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LIGHT ISOTOPE ABUNDANCES IN SOLAR ENERGETIC PARTICLES MEASURED BY THE SPACE INSTRUMENT NINA

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ABSTRACT

This article reports nine solar energetic particle (SEP) events detected by the New Instrument for Nuclear Analysis (NINA) between 1998 October and 1999 April. NINA is a silicon-based particle detector mounted on board the Russian satellite *Resurs-01-4*, which has flown at an altitude of about 800 km in polar inclination since 1998 July. For every solar event, the power-law ^{4}He spectrum across the energy interval 10–50 MeV nucleon^{-1} was reconstructed and spectral indexes, γ, from 1.8 to 6.8 extracted. Data of ^{3}He and ^{4}He were used to determine the ^{3}He/^{4}He ratio, which for some SEP events indicated an enrichment in ^{3}He. For the 1998 November 7 event, the ratio reached a maximum value of 0.33 ± 0.06, with spectral indexes of $\gamma = 2.5 \pm 0.6$ and $\gamma = 3.7 \pm 0.3$ for ^{3}He and ^{4}He, respectively. The ^{3}He/^{4}He ratio averaged over the remaining events was 0.011 ± 0.004. For all events, a deuterium-to-proton ratio was estimated. An upper limit on the average value over all events was $^2\mathrm{H}/^1\mathrm{H} < 4 \times 10^{-5}$ across the energy interval 9–12 MeV nucleon^{-1}. Upper limits on the ^{3}H/^{1}H counting ratio for all events were determined. For the 1998 November 14 SEP event, the high flux of heavy particles detected made it possible to reconstruct the carbon, nitrogen, and oxygen flux.

Subject headings: solar wind — Sun: activity — Sun: flares — Sun: particle emission

1. INTRODUCTION

In 1970, Hsieh & Simpson (1970) discovered solar energetic particle (SEP) events with a greatly enhanced abundance of the rare isotope ^{3}He with the *Interplanetary Monitoring Platform* (*IMP-4*) satellite. Following this, many other experiments started to study solar ^{3}He-rich events. In such events, the ratio between ^{3}He and ^{4}He is strongly enhanced with respect to solar abundances ($\sim 4 \times 10^{-4}$) measured in the solar wind (Coplan et al. 1985; Bodmer et al. 1995). It was subsequently found that in these events, abundances of heavy elements were also unusual, with a Fe/O ratio about 10 times the value in the corona (see the review by Reames 1999).

The first hypothesis suggested that nuclear reactions of accelerated particles in the ambient of the solar atmosphere are the most probable source of ^{3}He. The presence of such reactions was independently confirmed by the detection of the 2.2 MeV neutron-proton recombination γ-line in solar flares (Chupp et al. 1973). Nowadays, γ-ray spectroscopy (Mandzhavidze, Ramaty, & Kozlovsky 1999) shows that there is presence of ^{3}He at the flare sites.

It is known that an enormous abundance of ^{3}He in SEPs does not correspond to an overabundance of ^{2}H and ^{3}H. While solar ^{3}He was detected by many observers, solar deuterium and tritium have proved to be very rare and difficult to detect in SEP events (Anglin 1975; Mewaldt & Stone 1983; Van Hollebeke, McDonald, & Trainor 1985; McGuire, von Rosenvinge, & McDonald 1986). Measured abundances of ^{2}H and ^{3}H in SEPs are consistent with the thin target model of flares (Ramaty & Kozlovsky 1974). However, it was shown (Anglin 1975 and references therein) that this model could not explain the 1000-fold enhancement in the ^{3}He/^{4}He ratio and also the enrichment of heavy elements. It became clear that selective mechanisms of ^{3}He acceleration were required (Fisk 1978).

SEPs are now believed to come from two different sources. The SEPs from solar flares usually have an enhancement in the ^{3}He/^{4}He ratio and an enhanced number of heavy ions with respect to solar abundances because of reso-

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nant wave-particle interactions at the flare site, where the ions are highly stripped of orbital electrons by the hot environment. However, the most intense SEP events, with particles of the highest energies, are produced by accelerations at shock waves driven by coronal mass ejections (CMEs). On average, these particles directly reflect the abundances and temperature of ambient unheated coronal material. Various aspects of gradual and impulsive SEP events have been compared in a variety of review articles (Reames 1999 and references therein).

Flares and CMEs can occur separately. Most flares are not accompanied by a CME, whereas many fast CMEs that produce gradual SEP events have associated flares. The most interesting events are therefore the "pure" ones, in which the two mechanisms are not acting together, and it is therefore easier to distinguish and characterize the acceleration processes involved.

The ^{3}He/^{4}He ratio can be used to characterize the two types of event. ^{3}He/^{4}He ~ 1 is not uncommon in impulsive events, while ^{3}He/^{4}He < 0.01 usually indicates gradual SEP events. However, this ratio is difficult to measure and is not available for a large sample of events (Chen, Guzik, & Wefel 1995; Mason, Mazur, & Dwyer 1999). Precise measurements of the ^{3}He/^{4}He ratio can provide new constraints on existing theories that discuss ^{3}He acceleration mechanisms and the propagation processes.

The aim of this article is to present measurements of light isotope abundances in SEP events detected in the period 1998 October–1999 April by the New Instrument for Nuclear Analysis (NINA). NINA was launched on 1998 July 10 from the Baikonur launch facility in Kazakhstan, on board the Russian satellite *Resurs-01-4*. The orbit of the spacecraft is Sun-synchronous, with an inclination of 98° and an altitude of approximately 800 km. In § 2, we describe the instrument briefly; in § 3, we discuss the algorithms of event selection and particle identification and the background analysis. Results are presented in § 4, and possible interpretations are given in § 5.

2. THE INSTRUMENT

The instrument NINA is optimized for the detection of galactic, solar, and anomalous cosmic rays in the energy window 10–200 MeV nucleon^{-1}. It is composed of 16 planes, each made of two *n*-type silicon detectors, 6×6 cm^2, segmented in 16 strips and orthogonally mounted so to provide the X and Y information of the particle track. The thickness of the first two detectors is 150 μm; all the others are 380 μm thick, for a total of 11.7 mm of active silicon.

The 16 planes are vertically stacked. The interplanar distance is 14 mm, but the first and second planes are separated by 85 mm, for a better measurement of the particle incident angle. The total telescope height is 29.5 cm. An aluminum layer 300 μm thick covers the detector. More details about the detector configuration can be found in Bakaldin et al. (1997) and Bidoli et al. (1999, 2001).

A veto system, ensuring the containment of particles entering the detector from above, is implemented by setting in anticoincidence strips 1 and 16 of planes 2–15 (lateral anticoincidence) and all strips of plane 16 (bottom anticoincidence). The request of containment inside the telescope defines the upper energy limits for particle detection, which is equal to about 50 MeV nucleon^{-1} for ^{4}He.

The threshold for energy deposits in the silicon layers is set to 250 keV (low threshold) in order to eliminate all relativistic protons that release only $\sim$100 keV in 380 μm of silicon. A second threshold, at 2500 keV (high threshold), further restricts the detection of protons. All results presented in this paper come from data acquired in high-threshold mode.

The instrument NINA is housed in *Resurs-01* on the top side external to the satellite, in such a way that it always points to the zenith during the flight.

3. DATA ANALYSIS

The study of SEP rare isotope abundances requires a careful analysis of the data collected. The background includes either noise and unidentifiable events, which can be eliminated by an off-line dedicated selection algorithm, or particles produced by secondary interactions in the material surrounding the NINA silicon tower. In order to detect only solar particles, the solar quiet background must be excluded also.

Table 1 shows the energy window of NINA for the atomic species mostly studied during SEP events, in high-threshold configuration. Figure 1 shows the geometric factor (GF) for the same isotopes.

3.1. *Event Selection and Mass Reconstruction*

The optimal performance of NINA in terms of charge, mass, and energy determination is achieved by requiring the full containment of the particle inside the detector with the lateral and bottom anticoincidence. Despite the presence of the lateral anticoincidence, some particles leave the detector between silicon planes. In order to eliminate this effect, tracks with energy deposits in strips 2 or 15 for any of the layers of the silicon tower are rejected off-line. This requirement reduces the GF of the instrument, and this is taken into account in calculations (Fig. 1). The segmented nature of the detector, in addition to measuring the total energy released, allows a very precise determination of the topology of the particle's path inside the instrument. With this information, it is possible to build a dedicated off-line track selection algorithm that rejects upward-moving particles, tracks accompanied by nuclear interactions, and events consisting of two or more tracks. A detailed description of the selection algorithm can be found in Bidoli et al. (2001).

The background reduction capability of the track selection algorithm was previously tested with beam test data and in the Galactic cosmic rays (GCR) analysis. Figure 2 shows E_1 plotted against E_{tot} for events collected during

TABLE 1

Energy Windows for Contained Particles in High-Threshold Mode

Particle	Z	Energy Window (MeV nucleon^{-1})
^{1}H	1	11–16
^{2}H	1	7–13
^{3}H	1	5–12
^{3}He	2	12–58
^{4}He	2	10–50
^{12}C	6	18–90
^{16}O	8	21–107

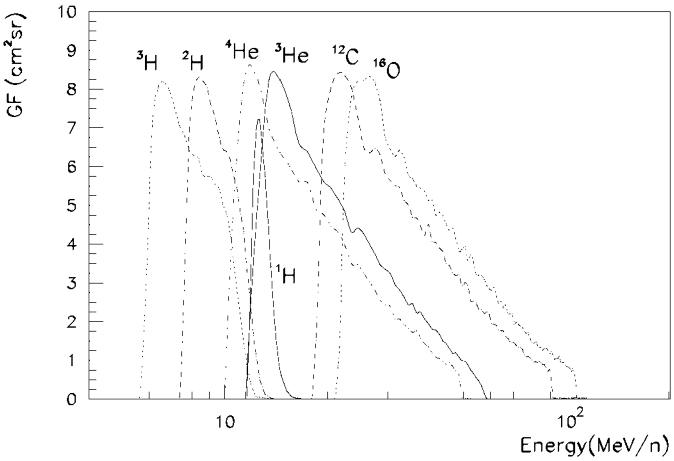

FIG. 1.—GF of NINA for ^{1}H, ^{2}H, ^{3}H, ^{3}He, ^{4}He, ^{12}C, and ^{16}O in high-threshold mode.

the 1998 November 7 SEP event, after the application of the track filter. E_1 is the energy released by the particles in the first silicon detector of the tower NINA, and E_{tot} is the total energy released by the particles in the silicon active layers, after particles lose energy in the aluminum cover (300 μm) of the detector. It is evident that almost all background was rejected, while eliminating on average only $\sim$3% events

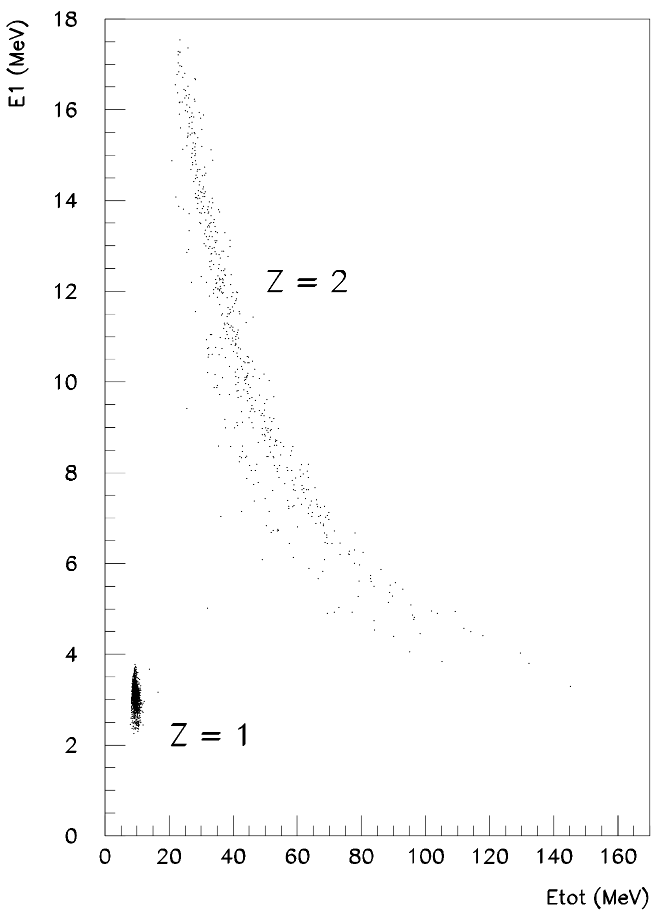

FIG. 2.—E_1 vs. E_{tot} for events collected during the 1998 November 7 SEP event, after the action of the track filter. Here E_1 is the energy released by particles in the first silicon detector, and E_{tot} is the total energy released.

from the whole sample. This is evidence of small background contamination in SEPs.

Charge and mass identification procedures are applied to events that survive the track selection algorithm. The mass M and the charge Z of the particles are calculated in parallel by two methods, in order to have a more precise particle recognition: one method uses the residual range, while the other uses an approximation of the Bethe-Bloch theoretical curve (Bidoli et al. 2001).

For a more complete rejection of the background, only particles with the same final identification according to the two methods are selected. Finally, a cross-check between the experimental range of the particle in the detector and the expected value according to the simulations gives a definitive consistency test for the event. These consistency cuts eliminate about 0.1% of tracks detected during SEP events.

3.2. *Background Estimations*

As anticipated above, in order to study rare isotope abundances (^{2}H, ^{3}H, and ^{3}He) in the analysis of SEPs, it is necessary to subtract the solar-quiet background. Secondary productions inside the instrument induced by high-energy solar particles must also be accounted for.

Solar-quiet background.—This includes Galactic particles (only ^{2}H and ^{3}He) and secondary ^{2}H, ^{3}H, and ^{3}He, which are produced by nuclear interactions of primary cosmic rays inside the 300 μm of aluminum that cover the first silicon plane of NINA.

We measured this background component during passes over the polar caps in solar-quiet periods; the average counting rate was $\sim(7.5 \pm 0.9) \times 10^{-5}$ events s^{-1} for deuterium, $\sim(3.7 \pm 0.6) \times 10^{-5}$ events s^{-1} for tritium, and $\sim(1.5 \pm 0.1) \times 10^{-4}$ events s^{-1} for ^{3}He, each of them relative to the energy interval reported in Table 1.

Secondary production by SEPs.—The amount of secondary productions inside the instrument, induced by interactions of solar particles, cannot be directly measured but can be inferred by estimations.

The most important reactions that can produce secondary ^{2}H, ^{3}H, and ^{3}He are the interactions of protons and α-particles with the aluminum cover:

1. $^{27}\mathrm{Al}\,(p, X)\ ^2\mathrm{H}, ^3\mathrm{H}, ^3\mathrm{He}, \ldots,$
2. $^{27}\mathrm{Al}\,(\alpha, X)\ ^2\mathrm{H}, ^3\mathrm{H}, ^3\mathrm{He}, \ldots.$

The ratio R between secondary ^{3}He and primary ^{4}He nuclei, considering reaction (1) and (2), is given by

$$R = \left(\frac{\sigma_p F_p}{F_\alpha} + \sigma_\alpha\right) \frac{N_A}{A} \rho \Delta x \,, \qquad (1)$$

where σ_p and σ_α are the cross sections for the reactions (1) and (2), respectively, F_p and F_α are the integral fluxes of incident protons and α-particles with sufficient energy to produce a secondary ^{3}He detectable by NINA ($E_p > 40$ MeV, $E_\alpha > 10$ MeV nucleon^{-1}), N_A is the Avogadro number, Δx the thickness of the aluminum cover, ρ the density of aluminum, and A its atomic weight.

To give an estimation of the ^{3}He secondary production in NINA, we adopt a value of $\sigma_p = 30$ mbarn (Segel et al. 1982; Michel et al. 1995) and $\sigma_\alpha = 100$ mbarn, as taken by the authors in Chen et al. (1995). Equation (1) then becomes

$$R = 2 \times 10^{-4} \left(0.3 \frac{F_p}{F_\alpha} + 1\right) . \qquad (2)$$

Here F_α is directly measured by our instrument. In order to evaluate F_p, we must propagate the proton flux, which we measure in the energy interval 12–14 MeV, to higher energies utilizing the proton spectral index from *IMP-8*.[2]

Table 3 reports the values of R estimated for the nine SEP events considered. The background coming from estimations using equation (2) is less than 10% of the solar-quiet background, except for one case (1998 November 14) in which an additional analysis was needed.

Similar calculations of the ratio R between secondary ^{2}H and primary ^{1}H nuclei, and between secondary ^{3}H and primary ^{1}H nuclei, give a result of $R \sim 10^{-5}$.

3.3. *Dead Time of the Instrument*

During solar energetic events, the counting rate is orders of magnitude higher than during solar-quiet periods, so the dead time of the instrument can have an important effect on flux measurements.

The time resolution of the trigger system in NINA is about 2 μs. If a particle produces a trigger, the signal from the detectors is amplified and shaped before being sampled by an ADC. The event is then stored in a first-in first-out (FIFO) for 2 ms. The data are read by the onboard processor, which performs pedestal subtraction and zero suppression for each channel, and then are stored in the memory. This procedure takes 10 ms.

In order to estimate the dead time of the instrument, Monte Carlo simulations of the performance of the data acquisition system were carried out, assuming a Poisson distribution of the particle fluxes. Figure 3 shows the ratio between the estimated dead time and the observational time of the instrument as a function of the measured rate. This ratio is fitted with an exponential function, and the parameters of the fit have been used in the exposure time program (see § 3.4). The uncertainty on the fit parameters is of the order of 10%, and this yields a maximal inaccuracy of 2% on the exposure time calculations for all the SEP events analyzed.

3.4. *Flux Measurements*

To be free from the effects of the rigidity cutoff due to the Earth's magnetic field, only events recorded in polar regions at L-shell > 6 have been considered for SEP analysis. Figure 4 shows the counting rate of ^{4}He and ^{16}O, as a function of energy, detected at two different geomagnetic latitudes. The acquisition rate does not vary between the cut L-shell > 6 and > 10.

Particle fluxes were reconstructed according to the following formula:

$$\text{flux}(E) = \frac{\Delta N(E)}{T\,\text{GF}(E)\Delta E} ,$$

where $\Delta N(E)$ is the number of particles detected with an energy between $E - \Delta E/2$ and $E + \Delta E/2$, T is the exposure time in orbit, which also takes into account the dead time of the instrument, GF(E) is the average value of the GF between $E - \Delta E/2$ and $E + \Delta E/2$ (see Fig. 1), and ΔE is the relevant energy bin.

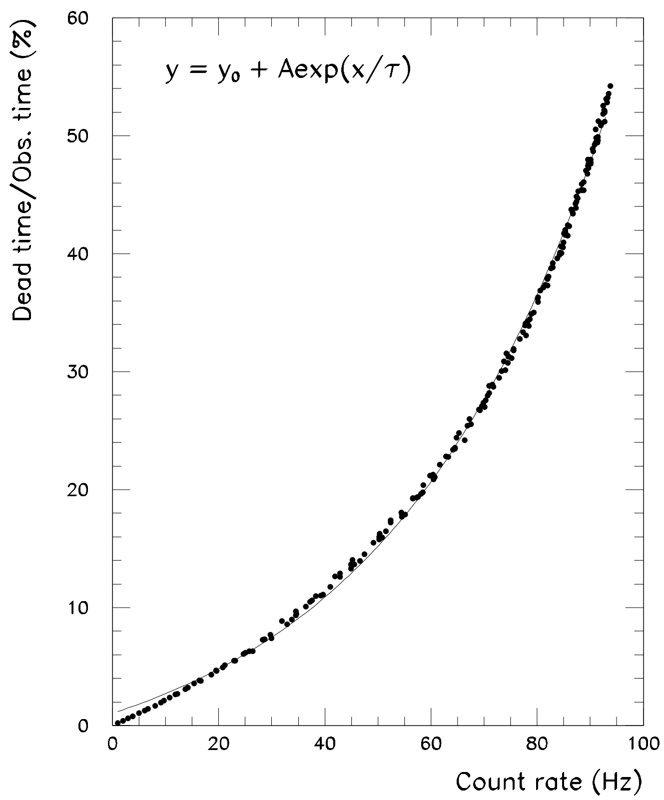

FIG. 3.—Ratio between the dead time and the observation time of NINA, as a function of the external rate. An exponential fit has been superposed.

4. SEP MEASUREMENTS

SEP events were identified by an unpredictable increase in the trigger rate of the instrument, at least 1 order of magnitude with respect to the averaged solar-quiet values. Nine such increases in the period 1998 October–1999 April have been chosen for analysis. To illustrate them, Figure 5 shows the counting rate of protons with energy of ~10 MeV as a function of time measured by NINA in this period, together with the *GOES-8* proton intensity (energy greater than 10 MeV).[3] NINA had some pauses in data recording due to the filling of the onboard memory or to data transmission problems.

A summary of all nine events observed by NINA is presented in Table 2, together with characteristics of the solar events that can be associated with the SEPs.[4] The event of 1998 November 14 was the most powerful; the counting rate increased almost 3 orders of magnitude with respect to solar-quiet periods, reaching a value of 70 Hz. Figure 5 indicates that the event lasted several days and was detected by our instrument in two separate emissions (Table 2). For the other events, we registered increases of 1 or 2 orders of magnitude on average. The events of 1998 November 6–8 and those of 1999 January 20–22 occurred in a very close period of time, and there might be effects of superposition between events. However, as shown later, their spectral characteristics and isotopic composition are very different. For this reason, we

[2] See http://nssdc.gsfc.nasa.gov/space/space_physics_home.html.

[3] See http://www.sel.noaa.gov/Data/goes.html.

[4] See gopher://solar.sec.noaa.gov:70/11/indices.

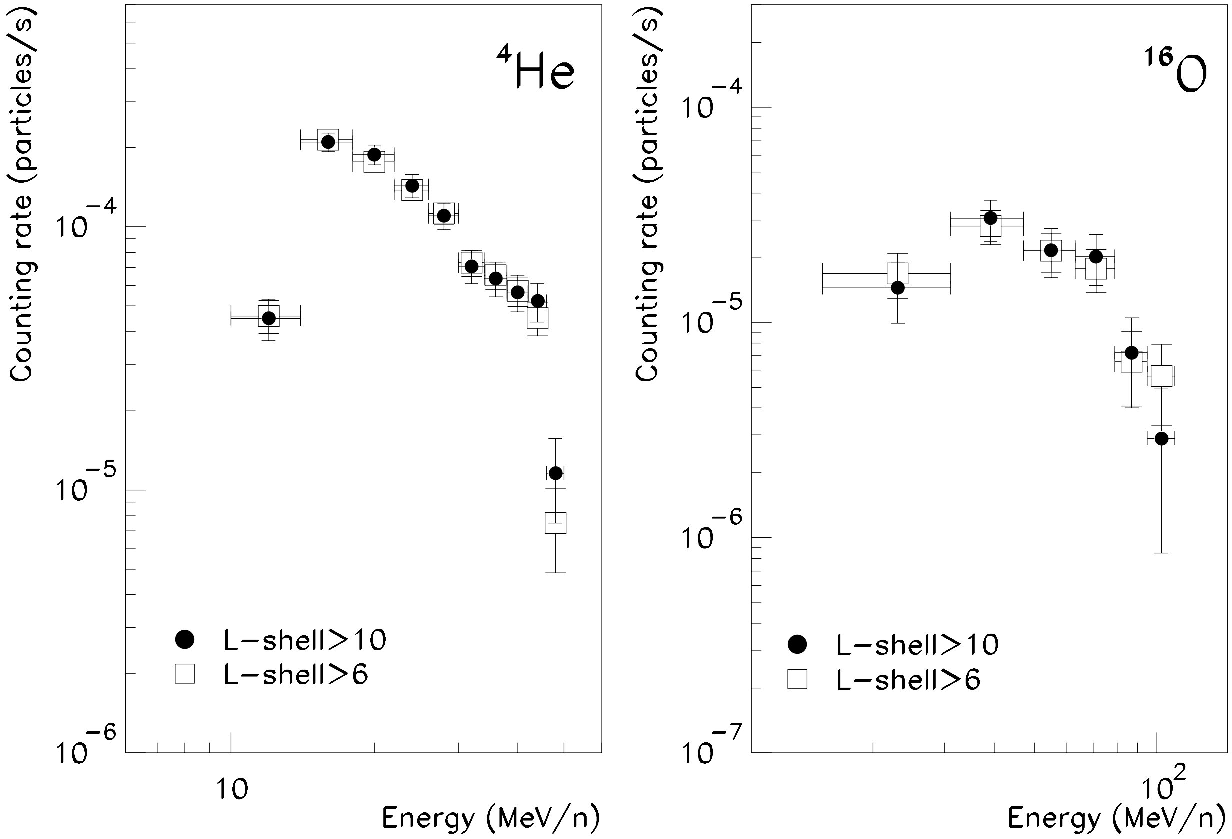

FIG. 4.—Counting rate, plotted as a function of energy, for ^{4}He (*left*) and ^{16}O (*right*) measured at different geomagnetic latitude

believe that these SEPs may have a different origin, and we studied their characteristics separately. As is evident in Figure 5, all chosen events are in good correlation with *GOES-8* observations.

^{4}He observations range from 10 to 50 MeV nucleon^{-1}. Figure 6 presents the ^{4}He fluxes that were reconstructed during every SEP event. The dashed line on the spectra is a fit of the solar-quiet Galactic background of ^{4}He, measured by our own instrument (Bidoli et al. 2001). Data of the Galactic background, in our energy range, are well reproduced by the function

$$B\left[E\left(\text{MeV nucleon}^{-1}\right)\right] = 9.6 \times 10^{-6} + 4.1 \times 10^{-9} \exp(E/6.7) \left(\text{cm}^2 \text{ sr s MeV nucleon}^{-1}\right)^{-1} . \quad (3)$$

TABLE 2

SEP EVENTS AND CHARACTERISTICS OF ASSOCIATED SOLAR EVENTS

SEP Date (1)	Observation Time (2)	NOAA (3)	Class (X-Ray/Hα) (4)	Location (deg) (5)	Time of X-Ray Event (UT) (6)
1998 Nov 6........	310.38–311.52	8375	C1.1/SF	N19W25	04:38
			C1.4/SF		04:56
1998 Nov 7........	311.52–311.89	8375	M2.4/...	...	11:06
1998 Nov 8........	312.34–312.87	8379	C2.4/SF	S20W67	20:20 (Nov 7)
1998 Nov 14......	318.36–318.54	8385	C1.7/BSL	N28W90	05:18
	320.60–322.25				
1998 Nov 22......	326.32–327.33	8384	X3.4/1N	S27W82	06:42
1998 Nov 24......	329.30–332.14	8384	X1.0/...	...	02:20
1999 Jan 20	20.96–22.93	...	M5.2 /...	...	20:04
1999 Jan 22	22.93–24.90	8440	M1.4/SF	N19W44	17:24
1999 Feb 16.......	47.23–49.04	8458	M3.2/SF	S23W14	03:12

NOTE.—Col. (2): NINA observation time (day of the year) for the SEP event. Col. (3): NOAA region number of the associated flare. Col. (4): Importance of the flare in terms of X-ray/Hα classification. Col. (5): Location of the flare in heliocentric coordinates. Col. (6): Starting time (hh:mm) of the X-ray event.

REFERENCES.—See gopher://solar.sec.noaa.gov:70/11/indices.

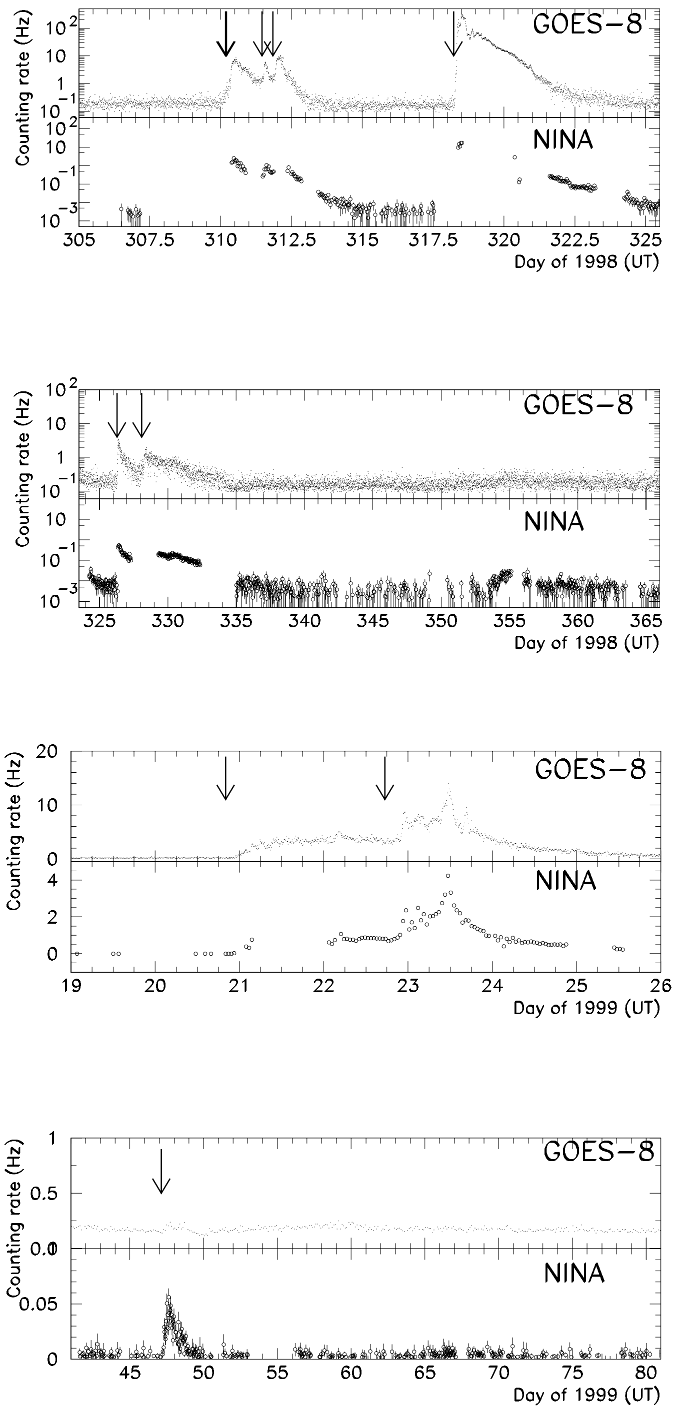

FIG. 5.—Proton counting rate for the period 1998 November–1999 March, for *GOES-8* (*top*; $E > 10$ MeV) and NINA (*bottom*). Arrows mark the candidate X-ray associated event, according to Table 2.

The energy spectrum during the SEP events was fitted by a power-law component plus the background (*solid line*)

$$S\left[E\left(\text{MeV nucleon}^{-1}\right)\right] = AE^{-\gamma} + B(E)\left(\text{cm}^2 \text{ sr s MeV nucleon}^{-1}\right)^{-1} . \quad (4)$$

The value of γ (spectral index) for each event is reported in Table 3. It varies considerably from event to event, ranging from 1.8 in the 1998 November 14 event to 6.8 in the 1998 November 8 event. It is interesting to note that the 1998 November 6 and 7 events occur in the same NOAA region (see Table 2) but present different values of the spectral index. The same holds for the 1998 November 22 and 24 SEP events, in contradiction to observations by Chen et al. (1995) with the *Combined Release and Radiation Effects Satellite* (*CRRES*), in which events in the same NOAA region tended to have similar spectral indexes.

Table 3 summarizes measurements of the ratio $(^3\text{He}_{\text{SEP}} - {}^3\text{He}_{\text{BG}})/{}^4\text{He}$ in the range 15–45 MeV nucleon^{-1} for the nine SEP events, where $^3\text{He}_{\text{SEP}}$ represents the total flux of ^{3}He that was measured during the SEP events, and $^3\text{He}_{\text{BG}}$ the estimation of its overall background, as discussed in § 3.2. During the 1998 November 7 and 14 SEP events, this ratio is 3 σ more than the solar coronal value.

For the 1998 November 7 SEP event, we reconstructed the masses of ^{3}He and ^{4}He (Fig. 7), and it was possible to plot the ^{3}He differential energy spectrum over a wide energy interval (Fig. 8). The ^{3}He spectrum, also fitted by a power law, is slightly harder ($\gamma = 2.5 \pm 0.6$) than that of ^{4}He ($\gamma = 3.7 \pm 0.3$). This implies that the $^3\text{He}/^4\text{He}$ ratio increases with energy in this event. This tendency is also confirmed by a comparison between our data and measurements taken on board the *Advanced Composition Explorer* (*ACE*; Ultra–Low-Energy Isotope Spectrometer [ULEIS]; Mason et al. 1999) over the energy range 0.5–2.0 MeV nucleon^{-1} and averaged over the period 1998 November 6–8. Extrapolating the ^{3}He energy spectrum measured by NINA to lower energies, the inferred $^3\text{He}/^4\text{He}$ ratio for this SEP event would be about 10^{-4}, in agreement with their value and much lower than what we obtain at higher energies.

For the 1998 November 7 SEP event, we reconstructed the time profiles of different nuclei. Figure 9 shows the time profile of the counting rate of ^{1}H, ^{3}He, and ^{4}He detected over the polar caps during this event. Every point on the plots corresponds to a passage over the pole, which lasted about 10 minutes. The profiles have been fitted by the function (Burlaga 1967)

$$\text{counting rate } [t(\text{days})] = A(t - t_0)^{-2.5} e^{-2.5 t_{\max}/(t - t_0)} \text{ Hz} , \quad (5)$$

where t is expressed in days (UT), t_0 corresponds to the beginning of the 1998 November 7 event, and A and $t_{\max}$ are the two parameters of the fit. Direct propagation from Sun to Earth takes, for 10 MeV nucleon^{-1} particles, roughly 1 hr. Taking into account this value and assuming that the main part of the particle emission occurs before $t_{\max}$, we estimate the time interval of particle emission at the Sun for the three nuclear species to be not more than 3 hr. This similarity suggests the same acceleration and transport mechanisms for the nuclear species, despite their different charge-to-mass ratio.

The strongest solar event that we detected, as already mentioned, was the one of 1998 November 14. Because of the very high flux intensities, which increased the noise of the detector, the ^{3}He spectrum was reconstructed only by nuclei that crossed at least seven silicon layers in the instrument, so having energies greater than 25 MeV nucleon^{-1}. Figure 10 shows the helium isotope mass reconstructions for tracks with at least seven views hit. Figure 11 presents the energy spectrum of ^{3}He and ^{4}He together. On the same figure, ^{4}He measurements from the Solar Isotope Spectrometer (SIS) on board the *ACE* are

TABLE 3
SUMMARY OF PHYSICS FEATURES OF SEP EVENTS

SEP Date	γ[a]	$^1H/^4He$[b]	$R(^3He/^4He)$[c]	$^3He/^4He$[d] ($\times 10^{-2}$)	$^2H/^1H$[e] ($\times 10^{-5}$)	$^3H/^1H$ ($\times 10^{-4}$)
1998 Nov 6........	4.7 ± 0.4	171 ± 16	3×10^{-3}	6.5 ± 4.3	<5.0	<1
1998 Nov 7........	3.7 ± 0.3	24 ± 2	6×10^{-4}	33 ± 0.6	<3.4	<2
1998 Nov 8........	4.5 ± 0.5	18 ± 2	5×10^{-4}	23 ± 10	<5.3	<14
1998 Nov 14......	1.78 ± 0.05	21.9 ± 0.5	5×10^{-4}	1.1 ± 0.3[f]	<1.7	<50
1998 Nov 22......	1.9 ± 0.4	22 ± 4	5×10^{-4}	<2.8	<5.1	<9
1998 Nov 24......	3.5 ± 0.2	17 ± 1	5×10^{-4}	4.1 ± 3.2	<35	<7
1999 Jan 20	2.8 ± 0.2	182 ± 14	3×10^{-3}	0.3 ± 0.6	<3.5	<6
1999 Jan 22	4.2 ± 0.1	166 ± 8	3×10^{-3}	-0.1 ± 0.6	<0.7	<3
1999 Feb 16.......	3.4 ± 0.7	12.2 ± 2.5	4×10^{-4}	-0.1 ± 8.0	<37	<90

[a] Energy: 10–50 MeV nucleon^{-1}.
[b] Energy: 12–14 MeV nucleon^{-1}.
[c] R is the estimated background ratio according to eq. (2).
[d] $^3He => {^3He_{SEP}} - {^3He_{BG}}$; energy: 15–45 MeV nucleon^{-1}.
[e] $^2H => {^2H_{SEP}} - {^2H_{BG}}$; energy: 9–12 MeV nucleon^{-1}.
[f] Energy is greater than 25 MeV nucleon^{-1}.

also reported.[5] For the 1998 November 14 event, there are other measurements of the $^3He/^4He$ ratio, performed by the *IMP-8* (Dietrich & Lopate 1999) and SIS instrument (Cohen et al. 1999). Their measured values are $r = 0.02 \pm 0.01$ in the energy interval 30–95 MeV nucleon^{-1}, and $r = 0.005$ in the range 8–14 MeV nucleon^{-1}.

During the 1998 November 14 SEP event, there was also a strong presence of heavy elements. Figure 12 presents the differential energy spectra for carbon, nitrogen, and oxygen compared to SIS data collected in the same period (day 317).

The high-threshold mode allowed the observation of hydrogen with its isotopes over the narrow energy windows shown in Table 1. Table 3 presents the ratios between deuterium and proton after background subtraction, in the range 9–12 MeV nucleon^{-1}. Since the two isotope measurements span two different energy regions (see Table 1), we measured the proton flux in the range 11–16 MeV and utilized the proton spectral index from *IMP-8*[6] to extrapolate the proton flux to the deuteron energy region. Because of uncertainties in the background estimation, these values can be considered as upper limits of the $^2H/^1H$ ratio. The average value of the ratio $^2H/^1H$ over all events is 4×10^{-5}; this value is in agreement with a previous measurement (Anglin 1975), which reported a $^2H/^1H$ ratio equal to $(5.4 \pm 2.4) \times 10^{-5}$ between 10.5 and 13.5 MeV nucleon^{-1}, when averaged over a large number of SEP events, consistent with solar abundance values (McGuire et al. 1986).

From our data, it was possible to estimate upper limits for tritium. The last column of Table 3 presents the ratio of counting rates of ^3H in the interval 6–10 MeV nucleon^{-1} and of ^1H in the range 11–14 MeV.

5. DISCUSSION

The isotope abundance ratio and the energy spectra of SEPs are related to the acceleration mechanisms and propagation processes involved.

Among the nine $^3He/^4He$ ratios calculated from our SEP events, only the 1998 November 7 one is clearly more than 3 σ above the background level. The energy spectra and counting rate profiles of ^3He and ^4He during this event were presented in Figures 8 and 9 and partially discussed in the previous section. By using the *IMP-8* spacecraft data,[7] it is possible to also extract the average value of the proton spectral index, γ, equal to 3.6 ± 0.1 in the energy range 11–74 MeV. This value is practically the same as the ^4He spectral index (see Table 3) measured by NINA for this SEP event.

The energy spectra of SEPs measured at 1 AU can be modified, with respect to the emission spectra, by propagation effects. The absolute value of the mean free paths of particles traveling from the Sun to the Earth can vary by 1 order of magnitude between individual events, but as shown in Dröge (2000), the shape of the rigidity dependence does not vary. This rigidity dependence is a power law with a slope equal to 0.3 in NINA's rigidity intervals. Since the ^3He rigidity, at the same energy per nucleon, is between that of proton and ^4He, it would be difficult in the 1998 November 7 SEP event to explain the hardness of the ^3He spectrum compared to that of ^4He and of protons only with diffusion effects from the Sun. The differences in the spectral shapes of ^3He and ^4He, observed at 1 AU in this event, most probably already existed during the SEPs emission.

Wave resonance is the most likely mechanism for ^3He acceleration in the 1998 November 7 SEP event (Roth & Temerin 1997). This mechanism accelerates both ^3He and heavy ions. The abundance of heavy and ^3He ions is determined by the temperature and density of the flare plasma and by the wave properties. It is interesting to note that data reported by the *ACE* (Klecker et al. 1999) identify this SEP event as gradual by the low Fe/O ratio. In this work, the ionic charge of several heavy ions, including iron, was determined. These measurements at low energy (0.2–0.7 MeV nucleon^{-1}) are consistent with an equilibrium plasma temperature of $\sim(1.3–1.6) \times 10^6$ K and with typical solar wind values, suggesting acceleration from a solar wind source. With a plasma temperature of $\sim$2 MK, Roth & Temerin (1997) predict the existence of a large population of oxygen

[5] See http://www.srl.caltech.edu/ACE/ASC/level2.
[6] See http://nssdc.gsfc.nasa.gov/space/space_physics_home.html.
[7] See http://nssdc.gsfc.nasa.gov/space/space_physics_home.html.

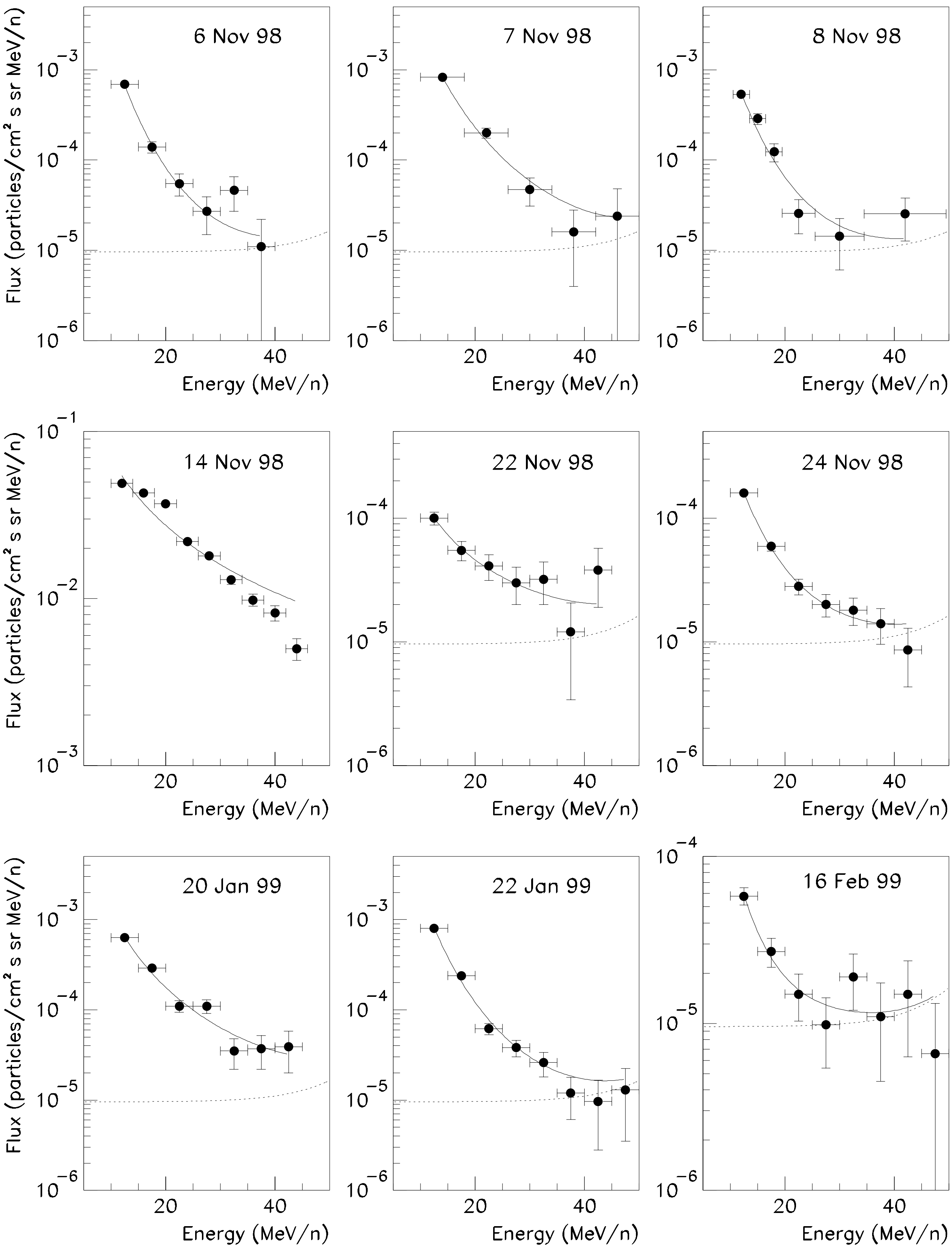

FIG. 6.—Differential energy spectrum for ^{4}He for the nine different SEP events detected by NINA. The dashed line (see eq. [3]) represents the background $B(E)$ of Galactic ^{4}He; a power-law spectrum $S(E)$ (*solid line*; see eq. [4]) has been superposed on the data.

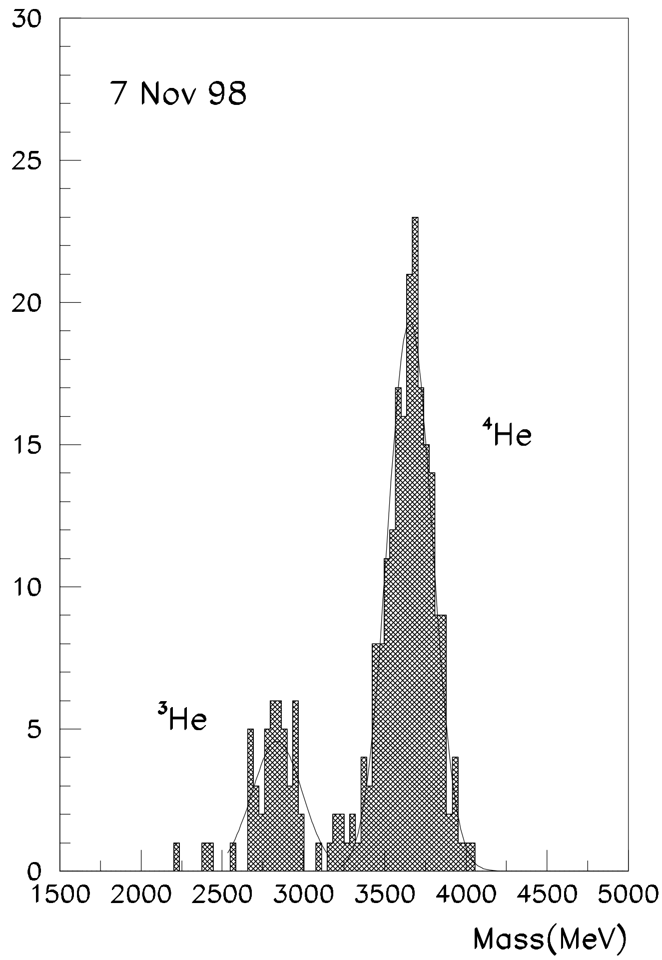

FIG. 7.—1998 November 7 SEP event: mass reconstructions for ^{3}He and ^{4}He.

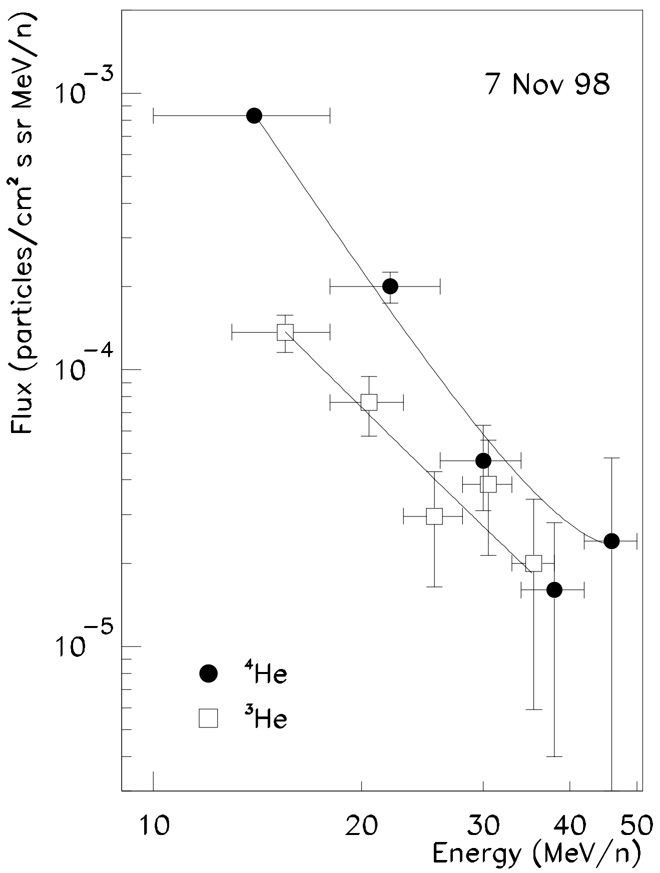

FIG. 8.—1998 November 7 SEP event: differential energy spectrum for ^{3}He and ^{4}He.

at the same energy per nucleon as ^{3}He, which was not observed by our instrument. Another possible reason for the discrepancy between this event characteristic measured by the two instruments is the narrow cone of emission for particles from ^{3}He-rich events (Reames, Kallenrode, & Stone 1991). It would be interesting to confront our measured spectral behavior of ^{3}He and ^{4}He with the predictions of this model, but complete spectral calculations are not yet available.

Some observations reported already since 1970 (Hsieh & Simpson 1970; Webber et al. 1975) that a small ^{3}He enrichment is also present in large events. Because of instrumental limitations of most of the experiments in space, however, systematic ^{3}He/^{4}He measurements in large events with small ^{3}He enrichment were not available. More recently,

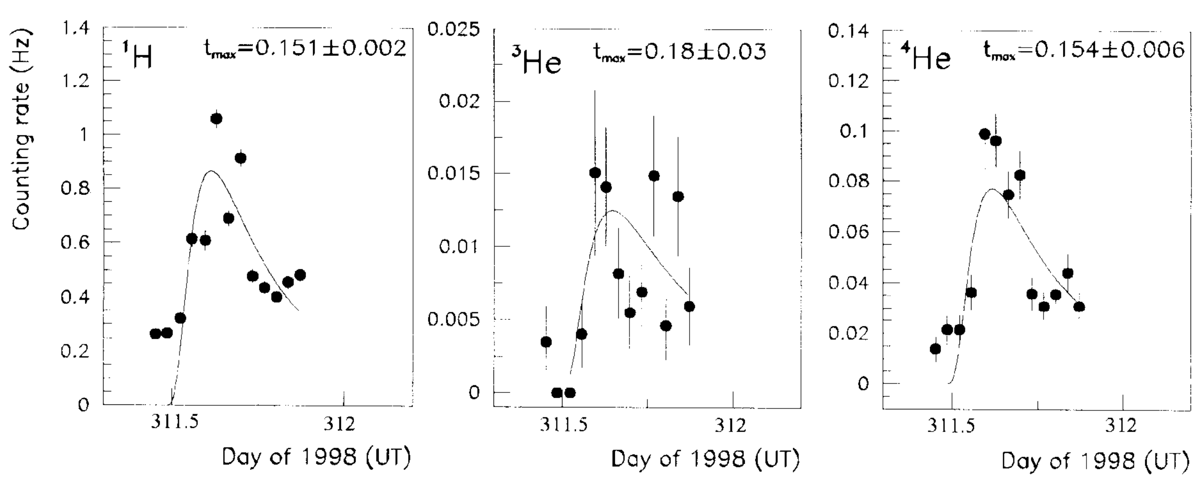

FIG. 9.—1998 November 7 SEP event: time profile of the counting rate of ^{1}H (*left*), ^{4}He (*center*), and ^{3}He (*right*) during the SEP event. Here t_{max} (days) is the fit parameter appearing in eq. (5), which corresponds to the maximum of the time profile.

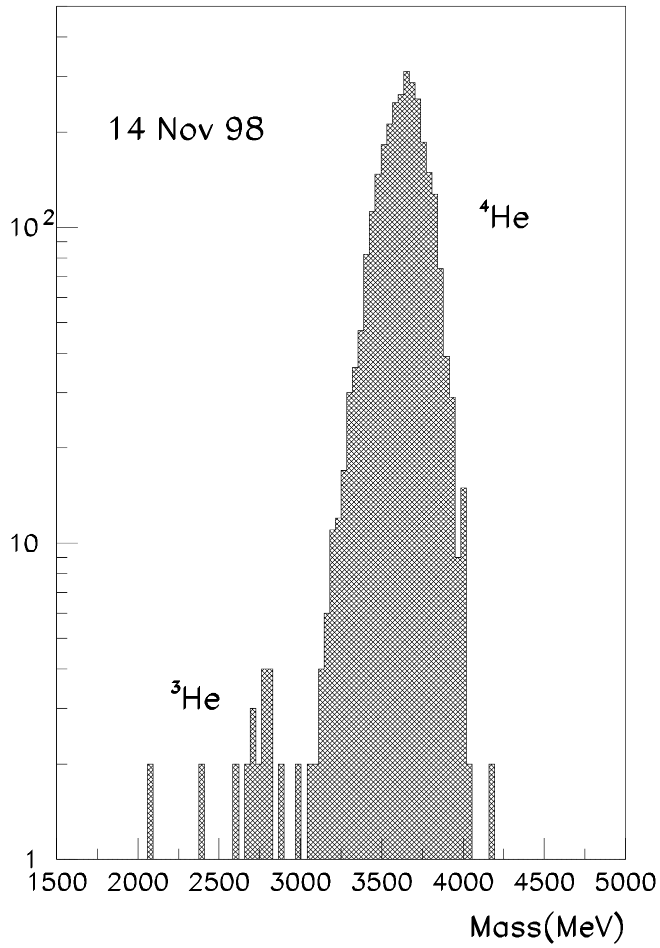

FIG. 10.—1998 November 14 SEP event: mass reconstructions for ^{3}He and ^{4}He (energy greater than 25 MeV nucleon^{-1}).

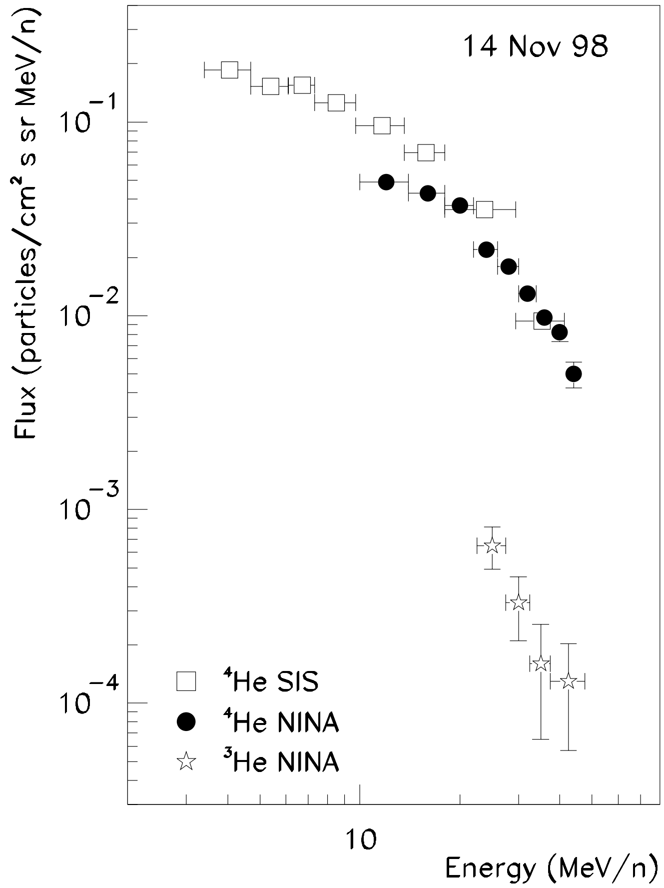

FIG. 11.—1998 November 14 SEP event: differential energy spectrum for ^{3}He (energy greater than 25 MeV nucleon^{-1}) and ^{4}He, measured on day 317 (see Table 2). The open squares are data from SIS (*ACE* satellite), taken in the same period.

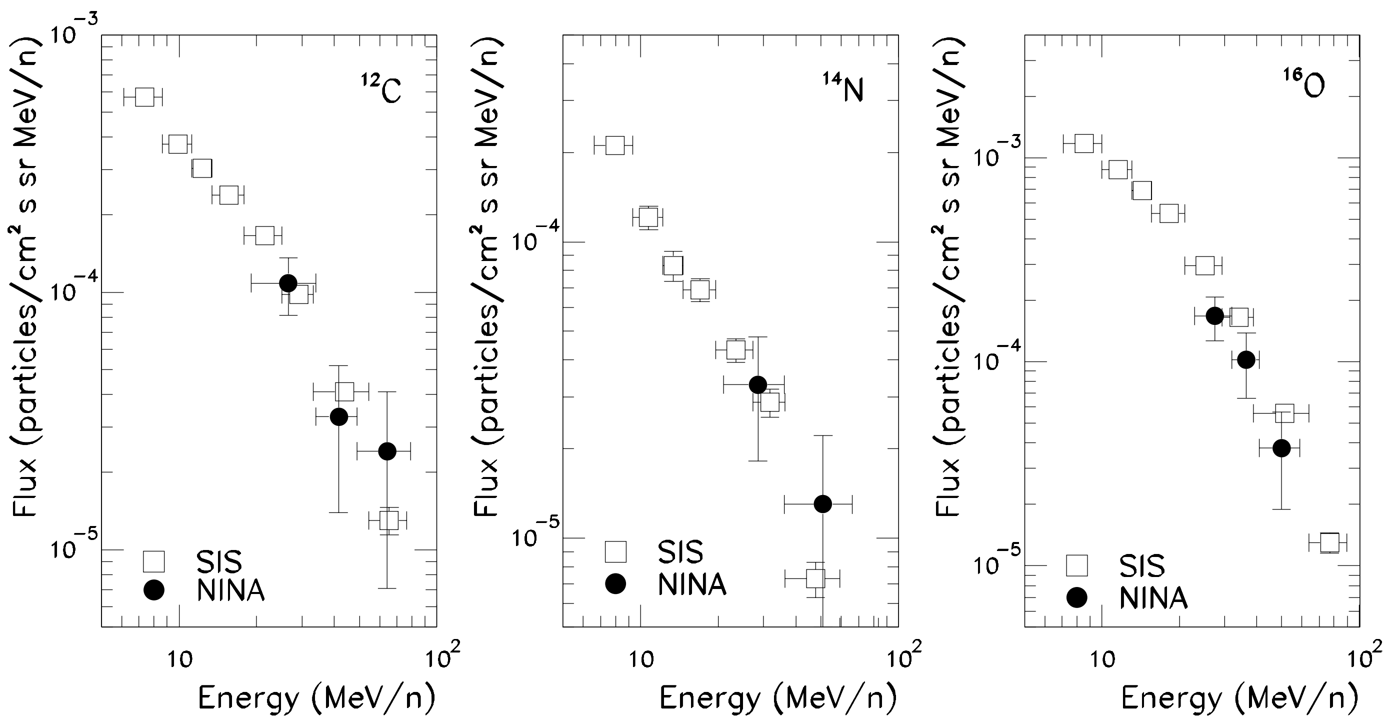

FIG. 12.—1998 November 14 SEP event: differential energy spectra for ^{12}C, ^{14}N, and ^{16}O, measured on day 317 (see Table 2). The open squares are data from SIS (*ACE* satellite), taken in the same period.

Chen et al. (1995) analyzed 16 SEP events and found that even extremely large SEP events had a value of ^{3}He/^{4}He greater than 0.5%—1 order of magnitude greater than solar wind values. This evidence was reported also by Mason et al. (1999), who observed 12 large SEP events with an average value of ^{3}He/^{4}He about $(1.9 \pm 0.2) \times 10^{-3}$.

To explain this enrichment, Mason et al. (1999) suggest that residual ^{3}He from impulsive SEP events forms a source material for the ^{3}He seen in some large SEP events. In such cases, the ^{3}He is accelerated out of this interplanetary suprathermal population by the same process that energizes other particles at these energies, namely, the interplanetary shock.

Our ^{3}He/^{4}He ratio measurements, reported in Table 3, seem to confirm the fact that in all SEP events there is a quantity of ^{3}He greater than that typical of solar coronal values (^{3}He/^{4}He about 4×10^{-4}). If we average the ^{3}He/^{4}He ratio over all events detected by NINA, except the 1998 November 7–8 that is clearly ^{3}He enriched, we obtain the value $(1.1 \pm 0.4) \times 10^{-2}$.

Nuclear interactions in acceleration regions can also contribute to the high value of the ratio ^{3}He/^{4}He, with respect to coronal values. As stated in § 1, at flare physical sites the possible presence of secondary particles from nuclear interactions (Ramaty & Murphy 1987) should not be excluded. Such interactions also produce ^{3}H and ^{2}H, which are the signature of the process. From γ-ray spectroscopy there is evidence for the presence of ^{3}He and ^{2}H at the flare sites (Mandzhavidze et al. 1999; Chupp 1983; Terekhov et al. 1993). Usually, all secondary particles are trapped in the flare loops, but some of them can escape into the interplanetary space.

Particles escaping from Sun during acceleration traverse a small amount of material and do not undergo many interactions. It is therefore difficult to separate solar deuterium particles from the galactic and instrumental background. In our measurements, the values of the deuterium flux are close to the instrumental limit. For most of the SEP events, there was not an appreciable quantity of ^{2}H, and in some cases we could determine only upper limits on the ratio ^{2}H/^{1}H (see Table 3). In the 1998 November 24 SEP event, however, there are possible indications of an excess of the deuterium counting rate (Bakaldin et al. 2001). This possibility is now under further investigation.

The average value of the ratio ^{2}H/^{1}H, over all our events, is less than 4×10^{-5}, which corresponds to about 0.1 g cm^{-2} thickness of traversed material for protons with energy about 30 MeV (Ramaty & Kozlovsky 1974, their Fig. 10). This thickness gives a ^{3}He/^{4}He ratio of about 10^{-3}, which is lower than our average value. However, it should be noted that the ^{2}H/^{3}He ratio measured by probes in the interplanetary space may be depressed by a factor of 10 because of differences in ^{2}H and ^{3}He angular distribution and propagation processes (Colgate, Auduouze, & Fowler 1977). A theoretical analysis of this ratio depends on the solar flare model used, which is still very controversial and beyond the scope of this paper.

In conclusion, the measured level of the deuterium presence in SEPs, coming from secondary interactions in the solar ambient, cannot exclude that part of the ^{3}He contents in large SEP events may also have this origin.

6. SUMMARY

We have determined the ^{3}He/^{4}He ratio and helium energy spectra over the energy range 10–50 MeV nucleon^{-1} for nine SEP events measured in the period 1998 October–1999 April by the instrument NINA. The most interesting of these events was recorded on 1998 November 7, when the ratio reached a value of about 30% but also presented features typical of a "pure" gradual event (Klecker et al. 1999). The similarity of the time profiles for the ^{1}H, ^{3}He, and ^{4}He emissions in the event implies that these isotopes underwent the same acceleration mechanism.

The other SEP events yield an average value of the ^{3}He/^{4}He ratio slightly higher than that typical of the solar wind. The average value of the ^{2}H/^{1}H upper limits, over all our events, is equal to $^2\mathrm{H}/^1\mathrm{H} = 4 \times 10^{-5}$. This level of deuterium in SEP events, coming from secondary interactions in the solar ambient, cannot exclude that part of the ^{3}He contents in SEPs may also have this origin.

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