The first gradual solar energetic particle event with an enhanced $^3$He abundance on Solar Orbiter

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ABSTRACT

The origin of $^3$He abundance enhancements in gradual solar energetic particle (SEP) events remains largely unexplained. Two mechanisms have been suggested: the reacceleration of remnant flare material by coronal mass ejection (CME)-driven shocks in interplanetary space, and concomitant activity in the corona. We explore the first gradual SEP event with enhanced $^3$He abundance that was observed by Solar Orbiter. The event started on 2020 November 24 and was associated with a relatively fast halo CME. During the event, the spacecraft was at 0.9 au from the Sun. The event-averaged $^3$He/$^4$He abundance ratio is 24 times higher than the coronal or solar wind value, and the timing of the $^3$He intensity was similar to that of other species. We inspected available imaging, radio observations, and the spacecraft magnetic connection to the CME source. The most probable cause of the enhanced $^3$He abundance are residual $^3$He ions remaining from a preceding long period of $^3$He-rich SEPs on 2020 November 17–23.

Key words. Sun: particle emission – Sun: abundances – Sun: flares – Sun: coronal mass ejections (CMEs) – acceleration of particles

1. Introduction

Solar energetic particles (SEPs) are produced by mechanisms related to magnetic reconnection in flares or jets in impulsive SEP (ISEP) events and by coronal mass ejection (CME)-driven shocks traveling through the corona and interplanetary space in gradual SEP (GSEP) events. One of the most strikingly distinct characteristics of these groups is their different elemental composition. The ISEP (or $^3$He-rich) events have higher $^3$He and heavy-ion abundances than are found in the corona or in the solar wind, while the abundances of GSEP events are similar to coronal values. High-resolution mass spectrometers on board the Advanced Composition Explorer (ACE) have often revealed small enhancements of $^3$He and Fe abundances in GSEP events (e.g., Mason et al. 1999a,b; Cohen et al. 1999; Wiedenbeck et al. 2000; Desai et al. 2016), thus blurring the distinction between jet- and CME-related SEPs. While the Fe/O enhancement in GSEP events can result from magnetic rigidity-dependent transport effects due to the lower charge-to-mass ratio of Fe compared to O, this effect is not expected for $^3$He/$^4$He enhancement (e.g., Mason et al. 1999b). Thus, a $^3$He enhancement unambiguously indicates the presence of flare material in GSEP events (e.g., Desai et al. 2016).

Mason et al. (1999a) reported two GSEP events on 1997 November 4 and November 6 with a 0.5–2.0 MeV nucleon$^{-1}$ $^3$He/$^4$He ratio that was higher by a factor of 4 than the average solar wind value of $(4.8\pm0.5)\times10^{-4}$ (Ogilvie et al. 1980). Mason et al. (1999b) examined 12 GSEP events and found a finite $^3$He/$^4$He ratio that was from 4.7 to 135 times the average slow solar wind $^3$He/$^4$He of $(4.08\pm0.25)\times10^{-4}$ (Gloeckler & Geiss 1998). The $^3$He/$^4$He ratio in GSEP events was also enhanced compared to the average GSEP value. The 5 events in Mason et al. (1999b) showed similar $^3$He and $^4$He time-intensity profiles, indicating a common acceleration and transport origin. These authors suggested that residual $^3$He ions from ISEP events, which were found to be commonly present in the interplanetary medium at 1 au, form a source material for the $^3$He that is observed in GSEP events. Similarly, Tylka et al. (2005) proposed that enhanced Fe/O in GSEP events may be produced by the acceleration of a remnant suprathermal Fe-rich ion population from previous small flare events. Desai et al. (2016) identified 27 out of 46 GSEP events with a finite $^3$He mass peak and a $0.5–2.0$ MeV nucleon$^{-1}$ $^3$He/$^4$He ratio between $\sim1.5$ and $\sim194$
times the average slow solar wind value (Gloeckler & Geiss 1998). A flare component that is simultaneously produced in the parent active regions (ARs; Von Rosenvinge et al. 2000; Cane et al. 2003, 2006; Ko et al. 2013) or in other sites in the corona (Ko et al. 2013) has been proposed as cause of the Fe/O and \(^{3}\text{He}/^{4}\text{He}\) enhancement in GSEP events. The longitude of the observer relative to the source AR (Cane et al. 2003) and the nature of the photospheric field to which the observer is magnetically connected (Ko et al. 2013) have also been suggested to affect the Fe/O ratio.

The unresolved question of whether residual flare material in interplanetary space or concomitant coronal activity dominates \(^{3}\text{He}\) abundance enhancements in GSEP events can be thoroughly explored with new high-resolution in situ and remote measurements from Solar Orbiter (Müller 2020) at close distances from the Sun. In this study, we investigate the first GSEP event with enhanced \(^{3}\text{He}\) abundance measured by Solar Orbiter and analyze the origin of the observed \(^{3}\text{He}\) enhancement. The event started on 2020 November 24. It is also the first significant SEP event observed by this mission that has high proton intensities. At suprathermal energies (<1 MeV nucleon\(^{-1}\)), this event shows higher proton intensities than the following SEP event on 2020 November 29 (Kollhoff et al. 2021), which was observed at widely (~230\(^{\circ}\)) separated spacecraft and is associated with the same AR as the 2020 November 24 event.

2. Instrumentation

The 2020 November 24 event abundance measurements were obtained by the Suprathermal Ion Spectrograph (SIS) of the Energetic Particle Detector (EPD) suite (Rodríguez-Pacheco et al. 2020) on board Solar Orbiter. SIS is a time-of-flight mass spectrometer that measures elemental composition from H through ultra-heavy nuclei in the kinetic energy range of ~0.1–10 MeV nucleon\(^{-1}\). SIS has two telescopes, one (SIS-A) pointing at 30\(^{\circ}\) (sunward) and the other (SIS-B) at 160\(^{\circ}\) (anti-sunward) to the west of the spacecraft-Sun line. The energetic proton measurements were obtained from the High-Energy Telescope (HET) of the EPD suite. HET has four viewing directions, with one unit pointing sun- and anti-sunward along the average Parker spiral, and the other unit pointing out of the ecliptic. We also used electron measurements from EPD made by the SupraThermal Electron Proton (STEP), Electron Proton Telescope (EPT), and HET instruments. To determine the interplanetary magnetic field (IMF) polarity, we used magnetic field data from the magnetometer (MAG) on board Solar Orbiter (Horbury et al. 2020).

The coronal activity associated with the event was examined using extreme-UV (EUV) and white-light images from the EUV imager (EUVI) and COR2 coronagraph on Solar Terrestrial Relations Observatory A (STEREO-A; Howard et al. 2008). Solar Orbiter EUV imaging observations from the Extreme Ultraviolet Imager (EUI; Rochus et al. 2020) were not available for the 2020 November 24 event. Furthermore, we inspected radio data from the STEREO-A WAVES (Bougeret et al. 2008) and the Solar Orbiter Radio and Plasma Waves (RPW; Maksimovic et al. 2020) instruments.

3. Observations

The selection of the examined event as a GSEP event is primarily based on abundance ratios that are comparable with the reference population. Furthermore, the event is associated with a large and fast CME, which is typically observed in GSEP events. Figure 1 displays an abundance plot for the event and reference population obtained in the GSEP survey by Desai et al. (2006).

3.1. Solar energetic ions

Figure 2 (left) shows the locations of selected spacecraft in the plane of the ecliptic as seen from the north on 2020 November 24 at 12:30 UT in heliocentric Earth ecliptic (HEE) coordinates. The dashed Parker spiral connects to the CME source longitude (E105 with respect to STEREO-A) as inferred from EUV STEREO-A observations (see Sect. 3.2 below). Solar Orbiter is well connected to the CME source site along a nominal Parker spiral IMF line. The angular separation between the Solar Orbiter magnetic footpoint longitude on the Sun and the longitude of the CME source is ~15\(^{\circ}\) for a nominal Parker spiral for a 350 km s\(^{-1}\) solar wind speed. We note that the solar wind measurements from the Solar Orbiter Solar Wind Analyser (SWA; Owen et al. 2020) are not available for the period of interest. The event was also observed by Parker Solar Probe (PSP), but neither by STEREO-A nor by spacecraft located near Earth (e.g., ACE). The longitudinal separation between Solar Orbiter and PSP of 145\(^{\circ}\) suggests widespread SEPs in the event. Solar Orbiter was at 0.9 au and PSP at 0.8 au from the Sun. The EPD/HET Solar Orbiter 1 hr omnidirectional proton intensities at 10 and 50 MeV for the examined event are displayed in Fig. 2 (right). There is no measured intensity enhancement at 50 MeV. The rapid onset of the event, seen just after the vertical dashed line marking the first appearance of the CME in the coronagraph, is preceded by a small proton enhancement at ~07 UT. There have been reports of EPD electron enhancements with onset at 06:51 UT at 53–85 keV (Wimmer-Schweingruber et al. 2021), which is likely related to this small proton event.

Figure 3 shows Solar Orbiter SIS measurements of the event on 2020 November 24–27. Figure 3a displays 1 h H, \(^{4}\text{He}, ^{4}\text{He}, \text{O}, \text{and Fe}\) intensity at 0.23–0.32 MeV nucleon\(^{-1}\). The 1 hr \(^{3}\text{He}\) intensity is plotted only if the 0.23–0.32 MeV nucleon\(^{-1}\)
The CME source. Nominal Parker spiral IMF lines assuming a 350 km s\(^{-1}\) solar wind speed are shown. Right: Solar Orbiter EPD/HET 1 h omnidirectional proton intensity, obtained by averaging the intensities of the four telescopes. The curve with blue squares, marked 10 MeV, is a combination of 11 energy bins between 7.0 and 11.3 MeV, and the curve with red triangles, marked 50 MeV, is a combination of 13 energy bins between 27.2 MeV and 75.1 MeV. The vertical dashed line indicates the first He count rates, respectively. The event on PSP was clearly seen at energies below ∼0.3 MeV nucleon\(^{-1}\) due to the lack of He counts above 0.4 MeV nucleon\(^{-1}\) (Fig. 3b). The \(^{4}\)He/\(^{2}\)He ratio is close to or lower than the GSEP value of ∼0.01 (e.g., Reames 1995; Kahler & Brown 2021). The Fe/O is close to or higher than the GSEP value of ∼0.1, but does not reach the ISEP value of ∼1 (e.g., Reames 1995). A decrease of \(^{4}\)He/\(^{2}\)He and Fe/O with increasing kinetic energy has previously been reported in GSEP events (e.g., Desai & Giacalone 2016).

The He mass histogram in Fig. 5 (left) shows a clear \(^{3}\)He peak that is well separated from the \(^{4}\)He peak. The event-integrated 0.5–2.0 MeV nucleon\(^{-1}\) \(^{3}\)He/\(^{4}\)He ratio of 0.0094±0.0014 is ∼23.5 times higher than the average \(^{3}\)He/\(^{4}\)He of (4.08±0.25)×10\(^{-3}\) in the slow solar wind (Gloeckler & Geiss 1998). Figure 5 (right) shows time profiles of 0.4–10 MeV nucleon\(^{-1}\) 1 h \(^{4}\)He and 6 h \(^{3}\)He count rates. We used 2.8–3.2 AMU and 3.3–6 AMU mass ranges for \(^{3}\)He and \(^{4}\)He count rates, respectively. \(^{4}\)He data points with one count are not plotted. \(^{3}\)He data points with one count are shown, and their error bars are marked by an arrow. The time profile of the \(^{3}\)He count rate is similar to the \(^{4}\)He time profile, except for a few \(^{3}\)He points with large errors near the end of the event. It has been argued that this similarity suggests the same acceleration and propagation histories (e.g., Mason et al. 1999b; Wiedenbeck et al. 2000).
Fig. 3. GSEP event with time profiles of various physical quantities. (a) Solar Orbiter SIS 1 hr H, \(^{3}\)He, \(^{4}\)He, O, and Fe intensity at 0.23–0.32 MeV nucleon\(^{-1}\). The H PSP curve is a combination of 1 hr H count rates (s\(^{-1}\)) from 14 energy bins between 0.023 MeV and 0.187 MeV from PSP IS\(\odot\)IS EPI-Lo. (b) Solar Orbiter SIS 3 hr \(^{4}\)He/H and Fe/O ratios at 0.23–0.32 MeV nucleon\(^{-1}\). The horizontal lines mark \(^{4}\)He/H and Fe/O in GSEP events (Reames 1995). (c) Solar Orbiter SIS mass vs. time at 0.4–10 MeV nucleon\(^{-1}\). (d) Solar Orbiter SIS \(1/\text{ion speed}\) vs. arrival times of 10–70 AMU ions. The measurements are from both SIS telescopes and averaged together. The vertical dashed line indicates the first appearance of the CME in the STEREO-A/COR2 coronograph. Sloped lines mark arrival times for particles traveling along the nominal Parker field line without scattering. The horizontal color bar on the top shows IMF polarity at Solar Orbiter. Red is negative, green is positive, and yellow is an ambiguous polarity.
3.2. Solar source

The examined SEP event is related to the partial halo CME with a reported speed of 892 km s\(^{-1}\) and width of 106\(^\circ\) that appeared in the COR2 coronagraph on board STEREO-A on 2020 November 24 at 13:24 UT, consistent with the estimated ion injection time at \(\sim\)13 UT. These values are from the automatically generated list of CMEs\(^1\) of STEREO-A (Robbrecht et al. 2009), which uses images from the COR2 coronagraph (field of view of 2.5–15 \(R_\odot\)). The Solar and Heliospheric Observatory (SOHO) Large Angle and Spectrometric Coronagraph Experiment (LASCO) manually identified CME catalog\(^2\) (Yashiro et al. 2004) reports a halo CME with a speed of 668 km s\(^{-1}\) that appeared in the C2 coronagraph (1.5–6 \(R_\odot\)) on 2020 November 24 at 13:25 UT. Figure 6 (top row) shows the CME expulsion between 12:20 and 12:35 UT on November 24. The CME eruption started around 12:25 UT from the area near \(\sim\)S20 at the east limb as viewed from

\(^1\) https://secchi.nrl.navy.mil/cactus/

\(^2\) https://cdaw.gsfc.nasa.gov/CME_list/
STEREO-A. In the same area, STEREO-A EUVI began to observe a small CME post-eruptive arcade (not shown) at $\sim$14:00 UT on November 24, indicating that the CME source was close to the east limb. On November 26, STEREO-A spotted the AR (number 12790) in which the CME originated. An estimated location of the AR was S25E105 (from the point of view of STEREO-A) at the time of the CME eruption. A jet-like eruption occurred $\sim$20 min after CME, apparently from the same area and in the same projected direction as the CME (Fig. 6, middle row arrow). Figure 6 (bottom row) shows the progression of the CME in the COR2 coronagraph.

Figure 7 shows full-disk STEREO-A EUV daily images between 2020 November 24 and November 27. The above-mentioned jet is marked in the leftmost panel. The large bright area that passed through the central meridian represents ARs 12786 and 12785, the sources of a long period of $^3$He-rich SEPs (Bučík et al. 2021). AR 12790, in which the CME (and probably the jet) originated, is marked in the two rightmost panels.

Figure 8 displays a photospheric magnetic field map with a potential field source surface (PFSS; Schatten et al. 1969) model coronal field around the onset of the CME. The PFSS model presents a simple approximation to the real global coronal field that neglects the effects of the forces and electric currents. The PFSS model was computed using the SolarSoft PFSS package, which uses the Solar Dynamics Observatory Helioseismic and Magnetic Imager line-of-sight magnetograms. The magnetograms are assimilated into the flux-dispersal model to provide the magnetic field on the full solar sphere (Schrijver & De Rosa 2003). The source surface that separates open and closed fields was set to the commonly used $2.5 R_\odot$ from the center of the Sun. Figure 8 shows that the Solar Orbiter magnetic footpoint longitude (blue triangle) for a nominal solar wind speed of 350 km s$^{-1}$ was close to the longitude of the CME source AR 12790. Furthermore, Solar Orbiter might be connected to AR 12790 via open negative-polarity coronal field lines emanating from the AR. We note that the in situ IMF polarity on Solar Orbiter (see Fig. 3) is consistent with the model prediction. The PSP footpoint (pink square) separation of $\sim$120$^\circ$ from the CME source AR might be the reason for the only small intensity increase that was observed on the spacecraft.
plasma frequency (~30 kHz). The start time of the type III burst, marked by an arrow in the middle panel, immediately precedes the first appearance of the CME in the COR2, marked by the vertical dashed line in the top panel. Figure 9 (bottom) displays Solar Orbiter electron $c/v$ vs. time spectrogram. This was formed using STEP, EPT, and HET data (top to bottom), which shows a dispersive energetic electron event. Although the observations are limited by the relatively low statistics, the inferred electron solar release time (SRT) at 13:09:41 UT agrees well with the type III burst onset shifted to the Sun at 13:11 UT.

Type III storms were observed by STEREO-A throughout 2020 November 23–29. They probably originated in the closely spaced ARs 12785 and 12786 (see Fig. 7), which showed a persistent brightening. As these regions rotated out of the STEREO-A view, the storm activity decreased.

4. Discussion

We examined the first intense GSEP event with an enhanced $^3$He abundance measured on Solar Orbiter. The $^3$He abundance is significantly (by a factor of ~24) enhanced above the coronal or solar wind abundance. The fundamental question concerning the origin of the $^3$He in the examined event is whether this $^3$He enhancement is due to remnant material left in the heliosphere or to simultaneous activity in the corona (e.g., a parent AR).

The timeline of the solar events is summarized in Table 1. Column 1 shows the type of activity. The instruments that observed the activity are given in parentheses. Columns 2 and 3 give the observed approximate times and the times shifted to the Sun, respectively.

A jet-like expulsion (see Fig. 6) was observed to closely follow (after ~20 min) the CME lift-off. If $^3$He-rich SEPs were produced in association with this jet, ions with kinetic energy, for instance, 0.23–0.32 MeV nucleon$^{-1}$, would arrive at Solar Orbiter at ~19–20 UT (assuming a nominal Parker spiral), which is consistent with the timing of the measurements of $^3$He in the event. However, no type III radio bursts (Fig. 9, middle), a signature of energetic electron production and escape, or energetic electrons (see Fig. 9, bottom) were observed in association with the jet. We recall that the type III radio burst and the electron event observed by Solar Orbiter are significantly later than the start of the jet. It is known that $^3$He-rich SEP events show a strong (~99%) association with type III radio bursts (e.g., Nitta et al. 2006), and only a few cases have been reported without type III bursts (Mason et al. 2009). Thus, it is unlikely that $^3$He was produced in the jet-like eruption.
On its way from the Sun, the event-associated CME shock wave can accelerate remnant $^3$He from a heliospheric reservoir. The reservoir creation requires $^3$He injections and preceding magnetic disturbances, such as interplanetary CMEs, that inhibit particle escape (e.g., Roelof et al. 1992; Reames 2013). The long period of energetic $^3$He on 2020 November 17–23 (Fig. 4 left) was caused by at least five ion injections: three on November 17, one on November 18, and one on November 20 (Bučík et al. 2021). The source in question rotated from E90 to E50 (viewed from STEREO-A), thus filling a substantial volume in the heliosphere with $^3$He. The median values of $^3$He/$^4$He and Fe/O at 0.2–2.0 MeV nucleon$^{-1}$ from these injections are 0.56 and 0.91, respectively. The $^3$He intensity gradually declines before the end of November 23. Using the LASCO CME catalog, we searched for November CMEs that preceded these ion injections. We looked for CMEs with angular widths $\geq 60^\circ$ and the position angle (PA; measured from north counterclockwise) of 0°–33° or 213°–360°. CMEs with PAs like this would travel toward the Sun on November 24 (Fig. 4 right).
hemisphere in which Solar Orbiter is located. Six CMEs met these criteria. These CMEs, whose linear speed varied between ~100 and ~300 km s\(^{-1}\), would travel to distances of 0.3–1.8 au at the liftoff time of the CME associated with the SEP event studied here. Therefore, the medium was appropriate for the confinement of \(^{3}\)He ions from prior events. However, the CME source AR 12790 lies about 100\(^\circ\) farther west from the AR 12786/785 complex (see Fig. 8), we assume that a broad shock from the CME extending well to the west into the reservoir accelerated the \(^{3}\)He seed particles.

In order to determine whether \(^{3}\)He was produced in the parent AR or in other sites on the Sun, we indicate that the examined event was accompanied by a type III radio burst and the causative electrons, commonly seen in \(^{3}\)He-rich SEP events. Unfortunately, we lack EUV imaging observation for a detailed examination of a possible jet activity behind the limb (from the STEREO-A perspective). Cane et al. (2006, 2010) pointed out that the presence of type III radio emission in GSEP events implies that ions accelerated in a concomitant flare can escape into interplanetary space. A direct magnetic connection of Solar Orbiter with the parent AR (see Fig. 8) might allow ion escape and their measurement in the November 24 event. Previously, Cane et al. (1991) suggested that enhanced heavy-ion abundances measured in well-connected GSEP events had a component from flare-accelerated particles. In the examined event, the Fe/O is consistent with GSEP events. The obvious temporal correlation between the \(^{3}\)He and other elements shown in detail in Fig. 5 indicates that the increased intensities are related to a single source. To argue that the \(^{3}\)He somehow appeared with just this timing and intensity as a result of independent activities requires constructing a very unlikely scenario. Therefore, we conclude that the most likely origin of the observed \(^{3}\)He enhancement is due to remnant material from a preceding long period of \(^{3}\)He-rich SEP injections.

A noteworthy feature in the examined period was the storm type III bursts observed by STEREO-A. It has been suggested that storm type III bursts (Fainberg & Stone 1970) are caused by trapped solar energetic electron beams on the coronal loops (e.g., Gopalswamy et al. 2004). It seems improbable that these closed sites provide suprathermal \(^{3}\)He for accelerations in GSEP events.

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