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Ultra-Heavy Elements Above 10 MeV/nucleon in Solar Energetic Particle Events

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Recent measurements from Wind/LEMT and ACE/ULEIS show that elements heavier than Zn (Z=30) can be enhanced by factors of ∼100 to 10,000 in impulsive solar energetic particle (SEP) events at energies below several MeV/nuc. Using data from the Solar Isotope Spectrometer (SIS) on ACE at energies from ∼10 to >100 MeV/nuc, we find that even large gradual events at these energies often are very iron rich and may appear similar in composition to impulsive events. Since August 1997, SIS has recorded ∼1000 nuclei with Z of 29 or greater, including measurable quantities of Zn, Ge and Se (Z=30, 32, and 34). Although quantitative analysis to obtain ultra-heavy abundances remains to be done, we present sample observations that establish the potential of extending ultra-heavy SEP measurements up to higher energies in order to test models of acceleration and abundance enhancements in both gradual and impulsive events.

1. Introduction and Data Analysis

The abundances of ultra-heavy (UH) elements (with Z>30) relative to oxygen have been found to be enhanced by surprisingly large factors (∼100 to 10,000) in some impulsive solar energetic particle (SEP) events at ∼400 keV/nuc by ACE/ULEIS [1] and at 3.3-10 MeV/nuc by Wind/LEMT [2], with much smaller (factors of a few) enhancements observed in some large gradual events below 10 MeV/nuc [2]. If the observed increase in Fe/O ratios with increasing energy above 10 MeV/nuc in some large gradual events [3] is due to the presence of flare material, either via direct access from the flare site [4] or by way of reacceleration of flare suprathermals at quasi-perpendicular shocks [5], one might expect to find very large UH enhancements in some gradual events at higher energies.

The Solar Isotope Spectrometer (SIS) instrument on ACE consists of two stacks of silicon solid state detectors and is primarily designed to measure the isotopic composition of species from He (Z=2) through Ni (Z=28) at energies of ∼10 to several hundred MeV/nuc using the dE/dx vs. residual energy technique [6]. To achieve the required resolution over this dynamic range, the pulse height analyzers were designed specifically for this limited interval in Z and saturate above certain energy deposits in the detectors, typically for particles heavier than Z∼40 (Zr) at large incident angles penetrating deep into a detector segment. The resulting loss of detection efficiency gradually increases for Z>40 and has not yet been fully modeled in detail.

Although limited in UH sensitivity, SIS attains excellent elemental resolution in this regime compared with previous studies at lower energies [1, 2]. Figure 1 shows histograms of nuclear charge in the UH range for all particles recorded by SIS during the ACE mission to date. Standard data cuts were applied requiring that particles stop in the instrument and that multiple calculations of nuclear charge using different combinations of energy-loss measurements be consistent in order to reject interacting particles and/or chance coincidences of multiple particles. For the lowest energy (“range 0”) particles, only two detectors are triggered, resulting in only one charge determination with no consistency check possible. Under low rate conditions, this is not a problem; however at high rates (such as during very large SEP events) a large-angle, out-of-geometry nucleus

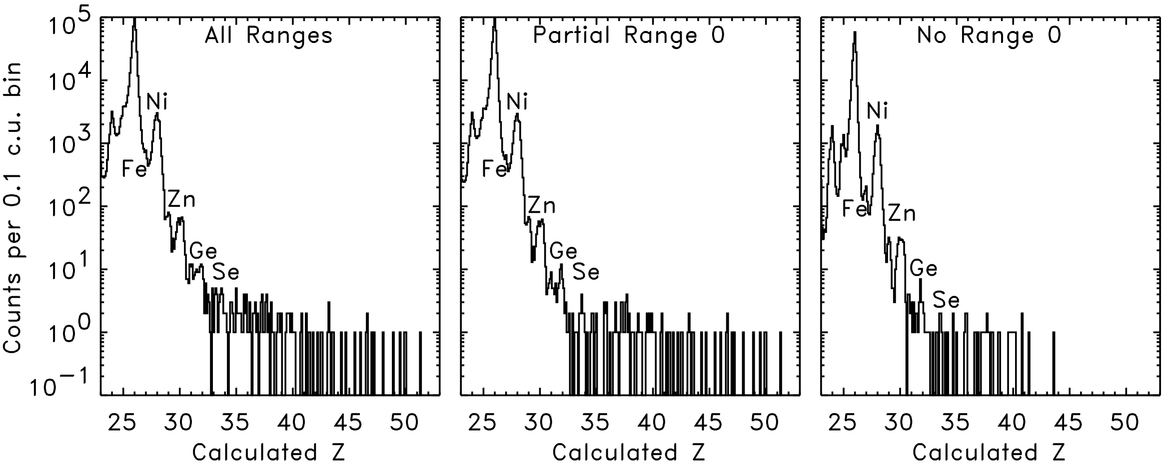

Figure 1. Nuclear charge histograms of particles recorded by SIS from 27 August 1997 through 21 June 2005. *Left:* Data from ranges 0-7 (∼10-168 MeV/nuc for Fe), *center:* data with cut on range 0 (see text), *right:* data from ranges 1-7 (16-168 MeV/nuc for Fe).

such as Fe stopping in the first detector in coincidence with a H or He nucleus stopping in the second detector can mimic the signal pattern expected for range 0 ultraheavies. This background can be greatly reduced by requiring that the energy deposit in the second detector for any range 0 particle exceeds the maximum expected for a He nucleus in that detector. (This drastic cut automatically rejects all range 0 He as well, but this is not a concern for this study.) Applying this cut results in the center-panel histogram in Figure 1, which has a noticeably smaller background in the Z=30-35 region. Rejecting all range 0 particles (*right panel*) further improves the resolution but with a significant loss of statistical accuracy and energy coverage. For this study we use the cuts illustrated in the center panel.

2. Discussion

Taking the detected events from the center panel of Figure 1 and omitting the highest energy ranges to reject the bulk of the galactic cosmic rays results in the histogram shown in Figure 2. This represents a summation over many SEP events, both very large and small, without any accounting for variations in instrument livetime, sampling and telemetry limitations, UH detection efficiencies, or differences in energy intervals and/or spectral shapes for the different elements. Nevertheless, it is instructive to compare the relative peak heights with those expected from standard solar system abundances [7]. Since SEP material is relatively underabundant in elements with a high first ionization potential (FIP), we have adjusted the expected abundances downward by a factor of 4 for all elements with a FIP greater than 10 eV. Note that because SEP intensity spectra fall steeply with energy and the measurements were made at a constant range for all elements, those elements lighter (heavier) than Fe will have lower (higher) energies and thus higher (lower) abundances than expected using a normalization at Fe, qualitatively as observed. From this figure, we conclude that the long-term, overall average composition of ∼10-50 MeV/nuc particles out to at least Z∼40 agrees reasonably well (within a factor of ∼2) with standard solar system values.

In the near future we will survey the entire data set in detail to study the UH composition of individual SEP events as well as the average UH composition of various types of events (e.g., impulsive, Fe-poor gradual, and

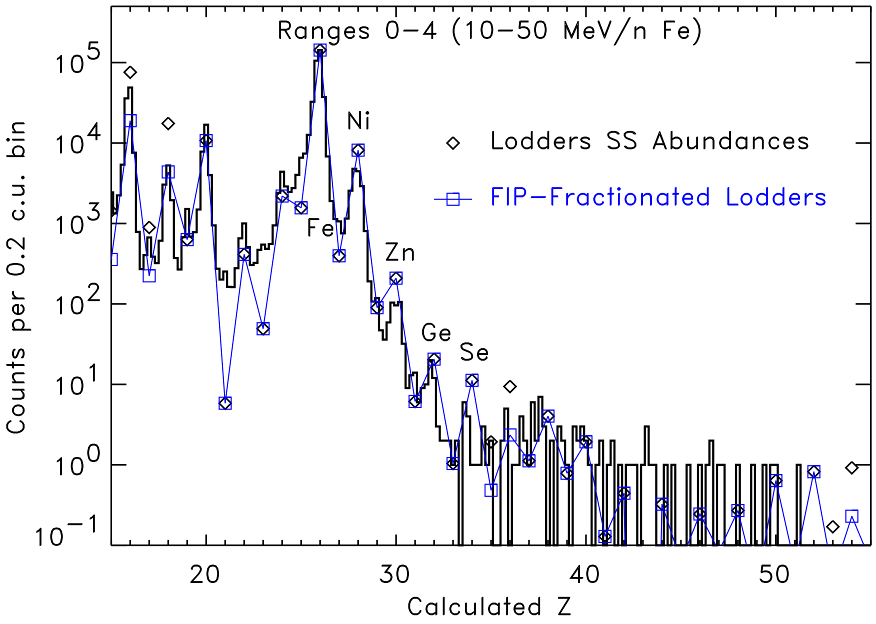

Figure 2. Mission-to-date nuclear charge histogram from ACE/SIS for ranges 0-4 (corresponding to ∼10-50 MeV/nuc at Fe), compared with standard solar system (SS) abundances [7] normalized to Fe (*diamonds*) and SS abundances after accounting for FIP fractionation (*connected squares*).

Fe-rich gradual). This study is not yet complete, but the data at hand indicate that such a project is feasible and that the results should prove interesting. This is illustrated by several examples in Figure 3. The 6 November 1997 event (*top left*) shows clear peaks for Zn and Ge (Z=30 and 32); UH abundances from this event have been previously reported [8]. The large 21 April 2002 event (*top right*) shows no particles heavier than Z=34, indicating that even in an event this large, background contamination in the UH region is negligible. Note that a measurement of the Zn abundance will be possible in this event. By some standards, the 20 August 2002 event (*lower left*) is the largest impulsive event of this past solar cycle [9]; in addition to Zn and Ge we find 15 particles between Z=33 and 47 (As and Ag).

The most remarkable UH event we have discovered so far in this study is that of 23 July 2004 (*lower right*). This is a very small event, with a GOES >10 MeV proton intensity which peaked at only ∼4 pfu; the 11 particles between Z=33 and 50 (As and Sn) therefore cannot possibly be due to chance coincidence background. The time profile is very rounded and extends for 1.5 days, looking nothing like a classic "impulsive" event. A series of 4 very short duration M-class x-ray flares occurred during this time from an active region near central meridian (W04 to W20), but with no obvious particle velocity dispersion and UH particle arrival times spread over nearly a day it is unclear which one or ones are associated with the SEP event. The 12-60 MeV/nuc Fe/O ratio is only about half that of the 20 August 2002 event and the Fe intensity about 50 times less, but the UH intensity is comparable, indicating that the UH enhancement does *not* correlate with the Fe/O ratio; this is consistent with a study of other events in Wind/LEMT [2]. The Fe spectrum is very soft, with a power-law index of ∼−4.7, which is also consistent with the report that the largest UH enhancements are associated with events with the *softest* Fe spectra [2]. Simply taking the ratio of particles between Z=33 and 50 to Fe and normalizing to solar, without correcting for different energy intervals, reduced UH efficiency, or FIP fractionation (all of which would serve to *increase* the enhancement) yields a (33<Z<50)/Fe enhancement of ∼80. Since the Fe/O

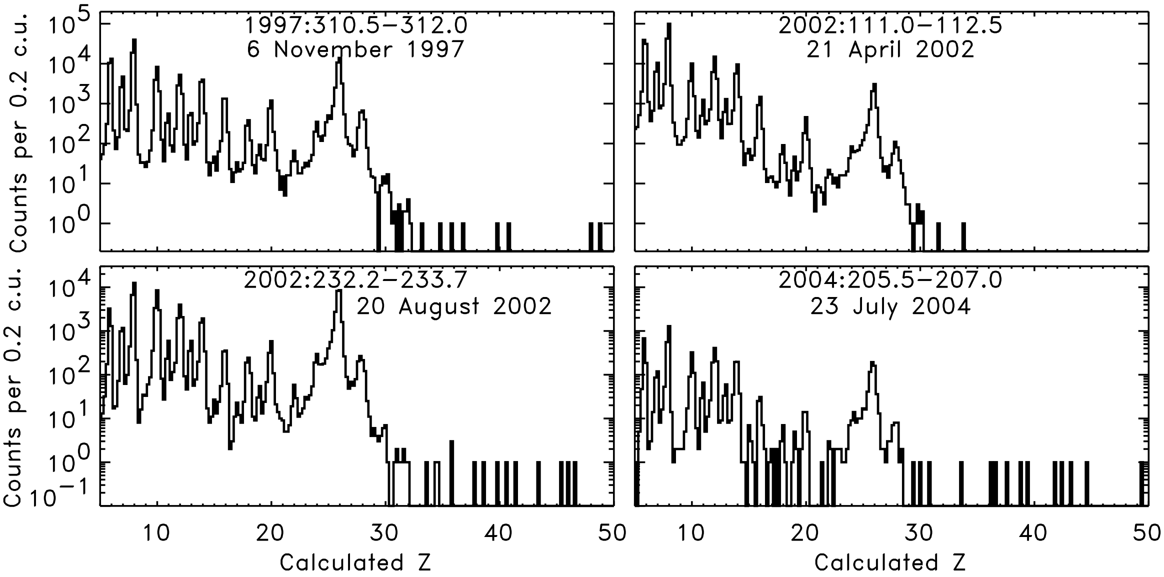

Figure 3. Nuclear charge histograms over ranges 0-4 for 4 selected time intervals, each 1.5 days long. The 23 July 2004 event (*lower right*) shows the largest UH enhancement uncovered in this study so far.

ratio in this event is ~0.76, or 5.7 times the average SEP value, this means the $(33<Z<50)$/O enhancement is ~400-500! Clearly this event merits further study, but already it demonstrates that large UH enhancements can exist in SEP events at energies >10 MeV/nuc.

3. Acknowledgements

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