Enhanced Abundances of ^{3}He in Large Solar Energetic Particle Events

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Abstract. Observations of a number of relatively large solar energetic particle (SEP) events that have occurred since the launch of ACE in August 1997 have shown that the ratio of ^{3}He/^{4}He can be enhanced over the solar wind value ($\sim 4\times10^{-4}$) by more than an order of magnitude in such events. Since particle acceleration in these "gradual" SEP events is thought to be caused by CME-driven shocks traveling through the solar corona and interplanetary medium, a source of ^{3}He in addition to the solar wind appears required to provide the seed material. Using data from the Solar Isotope Spectrometer on ACE, we have carried out a more detailed investigation of the characteristics of the ^{3}He enhancements at energies $>$ 5 MeV/nucleon in three large SEP events (4 Nov 1997, 6 May 1998, and 14 Nov 1998). We find that the ^{3}He/^{4}He ratios are essentially time-independent during the events, that the ^{3}He energy spectra are markedly harder than those commonly observed in impulsive events, and that the spectra of ^{3}He may be harder than those of ^{4}He.

INTRODUCTION

Particle acceleration in solar energetic particle (SEP) events is thought to be caused by two distinct mechanisms (1). First, the energy released by magnetic reconnection can cause acceleration at the site of a flare on the Sun, although the details of the mechanism remain uncertain. Second, the passage of coronal mass ejections (CMEs) thorough the corona and interplanetary space can drive a shock which will accelerate particles from the medium it is traversing.

Extensive efforts have been made to establish sets of observable characteristics of SEP events that can be used to distinguish which acceleration mechanism was operative in a particular event (2). Events classified as "impulsive" or "gradual" (based on the duration of the x-ray emission) are thought to be associated with acceleration by flares and CME-driven shocks, respectively. It is generally found that the SEP events with the highest particle intensities near Earth are of the gradual type.

Compositional signatures have also been extensively studied. In gradual events, heavy element abundances are generally consistent with coronal (or solar wind) values, with relatively modest fractionation which can be correlated with the mass-to-charge ratio (M/Q) of the ions (3). In impulsive events, more extreme deviations from coronal abundances are observed. Most notably the ^{3}He/^{4}He isotope ratio can exceed the solar wind value of $\sim 4\times10^{-4}$ (4) by as much as four orders of magnitude, and heavy elements exhibit a pattern of generally increasing enhancements with increasing atomic number, Z, with Fe/O reaching values $\sim 10\times$ the coronal value of 0.13 inferred from gradual SEP events (1). The extreme enhancements of ^{3}He are thought to result from selective heating by some resonant process acting on the preflare material. The degree of correlation between ^{3}He and heavy ion enhancements and the conditions under which such correlations occur are an active subject of debate and require further clarification.

In the prevailing view of the origin of SEP events one would expect very small values of the ^{3}He/^{4}He ratio in large, gradual events. Prior to the launch of the Advanced Composition Explorer (ACE) there were reports of a few large events with appreciable enhancements of this ratio and it had been suggested that such events could be of a "mixed" character containing both shock-accelerated material and flare-associated particles (see (2) and references therein). However, earlier instruments lacked the combination of sensitivity and resolution needed to detect ^{3}He in gradual events at levels much below $\sim 10\%$ of ^{4}He under normal conditions.

Isotope spectrometers on ACE are able to resolve ^{3}He

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at least down to levels of a few tenths of a percent of ^{4}He. At energies < 1 MeV/nuc, data from the Ultra-Low Energy Isotope Spectrometer (ULEIS) have shown the presence of significant ^{3}He enhancements in several gradual events (5, 6). At higher energies, $\gtrsim$9 MeV/nuc, observations with the Solar Isotope Spectrometer (SIS) indicate ^{3}He/^{4}He ratios exceeding $\sim$ 0.4% in at least half of the 11 large SEP events that occurred between November 1997 and June 1999 (7, 8).

SIS OBSERVATIONS OF SEP ^{3}He

The SIS instrument (9) identifies the charge and mass of energetic nuclei using measurements of dE/dx, total energy, and trajectory in stacks of silicon solid-state detectors. For the present study where it is necessary to identify small fluxes of ^{3}He in the presence of significantly larger ^{4}He intensities, we consider particles which stop in the fourth, fifth, or sixth detectors in the stack (called ranges 2, 3, and 4). For each of these nuclei there are between 3 and 5 mass measurements which are required to be consistent to reduce backgrounds. Figure 1 shows He mass histograms for these three ranges from three of the large SEP events that have been studied (4 Nov 1997, 6 May 1998, and 14 Nov 1998). In each of these histograms there is a clearly resolved ^{3}He peak. In some of the other large events the SIS data do not show a distinct ^{3}He peak, but sensitivity is sometimes limited either by low statistics or residual spill-over from ^{4}He.

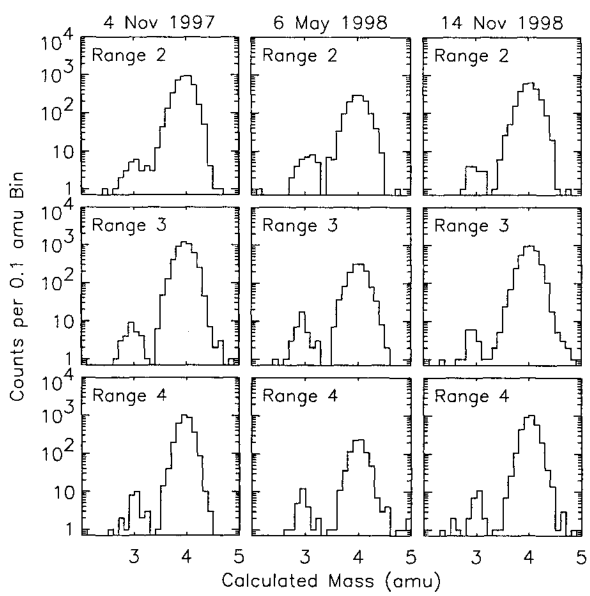

FIGURE 1. He mass histograms for SIS ranges 2 through 4 from three large SEP events. Energy intervals (MeV/nuc) for ^{4}He and ^{3}He in SIS are: Range 2, 6.5–7.6 and 7.7–9.0; Range 3, 7.7–10.1 and 9.1–11.9; Range 4, 10.2–13.8 and 12.0–16.3.

Figure 2 shows plots of ^{3}He and ^{4}He particle intensities vs. time for energies of 8.3 and 10.5 MeV/nucleon. For ^{3}He, these energies correspond to SIS ranges 2 and 3 (Fig. 1). The ^{4}He intensities were interpolated to the energies of the ^{3}He measurements.

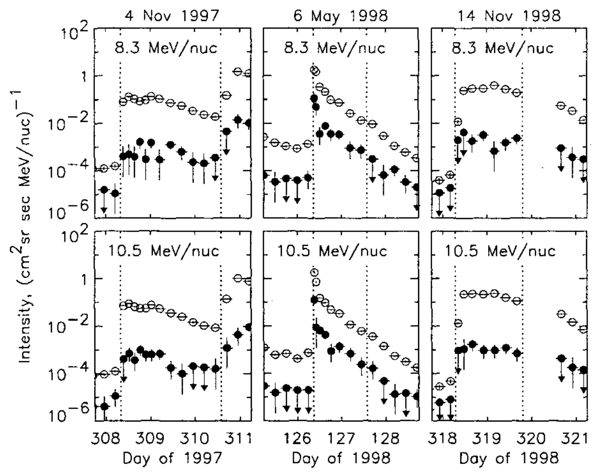

FIGURE 2. Time–intensity plots for He isotopes at 8.3 and 10.5 MeV/nucleon in three large SEP events. Filled points—^{3}He; open points—^{4}He. Dotted lines indicate start and stop times used for accumulating histograms in Fig. 1. A data gap occurred during the decline phase of the 14 Nov 1998 event.

The rise time of the particle intensities are short ($\lesssim$1–2 hr), as is commonly found when the Earth is magnetically well-connected to the acceleration site. These are consistent with the western-hemisphere locations which have been reported for the flares associated with these events (10). The intensity increases have relatively long durations (1–3 days) characteristic of gradual events, where particle acceleration continues as the shock propagates through the interplanetary medium. Shock associations have been reported for the events of 4 Nov 1997 (5) and 6 May 1998 (11). (The flare locations should also be the approximate locations from which CMEs driving the shocks were launched.)

In the 6 May 1998 event there is a brief "spike" in the intensities of ^{3}He and ^{4}He in the first hour or two of the event. A similar spike is also present for the heavy element fluxes in this event (10). The presence of this initial spike lasting less than 0.1 day is suggestive of a possible impulsive contribution to the event from flare-accelerated material. Temporal variations of abundances in this event are also discussed by Reames et al. (11) and von Rosenvinge et al. (12).

Since large enhancements of the ^{3}He/^{4}He ratio over the solar wind value of 4×10^{-4} are thought to be indicative of impulsive events, and impulsive event durations tend to be short ($\sim$hours), it is of interest to investigate whether this ratio varies over the course of the events we are investigating. In particular, does the intensity spike at the start of the 6 May 1998 event exhibit a distinctly greater enhancement of ^{3}He than the later, presumably gradual, phases of this event?

Figure 3 shows the time dependences of the ^{3}He/^{4}He values obtained from the ratios of the intensities shown in Figure 2. During the course of these events (delimited by the dotted vertical lines) no time variation of the ratio is evident, although the limited statistical accuracy of the ^{3}He measurements do not allow us to set very strong limits on this variation. We find that the ^{3}He enhancement in the 6 May 1998 event's initial spike is not appreciably greater than in the decay portion of the event.

The observation of time-independent ^{3}He/^{4}He ratios throughout these large events are similar to an example of time-independent helium isotopic composition reported by Mason et al. (6) at 0.7 MeV/nucleon in the event of 4 Jun 1999.

The average values of ^{3}He/^{4}He for the events studied here range from slightly less than 1% in the 14 Nov 1998 event to $\sim 5\%$ for the 6 May 1998 event. These values are all smaller than the 10% limit that traditionally has been used for identifying impulsive events on the basis of their ^{3}He/^{4}He enhancements. Nevertheless, they are 1 to 2 orders of magnitude greater than the solar wind ratio.

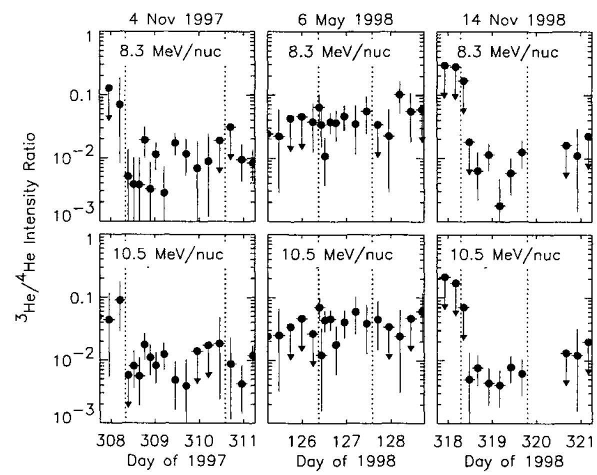

FIGURE 3. Time dependence of the measured ^{3}He/^{4}He intensity ratio at energies of 8.3 and 10.5 MeV/nucleon. Dotted lines indicate start and stop times used for the events. A data gap occurred during the decline phase of the 14 Nov 1998 event.

Figure 4 shows energy spectra for the helium isotopes obtained for the three large SEP events being investigated. The fluences shown are integrals of the intensities plotted in Figure 2 over the indicated event interval. (Note that the ^{3}He fluences have been multiplied by a factor of 50 to reduce the number of decades required for the plots.) The straight lines shown in Figure 4 result from power-law fits to the observed spectral points. The spectral indexes are summarized in Table 1. There is an apparent tendency for the spectra of ^{3}He to be somewhat harder than the corresponding spectra of ^{4}He, although the difference is greater than two standard deviations only in the 6 May 1998 event. Several authors have previously reported events with this characteristic (13, 14).

More significant is the comparison of the spectral indexes derived for ^{3}He in these large, presumably gradual, events with those found in events which have a clearly impulsive, ^{3}He-rich character. We have examined spectra of ^{3}He in ~ 40 such events observed between May 1998 and September 1999. Spectral indexes generally fell in the range -4.5 ± 1.5, with few instances of spectra as hard as those considered here (see also (13)).

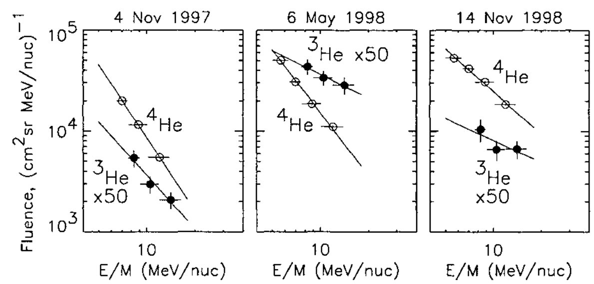

FIGURE 4. Energy spectra of ^{3}He and ^{4}He during the three large SEP events. Fluences are calculated as integrals over the time periods delimited by dotted lines in Fig. 2. Straight lines are least-squares fits of power laws to the observed spectra. Spectral slopes are summarized in Table 1.

Table 1. Slopes of Power-law Energy Spectra.

Event Start	Spectral Index [a] ^{3}He	^{4}He
4 Nov 1997	-1.77 ± 0.51	-2.41 ± 0.04
6 May 1998	-0.78 ± 0.50	-2.07 ± 0.05
14 Nov 1998	-0.72 ± 0.58	-1.40 ± 0.03

[a] Quoted uncertainties are 1σ statistical errors.

SUMMARY

The time and energy dependences of the abundances of ^{3}He and ^{4}He at energies > 5 MeV/nucleon have been examined in three large SEP events which were previously found to have significant enhancements of the ^{3}He/^{4}He ratio relative to its value in the solar wind. The isotope ratios show little, if any, variation throughout the course of the events, indicating that the ^{3}He enhancements are not the result of the occurrence of an impulsive, ^{3}He-rich event at the start of a larger gradual event with normal (i.e. solar-wind-like) helium isotopic composition. These observations do not rule out the possibility that the flare could be injecting material enriched in ^{3}He which is subsequently accelerated to MeV energies by the CME-driven shock (for further discussion see (12)).

The ^{3}He energy spectra are much harder than those found in typical, small, ^{3}He-rich events. In addition, there are indications that the spectra of ^{3}He may also be somewhat harder than the spectra of ^{4}He in the large events, although this result requires confirmation.

These observations further constrain models for the origin of ^{3}He abundance enhancements in SEP events and for the acceleration of particles in gradual events.

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