^{3}He/^{4}He Enhancements in Relativistic Solar Electron Events

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***Abstract*. Moses et al. (1989) identified 55 relativistic solar electron events observed by ISEE-3 in 1978-1982. About half of these events showed strong hardening in the rigidity spectrum above a few MV. The origin of this spectral hardening, and how these unusual events fit within our understanding of particle acceleration processes that occur at or near the Sun, is unclear. To further investigate these events, we report for the first time ^{3}He/^{4}He ratios at ∼13-24 MeV/nucleon for these events from the University of Chicago's Cosmic Ray Nuclei Experiment (CRNE) on IMP-8. We also use CRNE to examine proton fluences and proton/alpha ratios above 10 MeV/nucleon and electron/proton ratios. Large ^{3}He/^{4}He enhancements (exceeding 10%) are preferentially found among events with electron spectral hardening. This and other results favor an important role for stochastic acceleration in the events with electron spectral hardening, although the hardening could also suggest the operation of a second process, such as shock acceleration. The characteristics of the events without electron spectral hardening are consistent with those of shock-accelerated "gradual" SEP events, with a few having more modest ^{3}He enhancements that might be produced by flare remnants in the shock's seed population.**

***Keywords*: solar energetic particles, solar electrons, ^{3}He enhancements**

I. Introduction

A close connection between *non-relativstic* (<0.2 MeV) electrons and ^{3}He/^{4}He enhancements at ∼1 MeV/nucleon in impulsive solar energetic particle (SEP) events has long been known [1],[2]. Because of instrumental limitations, there have been comparatively few studies of *relativistic* solar electron events and, to our knowledge, no detailed studies of their ion characteristics. The most extensive study of relativistic solar electron events in the literature is that of Moses et al. (1989) [3]. This study identified 55 solar particle events with a significant flux (>3σ above background [4]) of relativistic electrons at >10 MeV using observations from ISEE-3 in 1978-1982. Data from two different electron instruments on ISEE-3 were combined to examine the electron rigidity spectra over the range of ∼0.1-100 MV. As illustrated by two of their events shown in Fig. 1, these spectra divided their event sample, roughly equally, into two classes: those in which the electron spectrum was consistent with a single power law, and those in which the electron spectrum significantly hardened above a few MV. They also found that the former (latter) events were associated with soft x-ray flares with durations of more than (less than) one hour. Apart from [4], this intriguing study has largely languished in the literature, with little pursuit of what insights these events might hold for the nature of particle acceleration processes at or near the Sun.

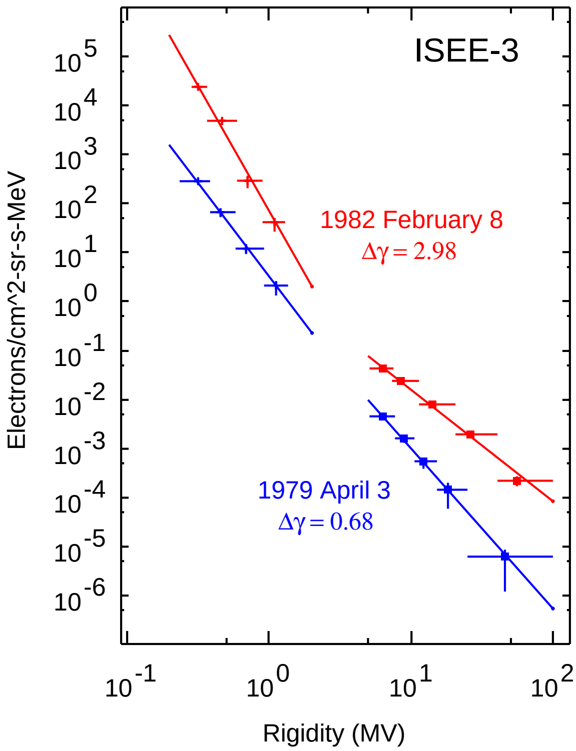

Fig. 1: Electron spectra in two events from Moses et al. (1989), with the change in the rigidity spectrum's power-law index ($\Delta\gamma$) noted for each. The upper event shows strong spectral hardening.

We have recently re-examined the Moses et al. events using data from the University of Chicago's Cosmic Ray Nuclei Experiment (CRNE) on IMP8. CRNE was designed to measure light isotopes of Galactic cosmic rays [5]. CRNE (and earlier versions of the instrument on other IMP spacecraft) also provided measurements of ^{3}He/^{4}He above ∼13 MeV/nucleon in solar energetic particle (SEP) events [6], [7], although the mass res-

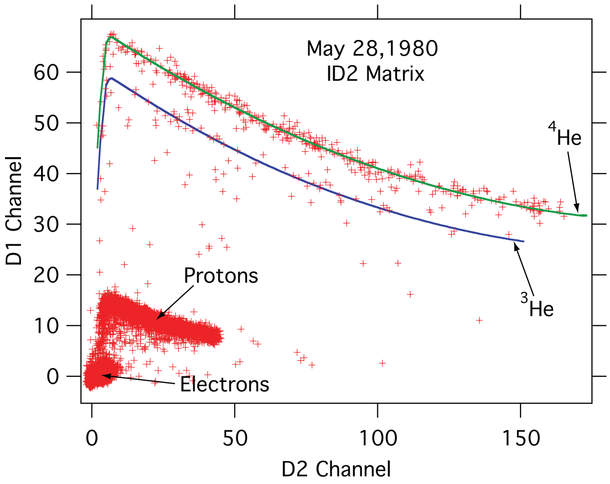

Fig. 2: Pulse-height analysis matrix for particles stopping in the second detector layer of CRNE in the impulsive SEP event of 1980 May 28.

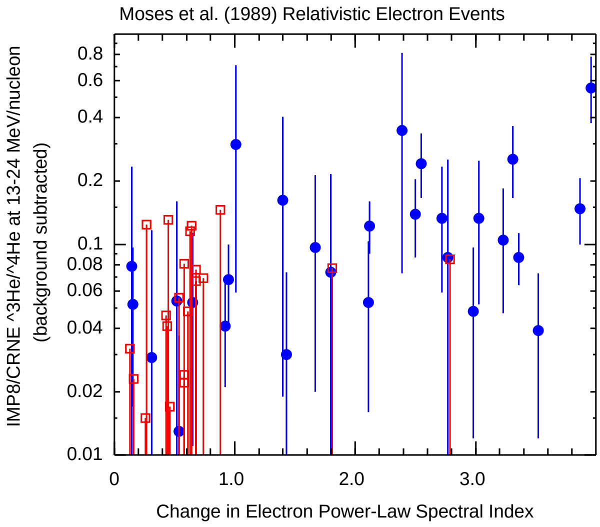

Fig. 3: IMP8/CRNE ^{3}He/^{4}He versus the change in the electron spectral index from Moses et al. (1989). Filled circles are measurements; open squares are upper limits. Before calculating the ratios, the ^{4}He fluences were corrected to 13-24 MeV/nucleon, the same energy interval covered by the ^{3}He.

olution often degraded in large events in which pulse pile-up and other effects broadened the ^{4}He track in the pulse-height-analysis (PHA) matrix. Fig. 2 shows the PHA matrix in an impulsive SEP event from the same epoch as the Moses et al. study. This particular event is not on the Moses et al. list, but has comparatively large ion fluences and better statistics with which to illustrate CRNE's ^{3}He/^{4}He resolution. The ^{3}He and ^{4}He tracks are well separated in the matrix, giving ^{3}He/^{4}He = 0.15 $\pm$ 0.02.

II. CRNE ^{3}He/^{4}He Observations

Moses et al. reported the start time of the soft x-ray flare associated with each of their electron events. We found the associated events in CRNE by comparing this time with the onset of >1 MeV electrons. Four of the Moses et al. events were omitted due to less than 10% CRNE data-recovery during the first 12 hours of the event. Two other events were dropped due to significant background from other events. Of the 49 events that remained, CRNE yielded ^{3}He/^{4}He measurements for 28 events. These measurements are plotted in Fig. 3 versus $\Delta\gamma$, the change in the electron power-law index reported by Moses et al. (1989). The measurements are represented by filled circles. Twenty-one events for which we were able to obtain only an upper limit are represented as open-squares. The ^{3}He/^{4}He ratios shown in Fig. 3 have been background subtracted. This background is typically $\sim$3-4%, but is often higher in the large-fluence events.

The numbers of He ions collected by CRNE in the Moses et al. events are generally small. To illustrate the CRNE He mass-resolution for these events, we therefore sum the counts in the PHA matrix for many events. Fig. 4 shows the histogram of the top-detector's (D1, the vertical axis in Fig,2) channel displacement from the ^{4}He track in the matrix. In this plot, the histograms are summed separately for two groups of events: those with electron spectral hardening (i. e. , $\Delta\gamma \geq 1$), and those without electron spectral hardening ($\Delta\gamma < 1$). (The six largest events – all of which are without electron spectral hardening – are not included in the latter sum because of the excess broadening of their ^{4}He distributions.) The excess counts in the ^{3}He region are clearly seen in the histogram from events with electron spectral hardening but not in the histogram from the other events.

Among the 22 events with significant electron spectral hardening ($\Delta\gamma \geq 1$), 12 have measured ^{3}He/^{4}He > 10%. The statistical uncertainties on these measurements are large; however, the weighted mean value of ^{3}He/^{4}He among these 12 events is 14.5 $\pm$ 1.7%. Among the 27 events without electron spectral hardening ($\Delta\gamma < 1$), none has measured ^{3}He/^{4}He exceeding 10%. There are, however, five events in which the upper-limit lies above 10%. Thus, although we cannot say that large ^{3}He/^{4}He enhancements are absent in the events without electron spectral hardening, it certainly appears that these enhancements are more prevalent among the events with electron spectral hardening.

III. Other CRNE Observations

Moses et al. reported proton fluxes and electron/proton (e/p) ratios for only 35 of their 55 events. Fig. 5 plots CRNE event-integrated proton fluence at 10-20 MeV and >30 MeV versus $\Delta\gamma$ for 49 of the Moses et al. events. GCR backgrounds have been subtracted from these fluences. Although the distribution is not bimodal, it is clear that events with electron spectral hardening generally have much smaller proton fluences than those without spectral hardening. As a comparison to recent

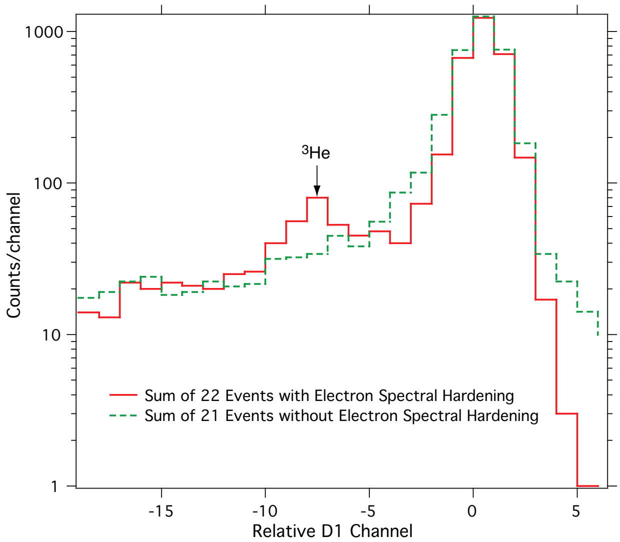

Fig. 4: Summed histograms of D1 pulse-height displacements from the ^{4}He track in the CRNE matrix for 22 events with electron spectral hardening and for 21 events without electron spectral hardening. The latter histogram has been renormalized to the same number of counts in the ^{4}He peak as in the former.

SEP studies, Tylka et al. (2005) selected large SEP events by requiring the >30 MeV proton fluence exceed 2 x 10^{5} cm^{-2}-sr^{-1}. None of the Moses et al. events with electron spectral hardening satisfies this criterion, although two come close. By comparison, more than half of the events without electron spectral hardening (16 out of 27) meet this requirement. Among these 16 events are the five Ground Level Enhancements (GLEs) that appear on the Moses et al. list.

Fig. 6 plots the CRNE e/p ratio versus $\Delta\gamma$. This ratio is based on fluences of particles that stop in the CRNE's second detector and therefore compares electrons at ~0.7-2.0 MeV to protons at ~10-20 MeV. Moses et al. 1989 and Dröge et al. 1989 obtained qualitatively similar results using ratios evaluated with peak intensities of electrons and protons at ~15 MeV. Events without (with) electron spectral hardening tend to have lower (higher) e/p ratios although, again, the distribution of e/p values is not bimodal. As pointed out by [4], the high e/p ratio in events with spectral hardening is due to a paucity of protons, not an excess of electrons. The pattern here is similar to that recently confirmed by Cliver & Ling (2007) when comparing impulsive and gradual SEP events from Cycle 23.

Finally, Fig. 7 plots the CRNE proton/alpha (p/α) ratio at 10-20 MeV/nucleon versus $\Delta\gamma$. Events with the smallest p/α ratios are preferentially found among events with electron spectral hardening, while the largest p/α ratios occur in events without electron spectral hardening. A broad range of p/α ratios of ~20-200 is found in both kinds of electron events.

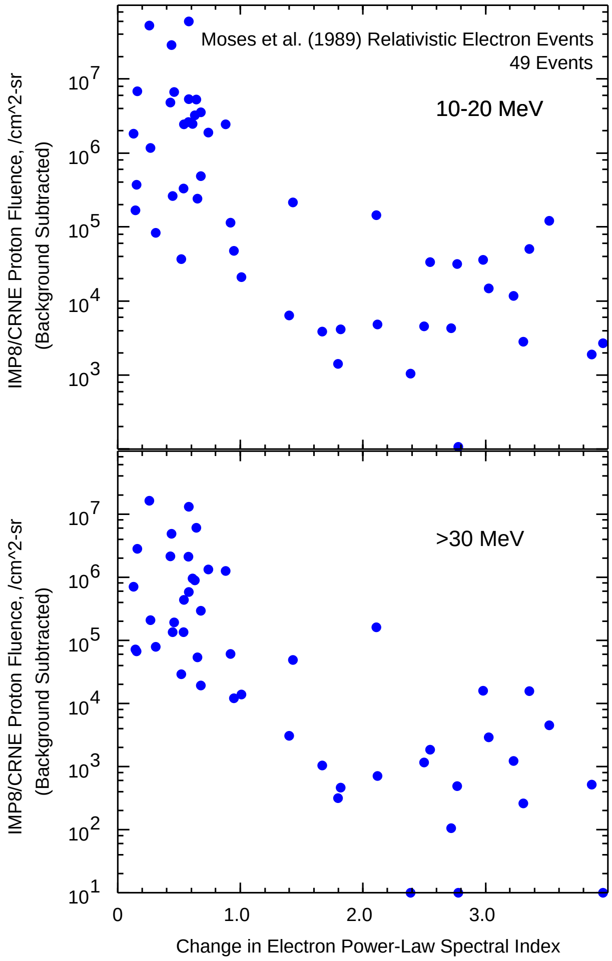

Fig. 5: IMP8/CRNE background-subtracted event-integrated proton fluence at 10-20 MeV (top) and at >30 MeV (bottom) versus Moses et al. (1989) electron spectral index change. Events along the bottom axis had no excess over background.

IV. Discussion

At CRNE energies, enhancements in ^{3}He are rare. Nevertheless, our survey of CRNE data during this time period turned up ~50 other events with >10% ^{3}He/^{4}He enhancements at ~13-24 MeV/nucleon, but which did not appear on the Moses et al. list. The ^{3}He/^{4}He ratios in these other events were often comparable to those shown in the Moses events, sometimes signifcantly greater. Like the event in Fig. 2, ^{3}He statistics were often higher in these other events. As far as we can see in the CRNE electron data, these additional events would not have been rejected on the basis of the secondary requirements in the Moses et al. event selection. Thus, relativistic electrons with spectral hardening may not be a necessary requirement for enhanced ^{3}He/^{4}He above ~13 MeV/nucleon. Alternatively, the ISEE-3 instruments might not have been sufficiently sensitive to register >10 MeV electrons at a >3σ level in these other ^{3}He-rich events.

Dröge et al. [4] attempted to fit the ISEE-3 electron

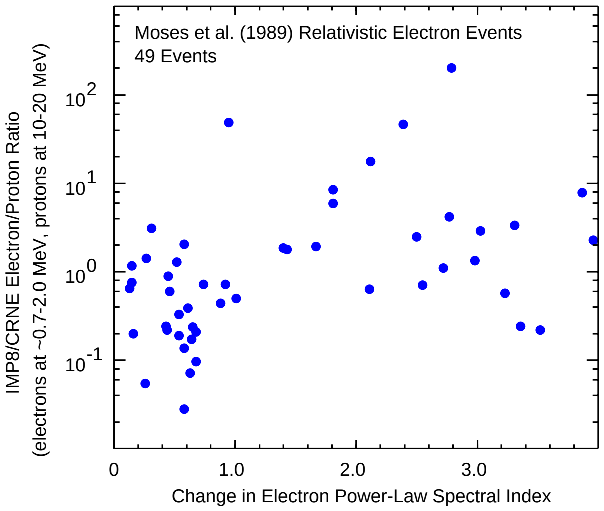

Fig. 6: IMP8/CRNE event-integrated electron/proton ratio versus Moses et al. (1989) electrons spectral index change.

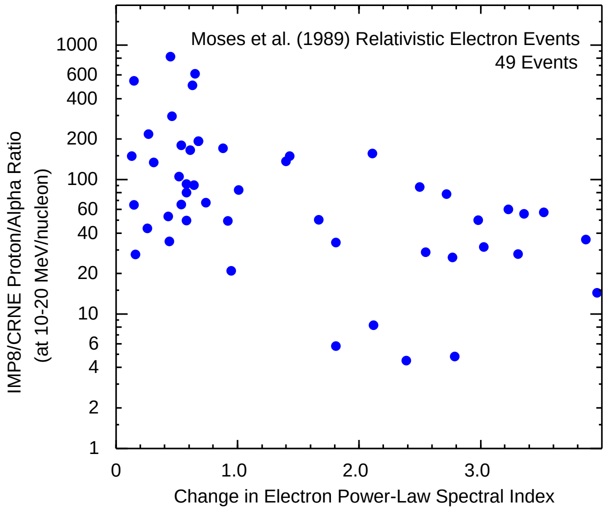

Fig. 7: IMP8/CRNE event-integrated proton/alpha ratio at 10-20 MeV/nucleon versus Moses et al. (1989) electrons spectral index change.

spectra using two models: (1) diffusive shock acceleration operating in the "high" corona and (2) stochastic acceleration taking place in compact magnetic loops in the "low" corona where the plasma density is high and ionization losses cannot be neglected. The stochastic model delivered satisfactory fits to both types of electron spectra. The Dröge et al. shock-acceleration model fitted the electron specta without spectral hardening using plausible compression ratios; but it could not reproduce the electron spectra with hardening. Dröge et al. noted, however, that a more complicated shock model, in which the back reaction of the accelerated particles modifies the shock structure [10], might be able to reproduce the electron spectra with hardening. But in this scenario, one should also ask why the shock modification leads to substantially smaller proton fluences.

For the events without electron spectral hardening, general characteristics – proton fluence, α/p, e/p, and the broader distribution of source longitudes (not discussed here) – are all consistent with a CME-driven shock as the dominant accelerator. For most of these events, CRNE yielded only upper limits on the ^{3}He/^{4}He. For eight out of these 27 events, CRNE provided measurements, none as large as 10% and all but one with ^{3}He/^{4}He within two standard deviations of zero. If some of these more modest ^{3}He enhancements are indeed non-zero, they could be the result of flare-accelerated particles in the suprathermal seed population that have been subsequently boosted in energy by a shock [11],[12],[13].

In summary: (1) the electron events without spectral hardening appear to be shock-dominated; (2) as evidenced by the CRNE ^{3}He/^{4}He, events with spectral hardening have a strong flare component; (3) double power-law electron spectra could be the result of a stochastic acceleration process [4] or they could reflect contributions from both flare and shock accelerators. Further investigations of these alternatives will focus on low-frequency radio emssions that accompany the Moses et al. events.

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