Unusual isotopic composition of solar energetic particles observed in the November 6, 1997 event

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Abstract. Using the Solar Isotope Spectrometer on the Advanced Composition Explorer, we have measured the isotopic composition of solar energetic particles (SEPs) with energies of tens of MeV/nucleon during the November 6, 1997 solar event, including isotopes never before reported in SEPs, such as $^{54}$Ca, $^{44}$Ca, $^{54}$Fe, and $^{60}$Ni, as well as isotopes of C, N, O, Ne, Mg, and Si. Abundances are found to be enhanced by factors of $\sim 2$ relative to the standard solar system values for $^{22}$Ne/$^{20}$Ne and $^{26}$Mg/$^{24}$Mg. Overall, the enrichments of the isotope ratios show a correlation with the ratio of masses, $M_2/M_1$, scaling approximately as $(M_2/M_1)^2$, although significant deviations from this trend are evident.

Introduction

Solar energetic particles (SEPs) provide a direct sample of solar material that can be used to study the composition of the Sun's atmosphere, as well as particle acceleration and transport processes. However, during acceleration and transport through the interplanetary medium, fractionation processes may alter the composition by an amount which varies from event to event. Reames [1995] identifies two classes of SEP events, impulsive and gradual. In impulsive SEP events, the $^4$He abundance is often greatly enhanced, possibly by ion cyclotron wave resonances [Fisk, 1978; Temerin and Roth, 1992] or cascading Alfvén waves [Müller, 1998], which may also influence heavy ion composition. Variations in the elemental composition of large, gradual SEP events have been shown to be correlated with the ionic charge to mass ratio, $Q/M$ [Breneman and Stone, 1985]. When corrected for this fractionation, SEP abundances in gradual events can be used to obtain the elemental composition of the corona [Breneman and Stone, 1985; Garrard and Stone, 1993; Reames, 1995], which is important for elements difficult to measure spectroscopically. In principle, the isotopic composition of the corona can be determined in a similar manner [Mewaldt and Stone, 1989; Williams et al., 1998].

Isotopic measurements of SEPs to date have been limited to a few solar events and to elements up to silicon [Dietrich and Simpson, 1979, 1981; Mewaldt et al., 1979, 1981, 1984; Simpson et al., 1984; Williams et al., 1998], due largely to the limited collecting power and resolution of earlier instruments. Most measurements appeared to be consistent within large uncertainties with terrestrial abundances, with isolated differences [Mewaldt and Stone, 1989; Williams et al., 1998]. In the solar wind, there is evidence that heavy isotopes may be systematically depleted by a few percent [Kallenbach et al., 1998], depending somewhat on the solar wind velocity.

Shortly after launch of the Advanced Composition Explorer (ACE), the first two major particle events of solar cycle 23 took place [Mason et al., 1998]. The 6 November 1997 event studied here had unusually simple characteristics at energies measured by SIS. The spectra of all species from C to Ni at $\sim 12 - 60$ MeV/nucleon are fit by a single power law of $E^{-2.1}$ [Cohen et al., 1998], and the time profiles at these energies have simple exponential decays, with no evidence for acceleration by transient interplanetary shocks [Mason et al., 1998]. This should simplify the interpretation of our results.

Data Analysis

The Solar Isotope Spectrometer (SIS) includes two identical telescopes, each composed of a stack of 17 silicon solid-state detectors [Stone et al., 1998], with a combined geometry factor of 38 cm$^2$sr. Using measurements of the energy loss, residual energy, and trajectory of particles stopping in the instrument, the nuclear charge, $Z$, mass, $M$, and total kinetic energy, $E$, can be determined for particles with energies of $\sim 10$ to $\sim 100$ MeV/nucleon, with a mass resolution of $\sim 0.15$ to $> 0.3$ amu, depending on $E$ and $Z$.

Mass histograms of selected elements in the 6 November 1997 event are shown in Figure 1. Several of the isotopes shown, such as $^{34}$S, $^{37}$Cl, $^{38}$Ar, $^{44}$Ca, $^{54}$Fe, and $^{60}$Ni have not been previously resolved in SEPs. Consistency requirements among multiple determinations of $Z$ and $M$ were used to reject events that underwent nuclear interactions in the instrument or involved chance coincidences. The abundances in Table 1 were obtained using simple Gaussian fits or by counting events in the...
peaks in Figure 1, with no modeling of small tails at this stage of the analysis. Using measured quiet-time isotope fluxes in SIS (from 9/97 to 3/98), the background counts expected due to galactic cosmic rays and anomalous cosmic rays have been subtracted from these data. Small corrections of \( \pm 5\% \) were applied to correct relative isotopic abundances to equal energy per nucleon intervals.

The mass distributions in this SEP event are not typical of tabulated solar system isotope abundances [Anders and Grevesse, 1989], which are based mainly on terrestrial materials. The expected fractional abundances of \(^{25}\text{Mg}\) and \(^{26}\text{Mg}\), for example, are nearly equal, at 10\% and 11\% of Mg, respectively. This is clearly not the case in Figure 1, where \(^{26}\text{Mg}\) appears especially overabundant. Abundance anomalies exist for other isotopes as well (e.g., \(^{13}\text{C}\) and \(^{22}\text{Ne}\)), as listed in Table 1.

The abundances of heavy elements in this event are also enhanced, with Fe/O \(> 1 \) at energies > 10 MeV/nucleon [Cohen et al., 1998; Mason et al., 1998]. Elemental abundance variations in other gradual events have been found to scale reasonably well as a power law in the ion charge to mass ratio, \( Q/M \), with a different power law index, \( \gamma \), for each SEP event [Breneman and Stone, 1985]. If this arises from rigidity-dependent acceleration or transport processes, there must be mass fractionation as well, since two isotopes of the same element and same velocity will have different masses and rigidities. Since the average charge state \( Q \) should depend on \( Z \) and not \( M \), if elemental abundance enhancements scale as \( [(Q_1/M_1)/(Q_2/M_2)]^\gamma \), then the isotopic abundance enhancements should scale as \( (M_2/M_1)^\gamma \), where \( M_1 \) and \( M_2 \) are the mass numbers of the isotopes. A plot of the isotopic enhancement factor versus mass ratio is shown in Figure 2. Only statistical uncertainties in the SEP measurements are shown; no uncertainties are reported in the standard abundance compilations [Anders and Grevesse, 1989]. We have also not accounted for possible mass-dependent fractionation processes that may affect the coronal and/or solar wind isotope composition [Collier et al., 1998; Kallenbach et al., 1998].

**Results and Discussion**

In general, there is a correlation between the abundance enhancement and mass ratio, with greater enhancements at higher values of \( M_2/M_1 \). The fit in Figure 2 is required to pass through unity when the two masses are equal and shows that the mean observed enhancement scales as \( (M_2/M_1)^\gamma \), where \( \gamma = 7.16 \pm 0.34 \).
The isotopic enhancement factors reported here plotted vs. the observed Fe/O ratio (adapted from Williams et al., 1998). The only isotope measurements in impulsive events [Mason et al., 1994] find enhancements in $^{22}$Ne/$^{20}$Ne and $^{26}$Mg/$^{24}$Mg comparable to those reported here. Since higher energy particles ($>10$ MeV/nucleon) in the 6 November 1997 event have charge states and heavy ion enhancements characteristic of impulsive SEP events, while lower energy particles are more typical of gradual events [Cohen et al., 1998; Mason et al., 1998], some of the deviations from the $Q/M$ correlation may be a signature of particles accelerated during the impulsive phase of this event.

The $^{13}$C, $^{16}$O, $^{22}$Ne, $^{26}$Mg, $^{28}$Si, and $^{30}$Si abundances in this event tend to be higher compared to previous measurements, as illustrated in Figure 4. Moreover, the Fe/O ratio and the preferential enrichment of heavy ions is also greater than in most previously studied SEP events. Following Williams et al. [1998], the dotted curve in Figure 4 illustrates the mass fractionation expected, assuming 1) that the $Q/M$ ratio organizes both the elemental and isotopic enhancements, 2) that the Fe/O ratio adequately characterizes the $Q/M$ fractionation, and 3) that the ionic charge states are the same as measured in two large gradual events in 1992 at 15-70 MeV/nucleon [Leske et al., 1995]. However, SAMPEX measurements at similar energies in this event [Mazur...的情况下，可能不会简单地按$Q/M$比例变化。值得注意的是，$Q/M$比率很好地建立了与元素增强相关的概念，尽管它并不清楚它是否也适用于元素在突发事件中的增强。理论模型的突发SEP事件 [Fisk, 1978; Temerin and Roth, 1992; Miller, 1998] 建议，不寻常的增强性可能出现在除$^{3}$He之外的同位素中，这可能不会按$Q/M$定律变化。因此，$^{3}$He的唯一同位素测量在突发事件中在$^{22}$Ne上发现增强 [Mason et al., 1994] 和$^{26}$Mg/$^{24}$Mg的比较，与这些报告的结果类似。因为较高能量的粒子（大于10 MeV/nucleon）在1997年11月6日的事件中具有更高的电荷状态和重离子增强，而较低能量的粒子则更典型于渐变事件 [Cohen et al., 1998; Mason et al., 1998]，某些偏离$Q/M$相关性的原因可能是加速的粒子在突发阶段加速期间的特征。

在$^{13}$C, $^{16}$O, $^{22}$Ne, $^{26}$Mg, $^{28}$Si, 和 $^{30}$Si的丰度在这一事件中倾向于高于先前测量的丰度，如图4所示。此外，Fe/O比率和重离子的偏好丰度更高，这比在大多数先前研究过的SEP事件中更高。按照Williams et al. [1998]，图4中的虚线曲线说明了质量分馏预期，假设1）$Q/M$比率组织了元素和同位素的增强，2）Fe/O比率充分地特征化了$Q/M$分馏，和3）电荷状态的离子是相同的，如在1992年15-70 MeV/nucleon [Leske et al., 1995]。然而，SAMPEX测量在相似的能量中，这一事件 [Mazur...的情况下，可能不会简单地按$Q/M$比例变化。值得注意的是，$Q/M$比率很好地建立了与元素增强相关的概念，尽管它并不清楚它是否也适用于元素在突发事件中的增强。理论模型的突发SEP事件 [Fisk, 1978; Temerin and Roth, 1992; Miller, 1998] 建议，不寻常的增强性可能出现在除$^{3}$He之外的同位素中，这可能不会按$Q/M$定律变化。因此，$^{3}$He的唯一同位素测量在突发事件中在$^{22}$Ne上发现增强 [Mason et al., 1994] 和$^{26}$Mg/$^{24}$Mg的比较，与这些报告的结果类似。因为较高能量的粒子（大于10 MeV/nucleon）在1997年11月6日的事件中具有更高的电荷状态和重离子增强，而较低能量的粒子则更典型于渐变事件 [Cohen et al., 1998; Mason et al., 1998]，某些偏离$Q/M$相关性的原因可能是加速的粒子在突发阶段加速期间的特征。

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et al., 1998] show that the charge states are significantly higher for Fe than in the 1992 events. In addition, Cohen et al. [1998] find that the fractionation with respect to photospheric material associated with the first ionization potential (FIP) is apparently smaller in this event than is typical. Taking both effects into account results in an expected mass fractionation shown by the solid curve in Figure 4.

The results in Figure 4 show that SEP isotope abundances vary from event to event. This had not been so obvious in prior measurements with larger uncertainties made in events with much less fractionation. Although the mass fractionation may not agree precisely with expectations, the trend is towards greater heavy isotope enhancements with higher Fe/O ratios, as expected; this trend is clearest for those isotope ratios that are easiest to measure and least prone to background, namely $^{22}\text{Ne}/^{20}\text{Ne}$ and $^{26}\text{Mg}/^{24}\text{Mg}$.

The correlations in Figure 4 suggest that much of the observed mass fractionation in gradual events is associated with the same underlying mechanism responsible for the $Q/M$-dependent elemental fractionation. Variations from the $Q/M$ correlation may be due to additional fractionation processes, possibly arising from an admixture of flare accelerated particles or inaccuracies in our knowledge of actual coronal (as opposed to meteoritic or terrestrial) isotopic abundances. Studies of additional SEP events, both impulsive and gradual, may make it possible to distinguish some of these effects.

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References


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