in ^{3}He-rich SEP events.

A different process for creating a seed population enriched in heavy ions could arise from the fact that heavier ions have a greater affinity for electron pickup as they lose energy by ionization. Panel (a) shows *dE/dx* rates for O and Fe in hydrogen gas; below the Bragg peak at a few hundred keV/nucleon the Fe picks up more electrons and so its *dE/dx* rate is closer to O than above the Bragg peak. This allows Fe very near the end of its range to pass more easily through the material. An example of this property is shown in panel (b), where identical E^{-3} differential energy spectra for O and Fe are passed through 200 micro-g/cm^2 of H gas. The *blue* and *red* arrows mark the energies below which the particles are stopped: 85 keV/nuc for Fe, and 230 keV/nuc for O. The spectra after passage through the material are shown by the solid *blue* and *red* curves, where the Fe enhancement over O is clearly visible.

Integrating the 2 spectra in panel (b) after passing through the material, the number of Fe ions is enhanced by a factor of ~7 compared to O. Because of the steepness of the spectra, particles above a few hundred keV/nucleon do not contribute significantly. Panel (c) shows enhancements of 19 species from He through U passing through 200 micro-g/cm^2 of H gas calculated in the same manner. The 2 blue lines plot results for original E^{-3} and E^{-4} spectra, showing that steeper original spectra result in larger enhancements, but that for elements below Fe the effect is not large. The outlier point in panel (c) is for Ni, which arises from its *dE/dx* rate falling below Fe between ~20-200 keV/nucleon.

At solar coronal temperatures the H gas is ionized, resulting in a higher *dE/dx* as shown by the dashed lines in panel (a). However, the greater affinity for electrons persists so that the Fe and O *dE/dx* rates are closer together at low energies than above the Bragg peak, thereby preserving the enhancement mechanism. As an example, for 200,000 K, the calculated enhancement through Fe is roughly similar to panel (c), but with a factor of 10 less material thickness required (20 micro-g/cm^2) due to the elevated low energy *dE/dx* rates at high temperatures. We presume that a further acceleration step energizes the enhanced heavy ion seed population to the energies observed in ^{3}He-rich SEP events. For additional details and references see Mason and Klecker (ApJ, 862:7, 2018; http://doi.org/10.3847/1538-4357/aac94c).

Contributed by Glenn M. Mason (APL) and Berndt Klecker (Max-Planck-Institut für extraterrestrische Physik, Garching, Germany). See http://www.srl.caltech.edu/ACE/ACENews_Archives.html for an archive of earlier ACE News items. Address questions and comments to glenn.mason@jhuapl.edu