

# Multi-spacecraft Observations of Gradual Solar Energetic Particle Events with Enhanced $^3\text{He}$ Abundance

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## Abstract

Flare suprathermal ions with enhanced  $^3\text{He}$  and heavy-ion abundances are an essential component of the seed population accelerated by CME-driven shocks in gradual solar energetic particle (GSEP) events. However, the mechanisms through which CME-driven shocks gain access to flare suprathermals and produce spectral and abundance variations in GSEP events remain largely unexplored. We report two recent GSEP events: one observed by Solar Orbiter on 2020 Nov 24 (the first GSEP event on Solar Orbiter) and the other by ACE on 2021 May 29 (the most intense GOES proton event in the present solar cycle). The events were preceded by impulsive SEP (ISEP) events. Abundances and energy spectra are markedly different in the examined events at  $< 1$  MeV/nucleon. For example, in the May event, Fe/O is typical of ISEP events, a factor of 100 to 10 higher than Fe/O in the November event.  $^3\text{He}$  abundance in the November event is high, typical of ISEP events, while in the May event, it is much lower, though finite. The May event shows a hard  $^4\text{He}$  spectrum with a power-law index of -1.6, and the November event a soft spectrum with an index of -3.5. The events were associated with halo CMEs with speeds around 900 km/s. The November event was also measured by Parker Solar Probe and the May event by STEREO-A and Solar Orbiter. This paper discusses the origin of vastly different abundances and spectral shapes in terms of variable remnant population from preceding ISEP events. Furthermore, we discuss a possible direct contribution from parent flares.

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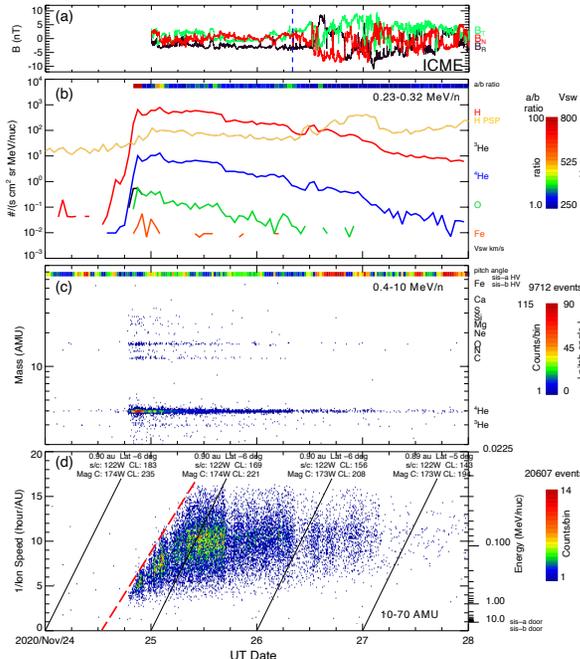
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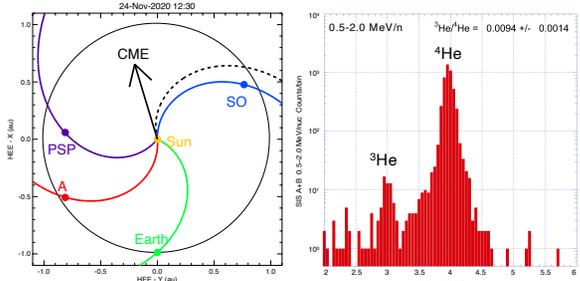
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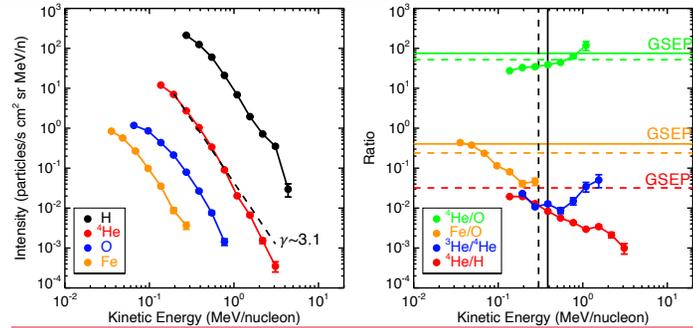
**Motivation.** The  $^3\text{He}$  enhancement is commonly detected in gradual CME-driven shock SEP events. The origin of the enhancement remains largely unexplored. Two mechanisms have been suggested - remnant flare material or concomitant activity in the corona, e.g., parent active region (AR).



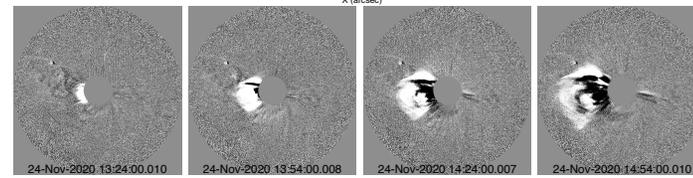
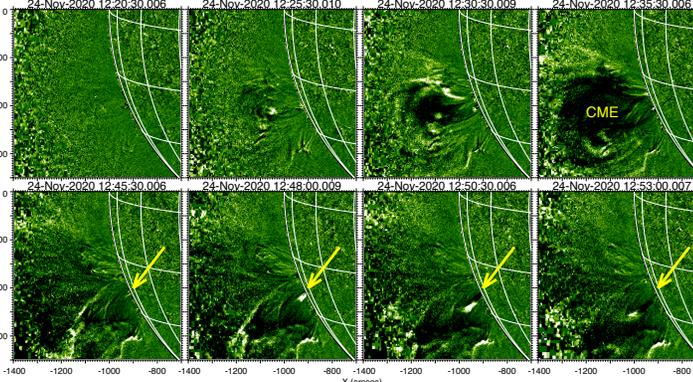
We examine the 2020 Nov 24, 1st gradual SEP (GSEP) event on Solar Orbiter (SO). The event shows enhanced  $^3\text{He}$  abundance. It was detected marginally on Parker Solar Probe (PSP) & only at < 200 keV/n (shown are H count rates in 1/s in panel b).



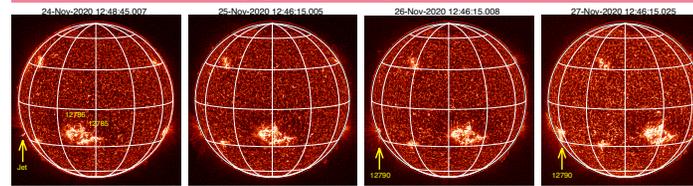
The event was not measured by STEREO-A or near Earth. The event  $^3\text{He}/^4\text{He}$  on SO is  $\sim 24\times$  higher than the coronal value.



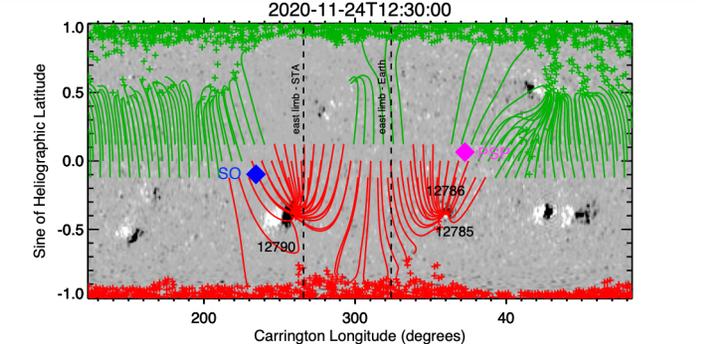
The event shows unusually soft spectra compared to typical low-energy GSEP event spectra with index  $\gamma \sim 1.5$ . The energy dependence of  $^4\text{He}/\text{H}$ ,  $^4\text{He}/\text{O}$ ,  $\text{Fe}/\text{O}$  is consistent with diffusive shock acceleration.



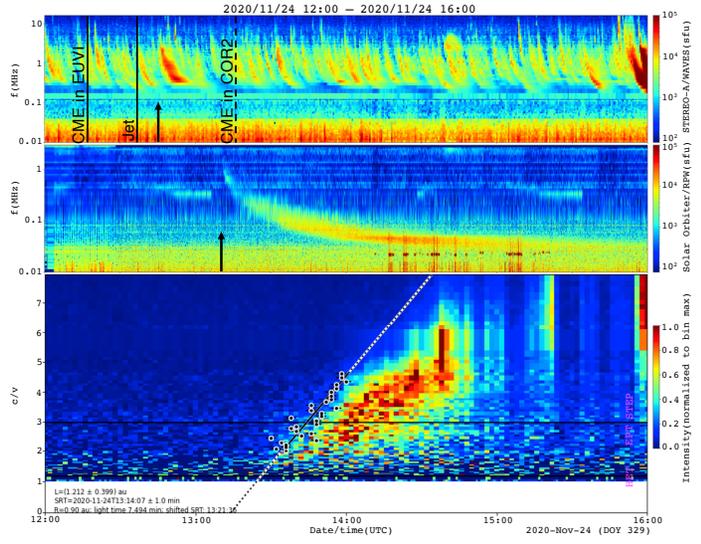
STEREO-A observations of (Top) Early evolution of the event-associated CME in EUVI 195 Å, (Middle) Following jet, (Bottom) Evolution of the CME (partial halo) in the COR2 coronagraph (reported speed 890 km/s).



Daily sequence of STEREO-A EUVI 304 Å images showing the CME source AR 12790 and probable source of the type III storms (ARs 12786, 12785).



PFSS model coronal open field lines that intersect ecliptic. SO could be connected to the CME parent AR. The SO & PSP magnetic foot-points are determined for 350 km/s.



(Top) Type III storms (the strong one marked by an arrow) seen by STEREO-A. The jet accidentally coincided with one storm type III. (Middle) The SO-observed event-related type III started at  $\sim 8 R_{\odot}$ . (Bottom) The type III-associated solar electron event measured on SO.

**Conclusions.** Possible origins of enhanced  $^3\text{He}$  abundance:

- Probable – (1) parent AR showing open field lines where SO was connected augmented by unusually soft spectra of GSEP event (2) remnant  $^3\text{He}$  from preceding  $^3\text{He}$  injections on Nov 17-20 (see SH25B-2084)
- Less probable – the jet without measured type III that followed the CME
- Improbable – magnetically closed type III storm sites