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Trans-Nickel Elements in Solar Energetic Particles

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Abstract

The trans-nickel elements ($Z \geq 29$) are some of the rarest in the Solar System; they typically are about 1/1000th to 1/10000th as abundant as iron ($Z = 26$). We present measurements of zinc and other trans-nickel elements in solar energetic particle (SEP) events observed by the Solar Isotope Spectrometer (SIS) in the energy range of 10-75 MeV/nuc. SIS is part of the Advanced Composition Explorer (ACE) spacecraft, presently in orbit about the Earth-Sun L1 point. The measured abundances of the trans-nickel elements are compared to tabulated meteoritic and photospheric abundances and to previous SEP measurements. The results may help to assess changes in composition due to SEP acceleration and transport.

1 Introduction

Solar Energetic Particle (SEP) events are transient outpourings of high-energy particles from the Sun. These events are somewhat roughly classified into two categories: gradual and impulsive (Reames, 1995a). An impulsive event is one in which solar particles are accelerated in association with a solar flare. Charge state measurements show that the ambient temperature of the material is about 10 MK (Luhn et al., 1987). These events typically last a few hours, and are generally confined to field lines connected to the flare site. Typically, impulsive events tend to be rich in ^{3}He and in heavy elements such as iron; ^{3}He will be enhanced by a factor of about 1000 with respect to solar wind values, while iron will be enhanced by a factor of about 10 (Reames 1995a).

In a gradual event, a coronal mass ejection drives a shockwave through the ambient corona and solar wind, accelerating the particles. The particles so accelerated have relative abundances similar to the corona and to the solar wind. The source temperature for particles in gradual events is about 2 MK, consistent with coronal material (Luhn et al, 1985, and Leske et al., 1995). Although particles do not usually diffuse across magnetic field lines, shockwaves do so easily. These events are therefore much larger spatially than impulsive events. The event duration is also much larger; gradual events typically last for days instead of hours (Reames 1995a). In both types of events, there is also an enhancement of particles with a lower first ionization potential (FIP) (Reames, 1995b and 1998).

The object of the current analysis is to compare abundances of ultraheavy elements in various SEP events to “standard” solar system abundances as presented by Grevesse et al. (1996), and to earlier measurements (Reames 1995b and 1998; Breneman and Stone, 1985). The larger geometry factor of SIS affords the opportunity to examine abundances in single events, and determine the degree of event-to-event variability.

2 Data Analysis

The observations reported here were made with the Solar Isotope Spectrometer (SIS) aboard the Advanced Composition Explorer (ACE) spacecraft. A complete description of SIS may be found in Stone et al. (1998). SIS includes a pair of solid-state particle telescopes, each comprised of 17 silicon wafers organized into ten detectors. The two outermost detectors are 75 micron thick octagonal silicon wafers, whose active areas are organized into 64 strips. These matrix detectors provide angle information, and make the first (sometimes only) energy measurements. The subsequent eight detectors (“stack” detectors) make further energy measurements; the last is used as a veto for penetrating particles. A particle’s atomic number and mass are calculated using the dE/dx vs. E method, where particle energy loss as a function of depth in the silicon is compared to a range-energy relation. Atomic numbers are calculated three different ways, using different detector combinations, and the three calculations are cross-checked for charge consistency to remove invalid events.

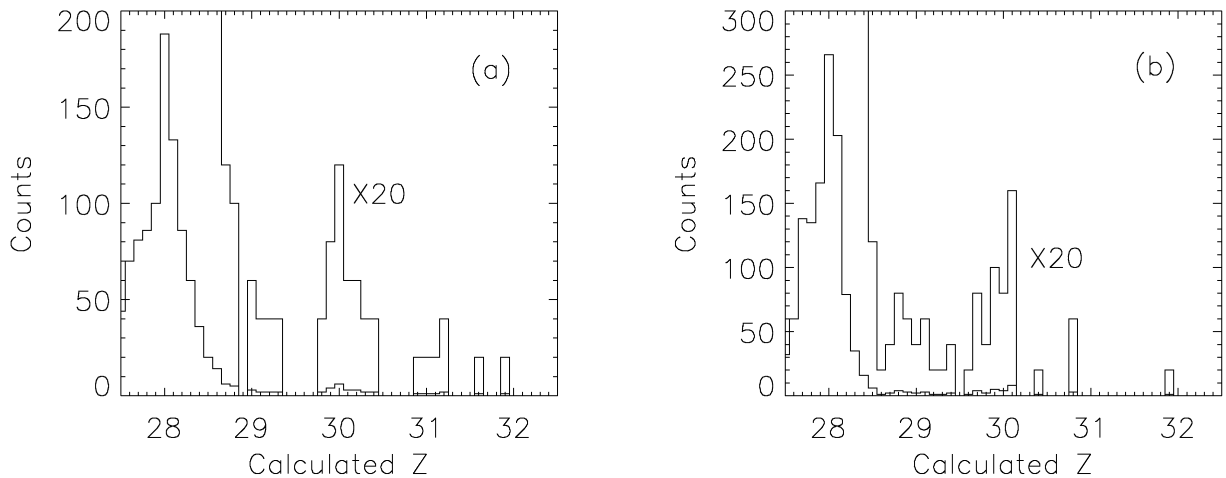

Figure 1: Total counts in the SIS instrument during the November 6, 1997 event, with various cuts: (a) particles in range 0; (b) particles in ranges 1 through 5.

ACE was launched on August 25, 1997, and has been in a halo orbit about the Earth-Sun L1 point. This location in space ensures that the instruments aboard ACE have access to a sample of solar matter that is not affected by Earth's magnetic field. For the current analysis, three SEP events were examined: they occurred on November 6, 1997, on September 30, 1998 and on November 14, 1998 during the Leonid meteor storm. These three events had among the largest enhancements of iron and other heavy nuclei of all the events observed since launch. During the November 1998 event, the spacecraft was pointed away from the Leonid radiant to protect the fragile instruments. This caused some data gaps in this event, since the high gain antenna was pointed away from Earth.

Figure 1 shows two histograms of particles observed during the November 6, 1997 event. Figure 1 (a) shows range 0 events, or particles that stopped in the second matrix detector. Figure 1 (b) shows particles that stopped in ranges one through five, in the stack. These figures illustrate the problem in measuring these rare elements: there are very few events above nickel. The only elements with well-defined peaks are copper ($Z = 29$) and zinc ($Z = 30$); gallium ($Z = 31$) and germanium ($Z = 32$) have far fewer events. The energy range for the elements observed here is from approximately 10 MeV/nuc to between 70 MeV/nuc for iron and 75 MeV/nuc for germanium and zinc.

Possible sources of background for these rare elements are chance coincidences between heavy particles incident at high angles on the first matrix detector and lighter particles penetrating to the second matrix detector, and possibly tails from iron and nickel. A further problem arises from the use of range 0 particles. In range 0, charge consistency cannot be determined, since there is only one determination of charge from the single measurement of dE/dx. Another consistency cut may be made, however: since both sides of a matrix detector belong to the same piece of silicon, the strip pulse heights on both sides should be about the same. If there is more than a few MeV difference, for strips in either matrix detector, the event is thrown out. At this point, the uncertainties are not completely understood, and so these data should be regarded as preliminary.

3 Results

Figure 2 shows the calculated abundances relative to iron for nickel, copper, zinc, gallium, and germanium. These abundances are for the November 6, 1997, September 30, 1998, and November 14, 1998 events. For comparison, measurements from Breneman and Stone (1985), and from ISEE 3 (Reames 1995b, 1998) are included, as are photospheric and meteoritic abundances from Grevesse et al. (1996).

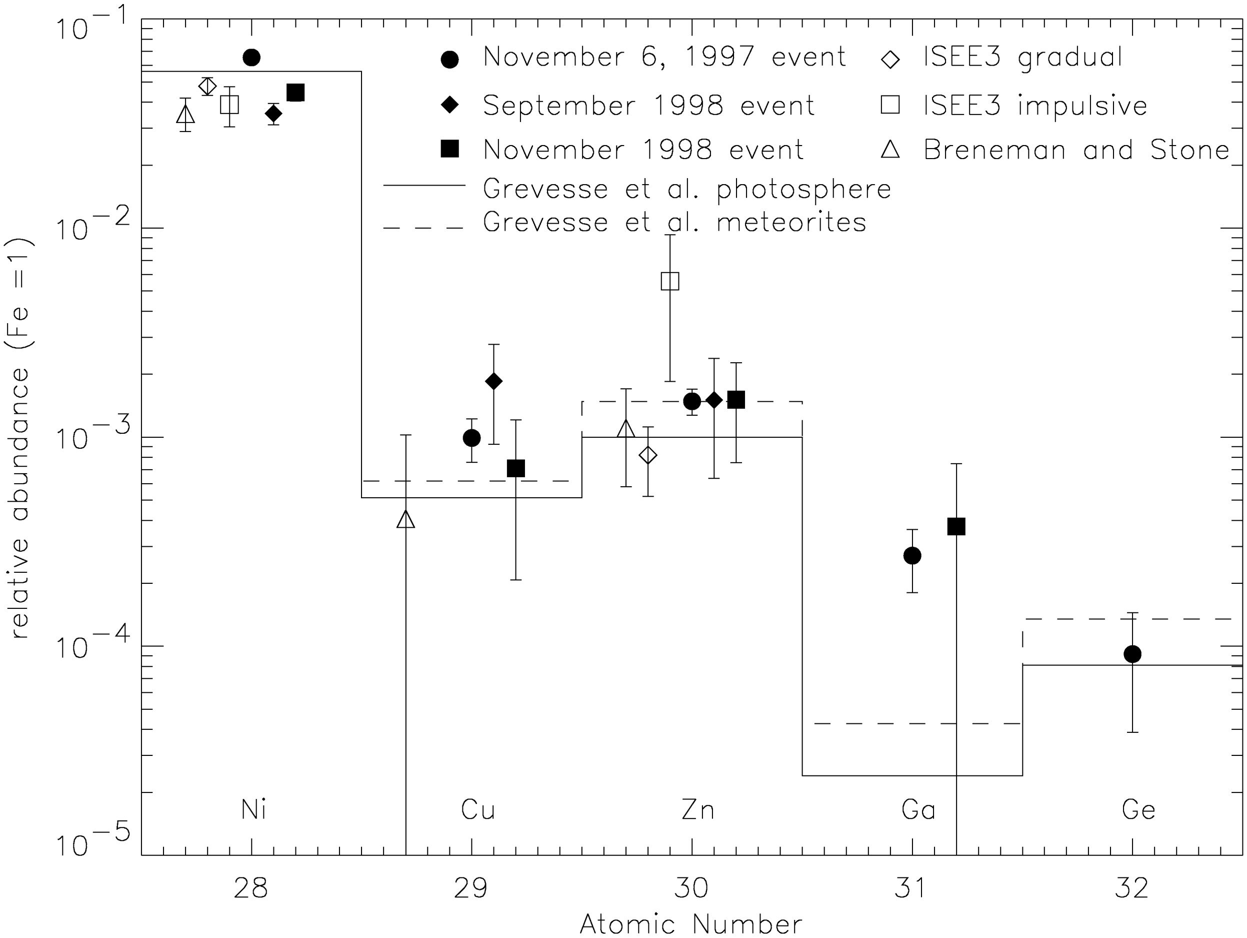

Figure 2: Abundances in three solar events relative to iron, compared to averages over many events from Breneman and Stone and ISEE 3. The photospheric and meteoritic abundances from Grevesse et al. are shown for comparison.

For most of the points in Figure 2, the relative abundances were calculated from the number of particles observed in ranges zero through five. Ranges six and seven were omitted because of possible contamination by galactic cosmic rays. For copper in the November 1997 event, the ratio was calculated using particles in ranges one through five. Copper appears to be better resolved from nickel when range zero is omitted in this event, as the nickel tail in range 0 is much larger than in higher ranges.

There do not seem to be any clear event-to-event trends in the abundances within the rather large uncertainties. In copper and zinc, the events are consistent with one another and with previous measurements. Nickel varies between the three events, but is similar to earlier event averages. For copper, gallium, and germanium, these are the first reported measurements in individual SEP events. When normalized to iron, the only elements that appear enhanced with respect to the solar system abundances are gallium and possibly copper.

In all of these events, iron is enhanced by a factor of about 10 relative to oxygen (Cohen et al., 1999). This enhancement is believed to arise due to Q/M fractionation. There are no charge state measurements for the trans-nickel elements. However, one might expect a smaller value for Q/M for these elements than for iron. This might be expected to lead to an even greater enhancement for the heavier nuclei than for iron. Except for gallium in the November 1997 event, there is no convincing evidence for such an enhancement.

This study has presented the first measurements for single-event abundances of the very rare trans-nickel elements. No clear trends appear in the three iron-rich events studied. Except for gallium, the enhancements observed for the trans-nickel elements appear to be comparable to those of iron. SIS is expected to return observations from L1 for at least three to four more years, through solar maximum. As more events are observed, a more complete picture of the abundance of these rare particles should develop.

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