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Light isotope abundances in SEPs measured by NINA

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Abstract. Observations of 9 Solar Energetic Particle events detected by the instrument NINA from November 1998 to April 1999 will be presented. NINA is a silicon-based space detector in orbit since July 1998 on board the Russian satellite Resurs-01-N4, which flies at low altitude (about 800 km) in polar inclination.

For every SEP event we reconstructed the power-law ^{4}He spectrum in the energy interval 10–50 MeV/n, extracting spectral indexes from 1.8 to 6.8. Data of ^{3}He and ^{4}He were then employed to determine the ^{3}He/^{4}He ratio, that turned out to be high for some SEP events showing the enrichment in ^{3}He. For the 7 November 1998 event this ratio reached the maximum value of 0.33 $\pm$ 0.06, with spectral indexes 2.5 $\pm$ 0.6 and 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 $\pm$ 0.004.

For all events we determined the deuterium-to-proton ratio. The average value of the ^{2}H/^{1}H ratio, over all events, was (3.9$\pm$1.4)$\times$ 10^{-5} in the energy interval 9–12 MeV/n. During 24 November 1998 event, however, this ratio resulted about 10 times higher than normal coronal values.

1 Introduction

Solar Energetic Particles are now believed to come from two different sources. The SEPs from solar flares have 1000-fold enhancement in ^{3}He/^{4}He and enhanced heavy ions with respect to solar abundances (impulsive events). However the most intense SEP events are produced by accelerations at shock waves driven by Coronal Mass Ejections. Various aspects of gradual and impulsive SEP events have been compared in a variety of review articles [(Reames, 1999) and references therein].

Especially the ^{3}He/^{4}He ratio characterizes the two types of events. ^{3}He/^{4}He $\sim$ 1 is typical in impulsive events, while ^{3}He/^{4}He $<$ 1% belongs to gradual SEP 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 propagation processes.

On the other hand it is known that to an enormous abundance of ^{3}He in SEPs does not correspond an overabundance of ^{2}H and ^{3}H. While solar ^{3}He was detected by many observers, solar ^{2}H and ^{3}H have proven to be very rare and difficult to detect in SEPs (Anglin, 1975; Mewaldt & Stone, 1983; Van Hollebeke, McDonald & Trainor, 1985; McGuire, von Rosenvinge & McDonald, 1986).

Aim of this article is to present measurements of light isotope abundances in 9 Solar Energetic Particle events detected in the period October 1998 – April 1999 by the instrument NINA. The telescope NINA was launched on the 10^{th} of July 1998 from the Baikonur launch facility, on board of the Russian satellite Resurs-01-N4. The orbit of the spacecraft is sun-synchronous, with 98 degrees of inclination and about 800 km of altitude.

2 Instrument

The telescope NINA is a tower composed by 16 planes, each made of two silicon detectors, segmented in 16 strips orthogonally glued so as to provide the X and Y information of the particle track. The first two detectors are 150 μm thick, while the thickness of all the others is 380 μm.

NINA geometrical factor for helium and hydrogen isotopes is about 10 cm^{2}sr, decreasing as a function of energy. The mass resolution of the instrument is about 0.15 amu for He isotopes and about 0.1 amu for H isotopes. The energy resolution is about 1 MeV. A detailed description of the instrument and its performance in orbit are reported by Bakaldin et al. (1997); Bidoli et al. (1999, 2001). NINA measurements of trapped light particles will be presented at

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SEP date	Observation time (UT)	NOAA	Class (X-ray/Hα)	Location	Time of X-ray event (UT)	γ	^{3}He/^{4}He $\times 10^{-2}$ [15–45 MeV/n]	^{2}H/^{1}H $\times 10^{-5}$ [9–12 MeV/n]
06.11.98	309.38 $\div$ 310.52	8375	C1.1 / SF	N19W25	04:38	4.7 ± 0.4	6.5 ± 4.3	< 5
			C1.4 / SF		04:56			
07.11.98	310.52 $\div$ 310.89	8375	M2.4 /-	-	11:06	3.7 ± 0.3	33 ± 6	3.4 ± 6.1
08.11.98	311.34 $\div$ 311.87	8379	C2.4 / SF	S20W67	20:20 (07.11)	6.8 ± 1.4	23 ± 10	5.3 ± 11.1
14.11.98	317.36 $\div$ 317.54	8385	C1.7 / BSL	N28W90	05:18	1.8 ± 0.1	1.1 ± 0.3	1.7 ± 2.3
	320.60 $\div$ 322.25							
22.11.98	325.32 $\div$ 326.33	8384	X3.4 / 1N	S27W82	06:42	1.9 ± 0.4	< 2.8	5.1 ± 9.0
24.11.98	328.30 $\div$ 331.14	8384	X1.0 / -	-	02:20	3.5 ± 0.2	4.1 ± 3.2	35 ± 14
20.01.99	19.96 $\div$ 21.93	-	M5.2 / -	-	20:04	2.8 ± 0.2	0.3 ± 0.6	3.5 ± 2.8
22.01.99	21.93 $\div$ 23.90	8440	M1.4 / SF	N19W44	17:24	4.2 ± 0.1	-0.1 ± 0.6	0.7 ± 1.1
16.02.99	46.23 $\div$ 48.04	8458	M3.2 / SF	S23W14	03:12	3.4 ± 0.7	-0.1 ± 8.0	37 ± 80

Table 1. SEP events and characteristics of suggested associated solar events. Second column: NINA observation time (day of the year) during the SEP event. Third column: NOAA region number of the associated flare. Fourth column: importance of the flare in terms of X-ray/Hα classification. Fifth column: location of the flare in heliocentric coordinates. Sixth column: starting time (hh:mm) of the X-ray event. Seventh column: spectral index γ from ^{4}He flux. Eight column: ^{3}He/^{4}He flux ratio. Ninth column: ^{2}H/^{1}H flux ratio.

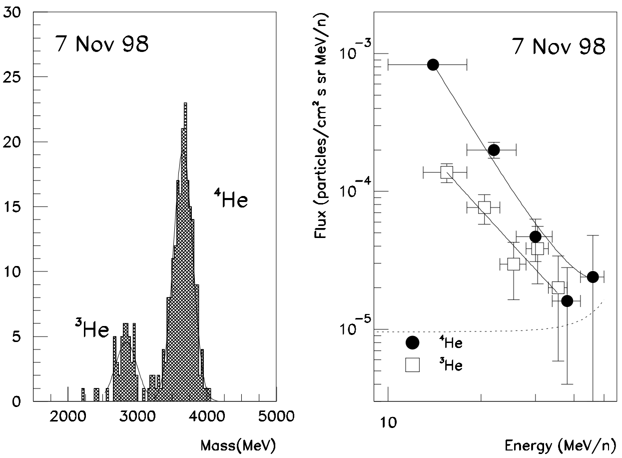

Fig. 1. 7 November 1998 SEP event: mass reconstructions (left) and differential energy spectrum for ^{3}He and ^{4}He (right). The dashed line represents the galactic background.

this Conference (Bakaldin et al., 2001).

3 SEP measurements

SEP events were identified by monitoring the occurrence of an unpredictable increase in the trigger counting rate of the instrument, increase of at least one order of magnitude with respect to the averaged solar quiet values. Nine such increases in the period October 1998–April 1999 have been detected and identified as Solar Energetic Particle events.

A summary of all nine SEP events observed by NINA is presented in Table 1, together with characteristics of the solar events that can be associated to the SEPs[1]. The event of 14 November 1998 was the most powerful, where the counting rate increased of almost 3 orders of magnitude with respect to solar quiet periods. It is visible from Table 1 that it lasted several days and was detected by our instrument in two separate emissions. For the other events we registered increases of one or two orders of magnitude on average. The events of 6-7-8 November 1998 and those of 20-22 January 1999 occurred in a very close period of time, so that there might be effects of superposition between events. However, their spectral characteristics and isotope composition are very different from one to another.

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

Helium observations range from 10 to 50 MeV/n. The energy spectrum $S(E)$ during SEPs was fitted by a power-law component plus the galactic background $B(E)$ measured by our own instrument in the same period (Bidoli et al., 2001):

$$S(E) = A\,E^{-\gamma} + B(E) \ \ [cm^2\ sr\ s\ MeV/n]^{-1} \ .$$

The value of γ (spectral index) for each event is reported in Table 1. We can see that it varies considerably from event to event, ranging from 1.8 in the 14 November 1998 event to 6.8 in the 8 November 1998. It is interesting to notice that the 6 November 1998 and 7 November 1998 occur in the same NOAA region but present different values of the spectral index. The same holds for the 22 November 1998 and 24 November 1998 SEP events.

In order to study the rare isotope abundances (^{2}H, ^{3}He) in the analysis of SEPs it is necessary to subtract the solar quiet background, and to take into account secondary productions inside the instrument induced by high energy solar particles. Table 1 summarizes the measurements of the ratio ^{3}He/^{4}He in the range 15–45 MeV/n for the nine SEPs, where ^{3}He represents the total flux that we measured after background subtraction. During the 7 and 14 November 1998 SEP events this ratio is 3 standard deviations more than the solar coronal value.

For the 7 November event we report in Figure 1 the reconstructed helium isotope masses (left) and the ^{3}He and ^{4}He differential energy spectrum in the full energy interval (right). The ^{3}He spectrum is slightly harder (γ = 2.5 $\pm$ 0.6) than ^{4}He (γ = 3.7 $\pm$ 0.3). This implies that the ^{3}He/^{4}He ratio increases with energy in this event. Extrapolating the ^{3}He energy spectrum measured by NINA to lower energies, the inferred ^{3}He/^{4}He ratio for this SEP event would be about 10^{-4}, in agreement with measurements taken on board ACE [ULEIS instrument, (Mason, Mazur & Dwyer, 1999)] in the energy range 0.5–2.0 MeV/n.

For the 7 November 1998 event we reconstructed the emission time profiles of different particles. We utilized a fitting function, which takes into account both the propagation in the solar corona and the diffusion of particles to the Earth (Burlaga, 1967):

$$Counting\,rate\,(t) = A\,(t-t_0)^{-2.5}\ \ e^{-2.5\,t_{max}/(t-t_0)}\ \ Hz,$$

where t is expressed in days, t_0 corresponds to the beginning of the 7 November 1998 event, and A and t_{max} are the two parameters of the fit. The values of t_{max} are equal to 0.151±0.002 for protons, 0.154±0.006 for ^{4}He, and 0.18±0.03 for ^{3}He. Direct propagation from Sun to Earth takes, for 10 MeV/n particles, roughly 1 hour; taking into account this value, and assuming that the main part of the particle emission occurs before t_{max}, it is possible to infer that the time for coronal propagation for the three nuclear species is not more than 3 hours.

The strongest solar event that we detected, as already mentioned, was the one of 14 November 1998. Due to the very high flux intensities, which increased the noise of the detector, in this event the ^{3}He spectrum was reconstructed only by nuclei which crossed at least 7 silicon layers in the instrument; the ^{3}He/^{4}He presented in Table 1 is in fact relative to the energy interval 25–45 MeV/n. For this event there are other measurements of the ^{3}He/^{4}He ratio, performed by the IMP-8 (Dietrich et al., 1999) and SIS instrument (Cohen et al., 1999). Their measured values are respectively R = 0.02 ± 0.01 in the energy interval 30–95 MeV/n, and R = 0.005 in the range 8–14 MeV/n.

Table 1 presents also the ratios between the deuterium and proton fluxes (last column) after background subtraction, in the range 9–12 MeV/n. Since the two isotope measurements span two different energy regions (11–16 MeV/n for protons and 7–13 MeV/n for deuteriums), we utilized the proton spectral index from IMP-8 data[2] to extrapolate the ^{1}H flux in the deuterium energy region. The ratio ^{2}H/^{1}H has an average value of about $(3.9 \pm 1.4) \times 10^{-5}$ for all events; this value is in agreement with a previous measurement (Anglin, 1975), which reported a ^{2}H/^{1}H ratio equal to $(5.4 \pm 2.4) \times 10^{-5}$ between 10.5 and 13.5 MeV/n, averaged over a large number of SEP events, consistent with solar abundance values (McGuire, von Rosenvinge & McDonald, 1986).

In the 24 November 1998 event, however, the deuterium emission was probably more intense, with a deuterium-to-proton ratio equal to $(3.5 \pm 1.4) \times 10^{-4}$, almost 10 times higher than the coronal value. Figure 2 presents the counting rate of deuterium during the months November–December 1998. To plot this picture, we utilized a technique that first calculates the time interval ΔT covering a fixed number N of successive events of deuterium. The counting rate is then equal to: (N-1)/(ΔT-τ), where τ is the dead time. The counting rate so evaluated is determined sequentially for each event, and assigned to the moment the first event was recorded (Efremova, Ozerov, & Khodarovich, 1997). In Figure 2 we have chosen N=7. Due to background conditions two days, corresponding to 14 November 1998 event, were excluded from the analysis.

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

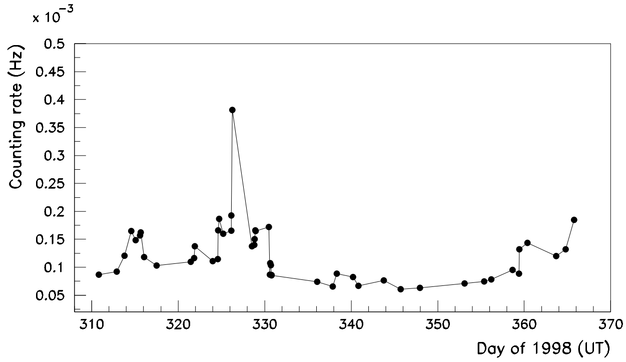

Fig. 2. Counting rate of deuterium (Energy > 9 MeV/n) during the months November–December 1998.

In Figure 2 a peak of counting rate is visible, in possible correlation with the 24 November 1998 SEP event. Figure 3 shows the mass resolution of hydrogen isotopes for the 24 November 1998 (right) together with the distribution of the 6 November 1998 (left). These two SEP events correspond to the maximum and the minimum of the deuterium component that NINA detected.

4 Discussion

The wave resonance (Roth & Temerin, 1997) is known to be the most likely mechanism for ^{3}He acceleration in SEP event (Reames, 1999), and probably acts during the 7 November 1998 event. This mechanism, however, accelerates both ^{3}He and heavy ions. The ratio of heavy and ^{3}He ions is determined by the temperature and density of the flare plasma, and by the wave properties. It is interesting to notice

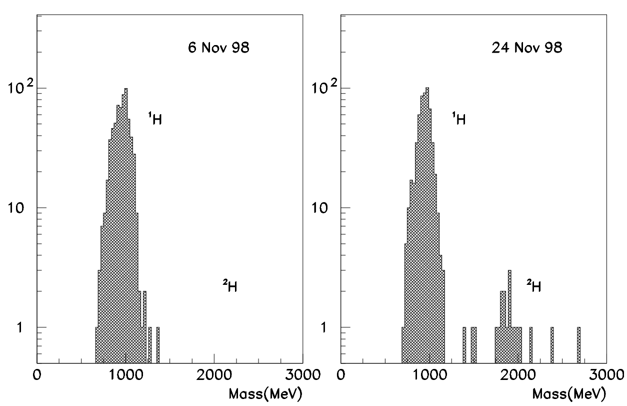

Fig. 3. 6 November 1998 and 24 November 1998 SEP event: mass reconstruction (Energy > 9 MeV/n) for the hydrogen isotopes.

that data reported by ACE (Klecker et al., 1999) identify this SEP event as gradual by the low ratio Fe/O. In this work the ionic charge of several heavy ions, including iron, was determined too. These measurements at low energy (0.2–0.7 MeV/n) are consistent with an equilibrium plasma temperature of ~ 1.3–1.6×10^6 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 oxigen at the same energy per nucleon as ^{3}He, which was not observed by our instrument. It would be interesting to compare our measured spectral behaviour 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. More recently, Chen, Guzik & Wefel (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%, one order of magnitude greater than solar wind values. This evidence was reported also by Mason, Mazur & Dwyer (1999), who observed 12 large SEP events with an average value of ^{3}He/^{4}He about $(1.9 \pm 0.2) \times 10^{-3}$.

Our ^{3}He/^{4}He ratio measurements, reported in Table 1, seem to confirm the fact that in all SEPs there is a quantity of ^{3}He greater than that typical of solar coronal values (^{3}He/^{4}He about 4×10^{-4}). Indeed, if we average the ^{3}He/^{4}He ratio over all events detected by NINA, except the 7–8 November 1998 which is for us clearly ^{3}He-enriched, we obtain the value $(1.1 \pm 0.4) \times 10^{-2}$.

To the high value of the ratio ^{3}He/^{4}He, with respect to coronal values, nuclear interactions in acceleration regions can also contribute. Such interactions produce also ^{3}H and ^{2}H, which are the signature of the process.

In our measurements the values of the deuterium flux are close to the instrument limit; for most of the SEPs there was not an appreciable quantity of ^{2}H, and in some cases we could determine only upper limits of the ratio ^{2}H/^{1}H. The average value of this ratio corresponds to about 0.1 g cm^{-2} thickness of traversed material (Ramaty & Kozlovsky, 1974), for protons with energy about 30 MeV.

But during 24 November 1998 SEP event the ^{2}H/^{1}H ratio was about 10 times higher than the solar corona abundance ratio. Despite the background estimations suffer from uncertainties, we have some arguments that exclude an under-estimation of the background and suggest a solar origin for the measured deuterium:

- the peak in ^{2}H count rate in 24 November 1998 SEP event does not correspond to a peak in the high energy proton and helium counting rates, whereas such particles are the main source of background production in our instrument;

- the ^{3}He/^{4}He ratio measured by NINA in the 6 November 1998, 14 November 1998 and 20 January 1999 events is consistent with other measurements (Mason, Mazur & Dwyer, 1999; Cohen et al., 1999). This suggests that we do not have a higher level of secondary ^{3}He background, and therefore of deuterium, in our measurements.

Following the hypothesis reported in the work by Mason, Mazur & Dwyer (1999) it could be suggested that the deuterium observed by NINA on 24 November 1998 was produced in previous impulsive events, and remained in the low corona before being erupted and accelerated. This suggestion is supported by observations of the Tibet solar neutron telescope, which observed possible solar neutrons in association with the flare of 23 November 1998 (Hoshida et al., 1999). In association to this, Yoshimori, Shiozawa & Suga (1999) reported gamma ray lines observed during 22 November 1998 event at the same NOAA region as for 24 November 1998 SEP event.

In the 24 November 1998 event perhaps a ^{3}He enrichment was also present (Table 1). The ratio ^{2}H/^{3}He measured by NINA was of the order of 1, as expected from the cross section ratio and propagation effects.

In conclusion, the presence of deuterium in SEPs, coming from secondary interactions in the solar ambient, suggests that part of the ^{3}He contents in Solar Energetic Particle events may also have this origin.

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