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Letter to the Editor

Common overabundance of ^{3}He in high-energy solar particles

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Abstract. Solar energetic particle (SEP) observations of the ERNE instrument (the Energetic and Relativistic Nuclei and Electron experiment) onboard the Solar and Heliospheric Observatory enable measurements of the ^{3}He intensity in the high-energy range, >15 MeV nucleon^{-1}, with a good statistical resolution. We report an overview of the ERNE observations for the period from 8 February 1999 to 7 December 2000. Significant intensities of ^{3}He are registered in all events with ^{4}He intensity exceeding ≈0.5 ion per (m^2 s sr MeV nucleon^{-1}). The abundance ratio ^{3}He/^{4}He is measured to vary in the range ∼0.003–2, well above solar wind values. A histogram of the daily ^{3}He/^{4}He ratio reveals a sharp maximum at ^{3}He/^{4}He ≈ 0.015. This is not expected in the impulsive-gradual paradigm of solar energetic particle events. We argue that the abundance ^{3}He/^{4}He ≈ 0.015 should be regarded as a "normal composition" of high-energy solar particles, instead of the previously assumed ^{3}He/^{4}He ≈ 5×10^{-4}. The ERNE registered also a number of ^{3}He-rich events with ^{3}He/^{4}He ∼ 0.1–1, which however are less frequent. We consider the common overabundance of ^{3}He as a signature of impulsive processes, which seem unavoidable during the development of the SEP-productive solar eruptions comprising coronal mass ejections and flares.

Key words. Sun: corona – Sun: flares – Sun: particle emission

1. Introduction

The ^{3}He-rich solar energetic particle (SEP) events are usually observed in the low-energy range, ∼1 MeV nucleon^{-1}, to have the ^{3}He/^{4}He abundance ratio as high as ∼0.03–3 (Kocharov & Kocharov 1984; Reames et al. 1994, and references therein). It is widely accepted that the ^{3}He-rich composition is produced by wave-particle interactions in flares, whereas a "normal" composition with nearly solar wind abundance, ^{3}He/^{4}He ≈ 5×10^{-4}, was expected for the shock-accelerated SEPs in gradual events (Reames 1995). Nevertheless, new observations in the low-energy range revealed a number of ^{3}He-rich events associated with interplanetary CME-driven shocks (Mason et al. 1999; Desai et al. 2001). However, the general statistics of the ^{3}He-rich events has not been updated since mid-1990s.

A few measurements of ^{3}He beyond 10 MeV nucleon^{-1} are available (Cohen et al. 1999; Clayton et al. 2000; Bakaldin et al. 2002; Torsti et al. 2002, 2003, and references therein). In particular, the most recent SOHO/ERNE observations have revealed ^{3}He enrichments in the energy range 15–30 MeV nucleon^{-1} with ^{3}He/^{4}He > 0.2, produced in solar eruptions comprising impulsive flares and CMEs. For the first time, the extremely high values of ^{3}He-to-^{4}He ratio were observed in the high-energy energy range. However no statistical overview was reported. In this Letter, we examine this issue further by surveying ^{3}He abundances in the high-energy range in all events observed over a 22 month period, from 8 February 1999 to 7 December 2000.

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2. Observations and analysis

The particle telescope ERNE/HED identifies ^{3}He nuclei in the energy range 15–120 MeV nucleon^{-1}. The accurate measurement of the particle flight trajectory, and at least four independent energy loss measurements make the separation of ^{3}He and ^{4}He isotopes confident. During conditions of low count rate ERNE is capable of analyzing all arriving particles. When the count rate is more than 150–200 particles in a minute, a priority system saves only a sample of protons (at least 10 protons). Instead it tends to save as many helium nuclei as possible. In still higher count rates only a sample of He nuclei is collected, and heavy nuclei are stored with highest priority. When ERNE is working in the sample mode, the ERNE on-board computer controls in several ways the development of real and sample number rates, and of the dead time, which makes the correction of sample rates into absolute particle intensities reliable. The description and details of the ERNE instrument are given by Torsti et al. (1995). In the present study we chose the energy channel 15–30 MeV nucleon^{-1} for both helium isotopes, ^{3}He and ^{4}He. The channel is close to the lower energy threshold of ERNE/HED. In the selected ^{3}He-energy channel the average geometric factor is 30.5 cm^2 sr.

We have carried out a survey based on the particle measurements by ERNE/HED from 8 February 1999 till 7 December 2000. During the survey period there were only a few periods

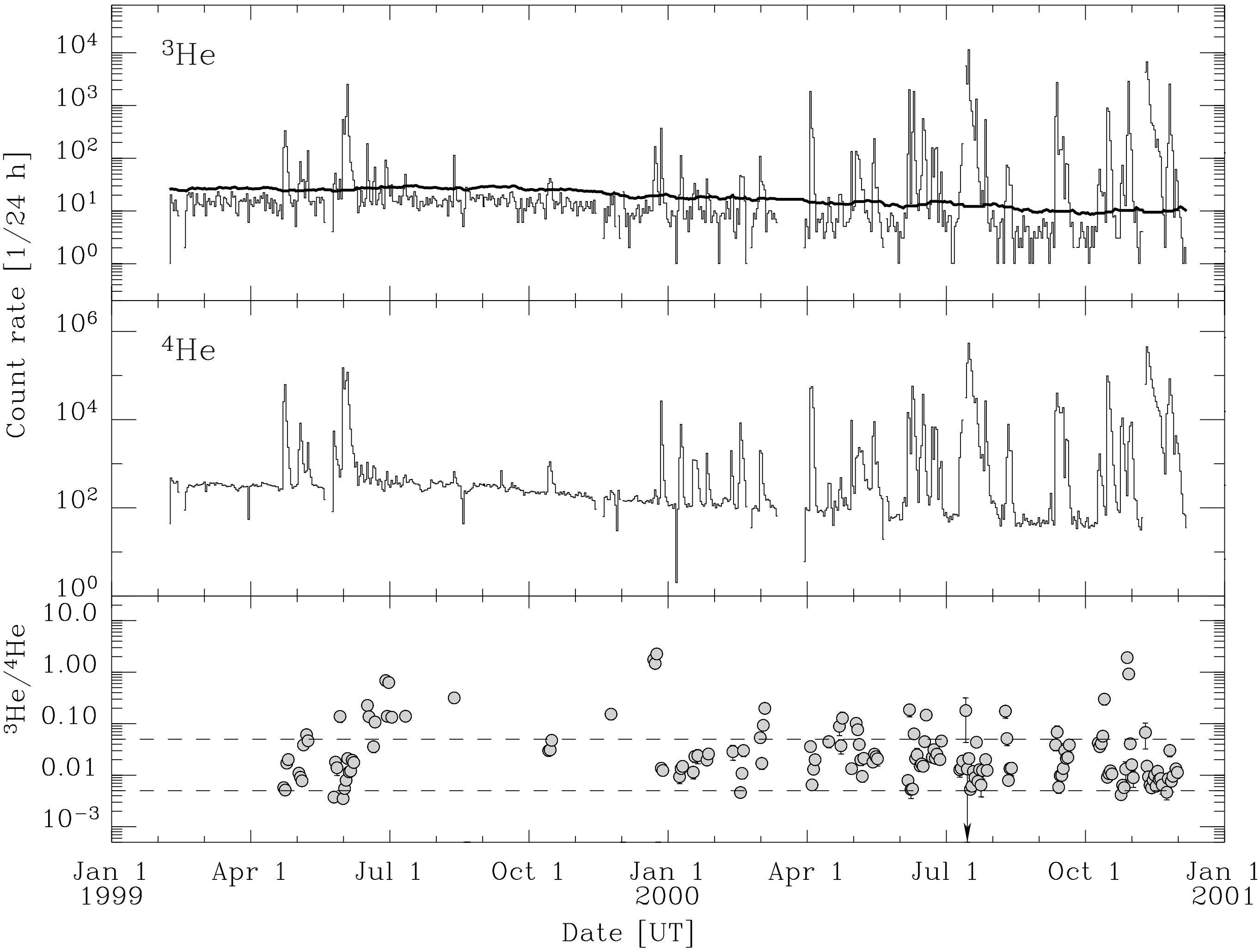

Fig. 1. Daily count rates of ^{3}He and ^{4}He and the abundance ratio ^{3}He/^{4}He on the ^{3}He event days in the energy range 15–30 MeV nucleon^{-1}. The slowly-changing line in the uppermost panel shows a selection limit for an ^{3}He event. A pair of dashed horizontal lines in the lowermost panel shows the levels ^{3}He/^{4}He = 0.005 and 0.05, between which the majority of the ^{3}He event days fall.

when either the spacecraft, or more often, the instrument was not in the observation mode. In the case of extreme count rates, as was the case during the 14 July and 9 November events in 2000, the analysis capacity was exceeded. In those occasions, the data have been excluded from the analysis. Figure 1 plots time profiles of ^{3}He and ^{4}He count rates during 1999–2000. The broken, nearly horizontal line in the uppermost panel displays a lower limit for the selection of ^{3}He events representing a gliding-average of the preceding non-event period raised by a threefold statistical error. During 1999–2000 the ERNE had 620 days with observations of at least 12 hours duration. Total number of observation days was 636. The ^{3}He and ^{4}He count rates exceeded the event selection limit during 167 (26%) and 243 (38%) days respectively. Figure 1 shows also the ^{3}He/^{4}He ratios on the ^{3}He-event days. On a few days the ^{3}He count rate in the high-energy channel is in excess of 1000 counts per day. For instance in the beginning of 14 July 2000 high ^{3}He-intensities were measured right before the temporary loss of measurement capacity and the intensities remained high also after the recovery of the instrument. On 30 October 2000 the absolute amount of measured ^{3}He ions was exceptionally high and the daily ^{3}He/^{4}He was close to 1. The corresponding particle event started on 29 October 2000 at about 18 UT and the ^{3}He/^{4}He ratio remained above 1 for the first 30 hours from the event onset. This event was described in detail by Torsti et al. (2002).

The left panel of Fig. 2 plots the daily average ^{3}He intensities versus the ^{4}He intensities on the ^{3}He event days, with galactic background subtracted. One can discern a systematic organization of points in the scatter plot. The organization indicates a clear correlation between the ^{3}He and ^{4}He intensities. Most of the events are located between the lines ^{3}He/^{4}He = 0.005 and 0.05, especially in strong events. On several days the ^{3}He/^{4}He ratio was in excess of 0.5. From the same figure one can see that no ^{3}He-event days with daily intensity less than 0.002 (m^2 s sr MeV nucleon^{-1})$^{-1}$ were found. This is because such intensities are below the typical background level. Consequently, there have not been

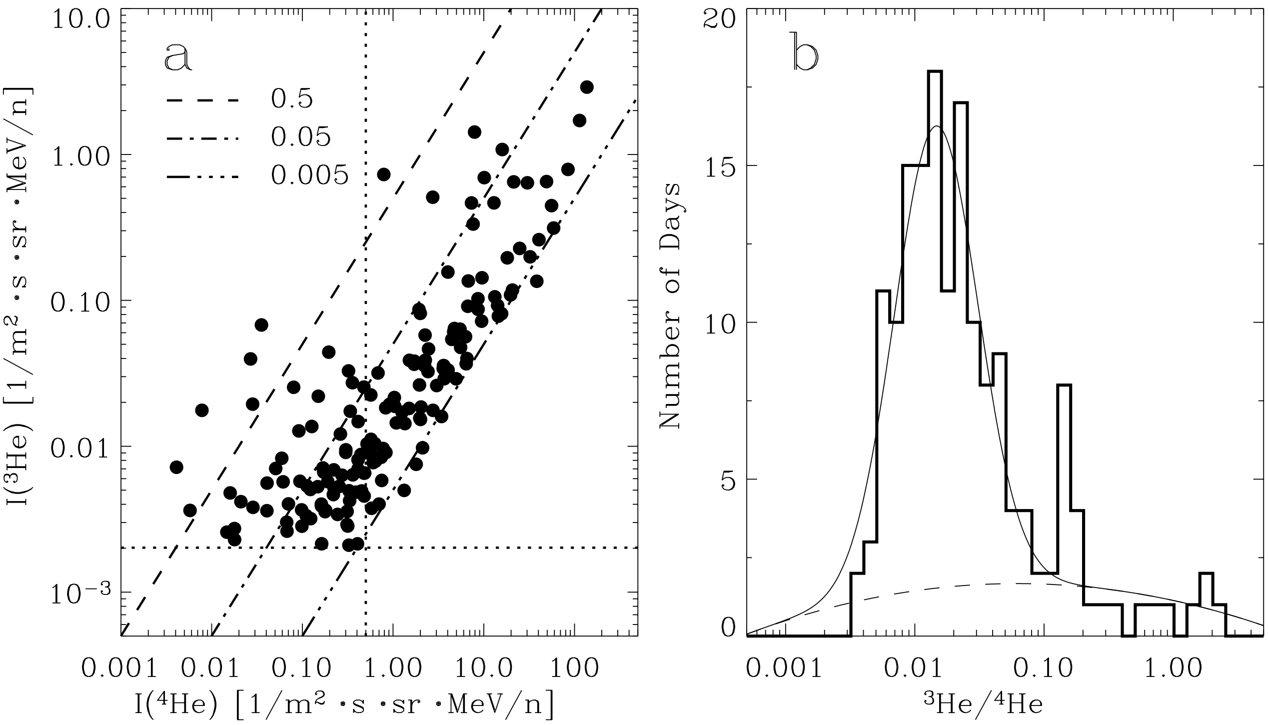

Fig. 2. Scatter plot of ^{3}He intensity vs. ^{4}He intensity, with background subtracted, on the ^{3}He event days in the energy channel 15–30 MeV nucleon^{-1} **a)** and the corresponding day-number distribution over the abundance ratio ^{3}He/^{4}He **b)**. The dashed lines in panel **a)** indicate the 0.005, 0.05, and 0.5 levels of the ^{3}He/^{4}He-ratio. The horizontal dotted line in the panel **a)** exemplifies an average ^{3}He background level. All ^{4}He enhancements with ^{4}He intensity exceeding the threshold level that is shown with the vertical dotted line were accompanied by a measurable amount of ^{3}He. Curve in panel **b)** shows a possible fit to the data histogram (χ^2 = 46.4 at 43 degrees of freedom). It reveals a main peak around ^{3}He/^{4}He = 0.015 and a high-abundance tail at ^{3}He/^{4}He > 0.1.

measurable ^{3}He intensities in many weak ^{4}He enhancements with the ^{4}He intensity <0.2 (m^2 s sr MeV nucleon^{-1})$^{-1}$. However for the strong enough events with ^{4}He intensity in excess of ≈0.5 (m^2 s sr MeV nucleon^{-1})$^{-1}$, the ^{3}He association is found to be absolute: all the helium events contain a measurable amount of the isotope ^{3}He. A statistical distribution of the ^{3}He enhancement days over the ^{3}He/^{4}He ratio is shown in the right panel of the figure. The distribution apparently consists of a narrow peak at ^{3}He/^{4}He ~ 0.015 and a wide substratum extending through ^{3}He/^{4}He ~ 1.

Based on the previous observations of ^{3}He-rich events in the low-energy range, the distribution of ^{3}He/^{4}He ratios is relatively flat in the range ^{3}He/^{4}He ≈ 0.03–2 and gradually declines as ^{3}He/^{4}He increases from ≈2 to 10 and beyond (see Fig. 2 in Reames et al. 1994 and Fig. 8 in Kocharov & Kocharov 1984). Recently Mason et al. (1999) discussed some low-energy events with ^{3}He/^{4}He ≈ 0.002, but the event number distribution has not been updated. We report on the ^{3}He-rich events recently observed at higher energies. Figure 2 indicates a very wide distribution of the high-energy events, which exhibits a narrow peak at moderate enhancements, ^{3}He/^{4}He ≈ 0.015, but changes slowly in the high enhancement range, ^{3}He/^{4}He ≈ 0.1–2. With the high-energy data in hand and based upon the previous low-energy experience, we fit the distribution shown in Fig. 2 with a sum of a narrow, Gaussian type distribution and a wide, quadratic function, which corresponds to the GAUSSFIT routine of IDL in respect to the variable log(^{3}He/^{4}He). The quadratic component of the distribution is qualitatively similar to the aforementioned low-energy distribution, but the Gaussian-type peak at ^{3}He/^{4}He ≈ 0.015 is new. Clearly, it is not what one might expect based on the impulsive-gradual SEP paradigm in the Reames' (1995) formulation.

3. Discussion and conclusions

Reames et al. (1985) found that virtually all low-energy ^{3}He-rich events are accompanied by impulsive 2–100 keV electron events. The electron-^{3}He rich events are widely known as impulsive events, because they are associated with impulsive solar soft X-ray bursts. However, the ^{3}He/^{4}He distribution is quite wide. For this reason, the representative values ^{3}He/^{4}He ~ 0.1–1 for impulsive events (Lin 1994) seem more appropriate than the widely quoted ^{3}He/^{4}He ~ 1 (Reames 1995). In the SEP classification tables by Lin (1994) and Reames (1995), a "normal" solar abundance ^{3}He/^{4}He ~ 5×10^{-4} is shown for the gradual SEP events. Unlike impulsive events, this value was not measured in SEPs but refers to the solar wind abundance. However, there are some observations of ^{3}He intensities in gradual events, and the abundances were found to be much higher, e.g., ^{3}He/^{4}He ~ 0.03 by Evenson et al. (1990). Recently Mason et al. (1999) reported for 12 large SEP events the average value ^{3}He/^{4}He = $(1.9 \pm 0.2) \times 10^{-3}$, also well above the solar value that was assumed to be "normal" for SEP events.

In the energy range of our present study, 15–30 MeV nucleon^{-1}, we observe the frequency of ^{3}He-rich events to decrease slowly as ^{3}He/^{4}He increases from ~0.05 to ~1 (Fig. 2). This part of distribution is qualitatively similar to the above-mentioned distribution of the low-energy impulsive events. Torsti et al. (2002, 2003) carefully studied the high-energy ^{3}He-rich events situated at the high ^{3}He-abundance end, ^{3}He/^{4}He > 0.2. Those events were associated with impulsive X-ray flares and CMEs, but onsets of ^{3}He events were delayed for many hours in respect to the flares. The delays as well as the observed spectrum of ^{3}He can be explained in a model in which the impulsive SEPs of MeV energies were reaccelerated at interplanetary shocks (Kocharov & Torsti 2003).

The most prominent feature of the distribution shown in Fig. 2 is a narrow peak at ^{3}He/^{4}He $\approx$ 0.01–0.02. In previous measurements of ^{3}He above 10 MeV nucleon^{-1}, the ^{3}He/^{4}He ratios in the range 0.001–0.01 could not be well resolved and no statistical study was performed. It is important to note that ^{3}He is measured in all sufficiently strong ^{4}He events. We find the most common abundance to be ^{3}He/^{4}He $\sim$ 0.01. Surprisingly, almost no room is left for the expected "normal" composition, ^{3}He/^{4}He $\approx 5 \times 10^{-4}$. A couple of strong events, which might appear at the low abundance range of Fig. 2, are missed in the ERNE data, but the majority of the SEP events has been measured, and the overall distribution clearly peaks at ^{3}He/^{4}He $\approx$ 0.015. Recall that ^{3}He enhancements at $\approx$0.5–2 MeV nucleon^{-1} in large SEP events were previously measured to be $\approx$0.002 (Mason et al. 1999).

In conclusion, we have analyzed the ^{3}He abundance observed with the high-energy detector of the ERNE instrument onboard SOHO during the 22 month period in 1999–2000 and find the following:

1. In all ^{4}He events with intensity exceeding $\approx$0.5 ion of ^{4}He per (m^2 s sr MeV nucleon^{-1}), significant fluxes of ^{3}He ions have been also detected.
2. The most frequent ^{3}He abundance is ^{3}He/^{4}He $\sim$ 0.01.
3. At a lower frequency, the ^{3}He/^{4}He ratio is observed to be as high as ~0.1–1.

We cannot rule out that in exceptional cases ^{3}He/^{4}He may be $\lesssim$0.001, but such a composition is definitely not typical in the energy range 15–30 MeV nucleon^{-1}. From an empirical standpoint, the most likely abundance, ^{3}He/^{4}He $\approx$ 0.015, should be regarded as "normal" for SEPs. We do not call into question other properties of gradual SEP events, but the abundance ratio ^{3}He/^{4}He $\approx 5 \times 10^{-4}$ that is shown in the widely known SEP-classification tables finds no support in the experimental data.

Recently, Kocharov et al. (2001) performed a statistical study of the ~10 MeV proton event occurrences in association with different types of CMEs. The results support an idea that production of SEPs depends not only on the final speed of CME but also on the magnitude of acceleration that CME experiences during its liftoff, and the SEP-producing CMEs are typified by impulsively accelerating CMEs accompanied by soft X-ray flares of different magnitude and coronal type II radio bursts. Cane et al. (2002) also performed a correlative study between >20 MeV solar proton events, CMEs, flares, and radio bursts. They found that essentially all of the proton events are preceded by groups of type III bursts (that are a flare phenomenon) and all are preceded by CMEs. The overabundance of ^{3}He in the majority of SEP events observed by the ERNE instrument during 1999–2000 means for us that the impulsive, flare-type processes always participate in production of SEPs. We consider accelerated ^{3}He ions, along with energetic electrons and radio bursts, as a signature of magnetic reconnection, which is unavoidable during development of solar eruptions comprising flares and the CME liftoff/aftermath processes at different coronal altitudes and locations.

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References

Bakaldin, A., Galper, A., Kodashov, S., et al. 2002, ApJ, 577, 513
Cane, H. V., Erickson, W. C., & Prestage, N. P. 2002, J. Geophys. Res., 107(A10), 1315, DOI: 10.1029/2001JA000320
Clayton, E. G., Guzik, T. G., & Wefel, J. P. 2000, Sol. Phys., 195, 175
Cohen, C. M. S., Mewaldt, R. A., Leske, R. A., et al. 1999, Geophys. Res. Lett., 26, 2697
Desai, M. I., Mason, G. M., Dwyer, J. R., et al. 2001, ApJ, 553, L89
Evenson, P., Kato, C., Kondo, I., Meyer., P., & Yanagita, S. 1990, Proc. 21st Internat. Cosmic Ray Conf. (Adelaide), 5, 374
Kocharov, L. G., & Kocharov, G. E. 1984, Space Sci. Rev., 38, 89
Kocharov, L., Torsti, J., St. Cyr, O. C., & Huhtanen, T. 2001, A&A, 370, 1064
Kocharov, L., & Torsti, J. 2003, ApJ, 586, 1430
Lin, R. P. 1994, Eos, 75(40), 457
Mason, G. M., Mazur, J. E., & Dwyer, J. R. 1999 ApJ, 525, L133
Reames, D. V., von Rosenvinge, T. T., & Lin, R. P. 1985, ApJ, 292, 716
Reames, D. V., Meyer, J. P., & von Rosenvinge, T. T. 1994, ApJS, 90, 649
Reames, D. V. 1995, Rev. Geophys., 33, 585
Torsti, J., Valtonen, E., Lumme, M., et al. 1995, Sol. Phys., 162, 505
Torsti, J., Kocharov, L., Laivola, J., et al. 2002, ApJ, 573, L59
Torsti, J., Kocharov, L., Laivola, J., Chertok, I., & Thompson, B. J. 2003, Sol. Phys., 214, 177