Solar Phys (2019) 294:33
https://doi.org/10.1007/s11207-019-1420-z

^{3}He-Rich Solar Energetic Particle Events with No Measurable ^{4}He Intensity Increases

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Received: 26 September 2018 / Accepted: 22 February 2019 / Published online: 18 March 2019

Abstract We investigated ^{3}He-rich solar energetic particle (SEP) events in the current solar cycle starting in 2009 through 2017. Both "impulsive" (flare-related) ^{3}He-rich and CME-related "gradual" events are included. In the former solar cycle, we found the number of observed ^{3}He-rich events correlated with solar activity. The same correlation is seen again in Cycle 24. Because of the comparatively weak activity, both the occurrence of ^{3}He-rich events and their intensities are significantly less than those from Cycle 23. Interestingly, we found in several of the ^{3}He-rich events that there is no measurable ^{4}He intensity increase above the instrument background. Previously, we found that there is a limit on the number of ^{3}He ions that can be released from the Sun in an impulsive SEP event, while there is no such limit on the ^{4}He ions (Ho, Roelof, and Mason in *Astrophys. J.*, **621**, L862, 2005). In this paper, we examine several of these ^{3}He-rich events in detail and discuss the lack of observable ^{4}He intensity increases and the implications for the enhancement and acceleration mechanism of this special type of SEP events.

Keywords Energetic particles · Particle acceleration · Wave/particle interaction

1. Introduction

^{3}He-enhanced solar energetic particle (SEP) events show an intriguing isotopic enrichment. The average solar wind plasma ^{3}He/^{4}He ratio is about 5×10^{-4} (Gloeckler and Geiss, 1998), and on rare occasions can be as high as 7×10^{-3} (Ho *et al.*, 2000). However, in certain

This article belongs to the Topical Collection:
Solar Wind at the Dawn of the Parker Solar Probe and Solar Orbiter Era
Guest Editors: Giovanni Lapenta and Andrei Zhukov

The original version of this article was revised due to typesetting mistakes made in the last paragraph of section **2. Observations**.

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SEP events, the ^{3}He/^{4}He ratio in energetic and suprathermal ions can be three to four orders of magnitude higher than the solar wind value (Reames, Meyer, and von Rosenvinge, 1994). They were often found to be accompanied with energetic electrons (10 – 100 keV) and type III radio emission. But there is no correlation to be found between the measured ^{3}He/^{4}He ratio with other accompanied observations (*e.g.* flare class, electron intensity). One conclusive result from previous studies is that the *occurrence* of ^{3}He-rich SEP events is associated with scatter-free nonrelativistic electron beams (Reames, von Rosenvinge, and Lin, 1985), but *not* the ^{3}He/^{4}He ratio enhancement factor itself (Ho *et al.*, 2001). Ho, Roelof, and Mason (2005) investigated the helium fluence, and found while the ^{4}He fluences can vary by 5 – 6 orders of magnitude the ^{3}He fluences in the same SEP events range is limited to only 2 orders of magnitude. This apparent limit of the ^{3}He fluence and its distribution has been suggested as an indicator of the size of the acceleration region (Reames, 1999; Ho, Roelof, and Mason, 2005), and the underlying isotope enhancement mechanism (Petrosian *et al.*, 2009). Hence, measurements of the fluence distribution of the helium isotopes are important to characterize this type of SEP event. In this paper, we report several ^{3}He-rich SEP events with no measurable ^{4}He intensity increase.

2. Observations

The energetic particle data presented in this paper are from the *Ultra-Low Energy Isotope Spectrometer* (ULEIS) on the *Advanced Composition Explorer* (ACE) spacecraft. ACE was launched in August 1997 and is currently in a halo orbit around the Sun-Earth L1 libration point ($\sim$ 200 Re) upstream of the Earth (Stone *et al.*, 1998). The ULEIS instrument is a high-resolution ion mass spectrometer that measures elemental and isotopic ion composition from 50 keV/nucleon to a few MeV/nucleon (Mason *et al.*, 1998). The ^{3}He-rich events described in this paper were selected using the ULEIS pulse-height-analysis (PHA) data from 2009 to 2017. We initially followed criteria similar to Ho, Roelof, and Mason (2005) to select all ^{3}He-rich events during the time period, namely: 1) the 0.2 – 2.0 MeV/nucleon event-averaged ^{3}He/^{4}He ratio must exceed 0.004 and have uncertainty less than 50% of the helium intensities; 2) the event is isolated and shows a measurable increase from the instrument background level; and 3) the event must last more than 1 h. From these criteria alone, there were 144 events during these time period. This is sharply lower than what was reported in the previous solar cycle. Using the same criteria, Ho, Roelof, and Mason (2005) reported 201 events from 1997 to 2002. Widenbeck and Mason (2014) studied ^{3}He in the interplanetary medium and found the fraction of time with ^{3}He present is significantly lower in the present cycle. We then further down-selected those events that have no noticeable ^{4}He intensity increases above ambient background (*i.e.* greater than 50% ^{4}He intensity increase within 1-h interval) associated with the ^{3}He intensity enhancement, which narrowed the list down to 16 events. Upon closer examination of these 16 events, a majority of them have elevated ^{4}He intensity, such that we could not definitively rule out whether there are no associated ^{4}He intensity increases with the ^{3}He time periods.

Table 1 lists the four events we selected in this study that have no measurable ^{4}He increase during the time period. Figure 1 shows the two events in 2013. The three panels in Figure 1 show: (top panel) nonrelativistic (38 – 103 keV) electron from ACE/EPAM (Gold *et al.*, 1998); (middle panel) ULEIS hourly averaged ion composition data at $\sim$ 1 MeV/nucleon; and (bottom panel) ULEIS pulse-height-analyzed (PHA) helium data. Enhanced ^{3}He time periods can be identified from the ULEIS PHA data as distinct increases

Table 1 ^{3}He-rich periods that have no measurable ^{4}He intensity increase.

Year	Start time (DOY Hr:Min)	Stop time (DOY Hr:Min)	^{3}He fluence, particles/(cm^2-sr MeV/nuc.)	^{4}He fluence, particles/(cm^2-sr MeV/nuc.)
2010	245 17:45	247 04:00	2130.5	1011.1
2013	207 12:15	209 08:50	1175.6	259.72
2013	211 06:00	214 02:10	3499.2	860.27
2016	035 06:00	036 00:00	1587.7	561.11

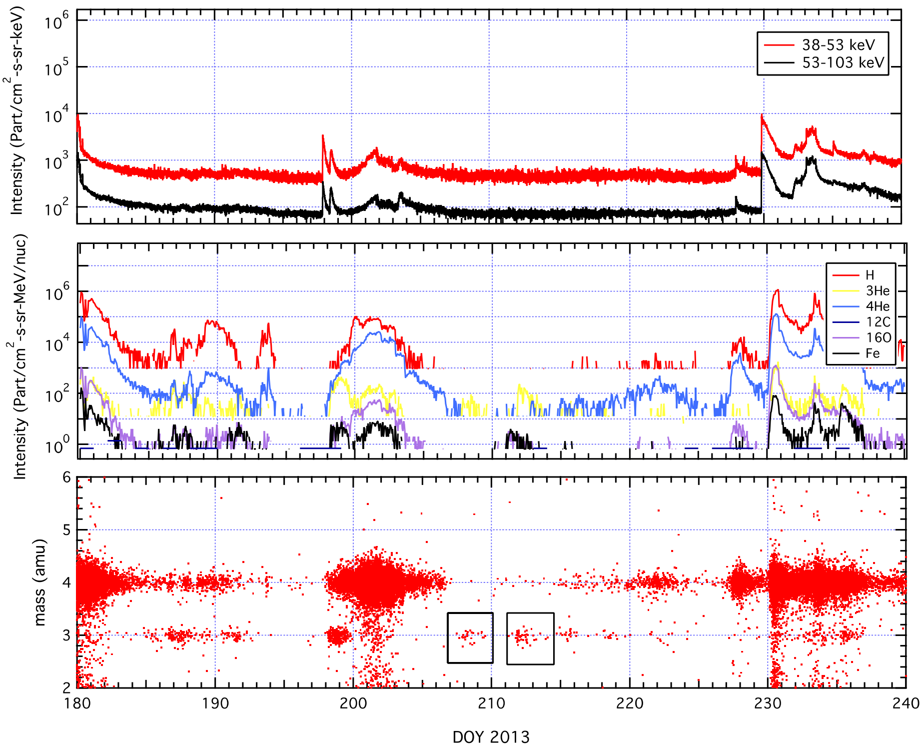

Figure 1 Energetic electron and ion composition measurement by ACE/EPAM and ACE/ULEIS during day of year (DOY) 180 to 240 in 2013. *Top panel*: 5-min averaged energetic electrons (38 – 113 keV); *middle panel*: hourly averaged low energy (∼ 1 MeV/nucleon) ion composition; *bottom panel*: high-resolution helium isotope data showing arrival times and masses of each ion detected. *Boxed* periods are discussed in the text.

in count rates in the ^{3}He mass track (*i.e.* at 3 amu), which is clearly separated from the more dominant ^{4}He mass track (*i.e.* at 4 amu). Several enhanced ^{3}He periods are clearly seen in the listed time periods. For example, there are clear ^{3}He ion events at day of year (DOY) 187, 191, 198, 207 and 211. The majority of the ^{3}He-rich events (*e.g.* DOY 187 and 198) are observed to also have corresponding ^{4}He intensity increases. The event on DOY 191 is one that has no noticeable ^{4}He increase above the 50% level from ambient. As shown by Ho *et al.* (2001), the nonrelativistic electrons are correlated with the ^{3}He-rich ion events. That correlation can also be seen in some of the events shown in Figure 1. Most notice-

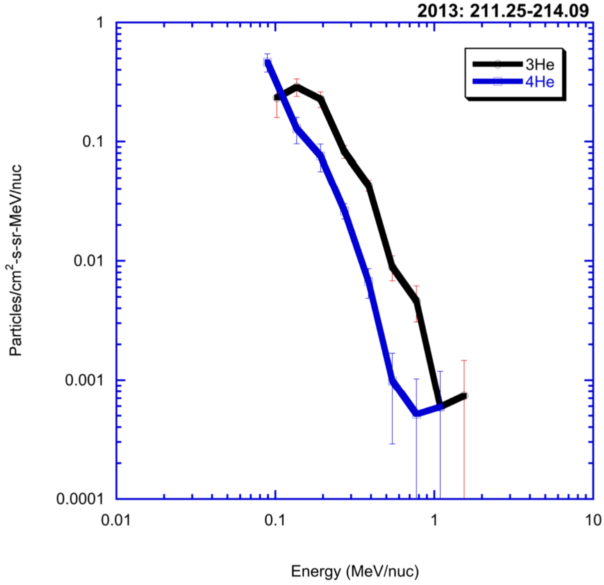

Figure 2 Event-averaged helium spectra for the event in 2013 on DOY 211.

able is the event on DOY 198, where you can also see the nonrelativistic electron injection accompanying the ion enhancement.

However, the two ^{3}He events that we identified on DOY 207 and 211 (square boxes in the bottom panel) have none of the usual characteristics. During both events there are no corresponding ^{4}He intensity increases or electron injections. Both the proton and helium intensities are at background level and the > 38 keV electrons show no new injection during these two ^{3}He-rich time periods. Figure 2 shows the event-averaged energy spectra of both helium isotopes for the event on 2013 DOY 211. The spectral slope of both the ^{3}He and ^{4}He are almost identical, but the intensity of ^{3}He are on average factor of 5 higher than ^{4}He above 200 keV/nucleon.

Figure 3 shows another event we identified in 2010 in the same format as in Figure 1. A sequence of three ^{3}He-rich periods can be seen between DOY 244 to 250. The first and last of these three events have both corresponding ^{4}He and electron intensity increases during the ^{3}He-rich period. However, the event on DOY 245 which came shortly after the initial event on 244 and immediately prior to another one on DOY 247 has no measurable ^{4}He and electron increase above background level.

Figure 4 shows the *in-situ* solar wind plasma and interplanetary magnetic field (IMF) measurements from ACE during the event on 2010 DOY 245. The solar wind speed (first panel) was steady at slow speed (< 450 km/s). Both the IMF (second and third panel) and the strahl electrons (last panel) pitch-angle data from DOY 245 to 247 also indicated that we were connected to a uniform solar wind source region since there is no change within the event interval. We note the solar wind (up to DOY 246.7) is more Alfvenic (fourth panel) than the typical slow wind, where we define $C_{vB} \equiv \frac{\Delta B \cdot \Delta v}{|\Delta B||\Delta v|}$, which could be used as a proxy for cross-helicity, a property that is a measure for turbulence (see Ko, Aaron, and Lepri, 2018); but otherwise nothing was unusual about the *in-situ* solar wind during the period when the ^{3}He was detected.

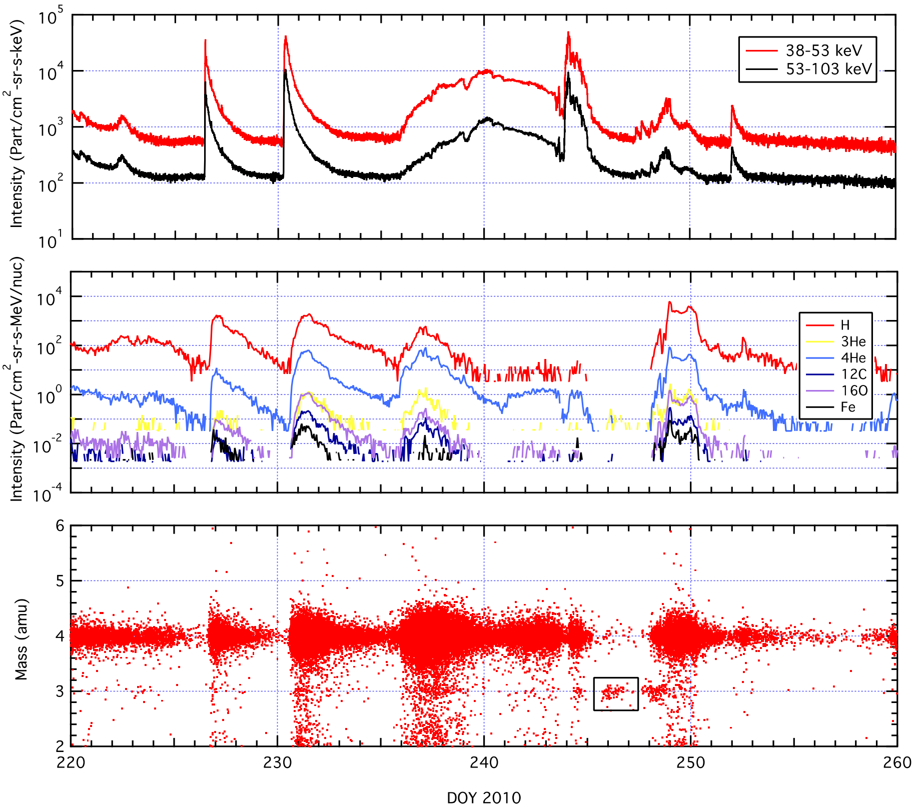

Figure 3 Same format as in Figure 1 but for time period in DOY 220 – 260 in 2010.

3. Discussion

We have shown cases of enhanced ^{3}He intensity with no measurable ^{4}He ion enhancement. These are unusual as we could only identity four from approximately one hundred ^{3}He events during the same time period. The enhancement of ^{3}He in certain SEP events has been studied since its discovery in the 1970s (see review by Reames, 1999). There are competing theories in explaining the remarkable enrichment of ^{3}He/^{4}He of $10^2 – 10^4$ times the typical solar wind abundance of $3 – 4 \times 10^{-4}$. The prevailing theories all involve some form of wave–particle resonate interaction. Fisk (1978) used ^{4}He generated electrostatic ion cyclotron waves in order to heat the ^{3}He and Temerin and Roth (1992) suggested that the excited electromagnetic ion cyclotron waves that could resonate with ^{3}He and thereby accelerate the ^{3}He directly. Recently, Liu, Petrosian, and Mason (2006) and Petrosian *et al.* (2009) have shown that stochastic acceleration by plasma wave turbulence can produce some of the observed ^{3}He and ^{4}He energy spectra. In their model, the relative abundances and spectra of the two helium isotopes are different because they interact with different wave modes.

In a large ^{3}He study, Ho, Roelof, and Mason (2005) found that there is an upper limit of the amount of ^{3}He ions can be accelerated in these events. They found that the fluence distribution of the ^{3}He is limited to a narrow range, while the ^{4}He fluence is not. Petrosian *et al.* (2009) argued that this steep variation of the fluence ratio could be explained by the level

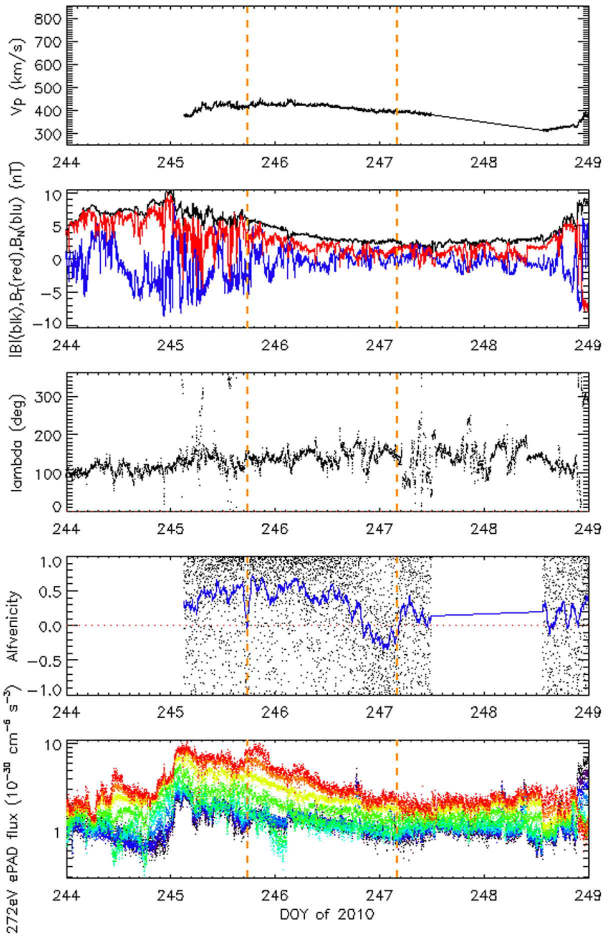

Figure 4 The *in-situ* solar wind data from ACE during the ^{3}He-rich period identified in 2010 DOY 245 – 247 (*dashed lines*). The solar wind velocity is shown in the *top panel*, while the IMF data are shown in *second* ($|B|$, B_T, and B_N) and *third panels* (λ, which is the angle defined as the angle from B_R towards B_T). The *fourth panel* shows the solar wind Alfvenicity (a *black dot* is 64-s data point and the *blue curve* is the 1-h running mean; see the text for further details). The *bottom panel* shows the halo electron (272 eV) pitch-angle data, 0 – 180° at 18° increments from *black* (0 – 18°, outward IMF) to *red* (162 – 180°, inward IMF).

of turbulence in their model, and they have successfully reproduced the observed fluence distributions from Ho, Roelof, and Mason (2005).

In this study, we followed the same criteria as defined by Ho, Roelof, and Mason (2005) and found over 144 ^{3}He-enhanced events from 2009 to 2017. The number of ^{3}He event is a lot lower than in the previous solar cycle which was as noted by Ho and Mason (2016) and Widenbeck and Mason (2014). Four ^{3}He-rich events were found without measurable ^{4}He increases. The observed ^{3}He fluence is small but well within the sensitivity of the ULEIS instrument. The ^{3}He fluences from these four events are measured to be 10^3 – 10^4 particles/(cm^2-sr MeV/nucleon), while the ^{4}He are all less than 10^3 particles/(cm^2-sr MeV/nucleon) (Table 1). These observed fluence levels provide further limits; this was done in Ho, Roelof, and Mason (2005) by establishing observable ^{3}He and ^{4}He fluences in these types of events. The measured fluences as shown by Ho, Roelof, and Mason (2005) and Petrosian *et al.* (2009) provide important information on the possible enrichment mechanism of ^{3}He. The events that we report here provide a new constraint on the possible ^{3}He enrichment/release mechanism because any wave–particle resonant interaction that is based on specific charge-to-mass ratio also has to explain why there could be abundant ^{3}He particles but no measurable ^{4}He above background.

Acknowledgement The work at JHU/APL was supported by NASA grant NNX17AC05G for support of the ACE ULEIS experiment.

Disclosure of Potential Conflicts of Interest The authors declare that they have no conflicts of interest.

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