HTML ABSTRACT + LINKS

Measurements of Heavy Elements and Isotopes in Small Solar Energetic Particle Events

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Abstract. Using the Solar Isotope Spectrometer on the Advanced Composition Explorer, we have examined the ~10-20 MeV/nucleon elemental and isotopic composition of heavy ($Z \geq 6$) energetic nuclei accelerated in 30 small solar energetic particle (SEP) events which occurred between 31 March 1998 and 2 January 2001. We have measured the average heavy element content, the ^{22}Ne/^{20}Ne ratio, and the ^{26}Mg/^{24}Mg ratio in these events, and find good agreement with past studies. We have categorized the events according to their ^{3}He/^{4}He ratios, and find significant enhancements in the neutron-rich heavy isotopes of Ne and Mg in the combined ^{3}He-rich data set: ^{22}Ne/^{20}Ne=0.17±0.05 and ^{26}Mg/^{24}Mg=0.25±0.05. We discuss the implications of these measurements for the acceleration of energetic nuclei in SEP events.

INTRODUCTION

Measurements of the elemental and isotopic composition of energetic nuclei from solar energetic particle (SEP) events can provide information about the acceleration mechanisms in these kinds of occurrences. SEP events have been classified into two main types: impulsive and gradual [1]. During gradual events, which have a duration on the order of days, the abundances of heavy SEPs have been shown to vary according to their charge-to-mass ratio [2]. The acceleration of the nuclei during these events is understood to occur at shock waves which are driven by coronal mass ejections (CMEs) [3, 4, 5, 6]. On average, the heavy element composition of SEP material from gradual events is expected to reflect that of the corona. Impulsive SEP events, however, commonly contain enhancements in ~MeV Fe (~10×) and in ~MeV Ne, Mg, and Si (~3×) relative to coronal abundances [7, 8]. Additionally, impulsive events frequently have ^{3}He/^{4}He ratios which are up to 3–4 orders of magnitude larger than the solar wind value of 0.0004 [9]. Impulsive SEP events typically last on the order of hours.

The observed differences between impulsive and gradual SEP events suggest that each has a distinct acceleration mechanism. As stated above, gradual events are known to be associated with CME-driven shocks. However, while the ^{3}He found in impulsive events may be selectively enhanced by ion cyclotron wave resonances [10, 11] or by cascading Alfven waves [12], the exact acceleration mechanism in impulsive events is not presently well understood. In this paper we have examined the heavy elemental and isotopic content of 30 small SEP events. We have classified the small events into two sub-groups according to their ^{3}He content, and have discussed the implications of their elemental and isotopic composition for possible acceleration models.

EVENT SELECTION

The Solar Isotope Spectrometer (SIS) consists of a pair of silicon solid state detector telescopes which measure the energy loss (E) and the rate of energy loss (dE/dx) of incident energetic nuclei with $10 \lesssim E \lesssim 100$ MeV/nucleon. Then, using the measured values of dE/dx and E, the charge and mass of the incident nuclei are derived through an iterative mathematical algorithm [13].

The 30 SEP events selected for this study were chosen according to three criteria. First, a set of 98 days between 31 March 1998 and 31 December 2000 were identified by requiring that their daily averaged SIS 11.0–26.5 MeV/nucleon Fe or 8.6–19.3 MeV/nucleon Mg fluxes be greater than a threshold of 5×10^{-7} particles/(s cm^{2}sr MeV/nuc), and that their daily averaged SIS 11.0–26.5 MeV/nucleon Fe fluxes be less than 2.5×10^{-6} particles/(s cm^{2}sr MeV/nuc). Second, the days which over-

CP598, *Solar and Galactic Composition,* edited by R. F. Wimmer-Schweingruber
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lapped with any of the known large, gradual SEP events were excluded from the study. Finally, the SIS ∼3–5 MeV/nucleon He fluxes on the selected days were examined subjectively for well–defined SEP event onset times and terminations. The 30 events with well–defined onset times and terminations became the final data set examined in this study, while the days which did not show well–defined time profiles in the ∼3–5 MeV/nucleon He flux were discarded. Even so, due to the frequent occurrence of this type of small SEP event, it is still probable that some of the selected "good" events contain multiple injections from the same region on the Sun. This problem is not expected to generate any significant uncertainty in the results of this study, however, because we are only reporting abundances which have been averaged over many SEP events.

TABLE 1. Event times, ∼4.5–5.5 MeV/nucleon ^{3}He/^{4}He ratios, and 11-22 MeV/nucleon Mg fluxes in (cm^{2}sr s MeV/nuc)$^{-1}$ for the 30 SEP events included in this study.

Event #	Time (Year:Day)	^{3}He/^{4}He	Mg Flux
0	1998: 93.1–104.8	0.035	1.7e-07
1	1998:119.7–121.3	0.045	1.9e-07
2	1998:121.3–122.2	0.041	5.7e-07
3	1998:147.4–148.6	0.066	7.6e-07
4	1998:167.7–170.6	0.042	7.3e-07
5	1998:249.1–251.2	0.100	2.5e-07
6	1998:251.6–254.2	0.177	4.3e-07
7	1998:270.2–272.1	0.110	1.0e-06
8	1998:294.1–297.0	0.037	1.2e-07
9	1998:309.7–311.7	0.045	1.6e-06
10	1998:311.7–316.4	0.062	1.5e-06
11	1998:327.5–334.9	0.041	2.3e-07
12	1999:147.3–148.4	0.039	3.9e-07
13	1999:172.7–176.0	0.064	1.1e-07
14	1999:320.7–321.8	0.062	3.5e-07
15	1999:321.7–327.2	0.043	3.4e-07
16	1999:362.0–364.2	0.053	1.2e-06
17	2000: 9.2– 13.5	0.037	3.9e-07
18	2000: 67.2– 68.8	0.090	4.2e-07
19	2000: 82.4– 87.2	0.041	1.1e-07
21	2000:125.3–126.7	0.071	4.0e-06
22	2000:136.7–138.8	0.038	6.4e-07
23	2000:138.8–140.7	0.039	7.7e-07
24	2000:144.7–147.9	0.196	1.9e-07
25	2000:169.2–172.9	0.054	1.6e-07
26	2000:175.3–177.2	0.051	1.4e-06
27	2000:177.2–180.6	0.032	3.9e-07
28	2000:224.0–225.4	0.038	1.0e-06
29	2000:225.4–226.6	0.045	2.2e-07
30	2000:226.6–228.6	0.044	7.1e-07

The final set of 30 events, listed in Table 1, were subdivided into two groups according to their total ∼4.5–5.5 MeV/nucleon ^{3}He/^{4}He ratios. Of the 30 events, 13 had ^{3}He/^{4}He ratios greater than or equal to 0.065, while 17 had ^{3}He/^{4}He ratios which were less than 0.065. In general, the latter 17 events had ^{3}He/^{4}He ratios which were measured between 0.04 and 0.065. This apparent lower limit of 4% is probably due to spillover contamination of the ^{3}He peak by the ^{4}He peak. Although the nomenclature "^{3}He-rich" has generally been reserved for SEP events with ^{3}He/^{4}He$\geq$0.1, we have designated the first sub-group with ^{3}He/^{4}He$\geq$0.065 as "^{3}He-rich" and the second as "^{3}He-poor" in order to preserve adequate measurement statistics in the ^{3}He-rich sub-group.

While the unweighted average ∼4.5–5.5 MeV/nucleon ^{3}He/^{4}He ratio in the ^{3}He-rich and ^{3}He-poor groups is ∼12% and ∼5% respectively, and impulsive events are expected to have higher ^{3}He/^{4}He ratios than gradual events, it is not clear that our two event sub-groups are cleanly divided as such. For example, the unweighted average duration of the events in the ^{3}He-rich (^{3}He-poor) subset is 2.4 (3.4) days, which is longer than expected for impulsive SEP events. It could be that while the ^{3}He-rich events contain a relatively large fraction of material which was originally accelerated in impulsive SEP events, they are not necessarily impulsive events. This idea stems from the theory by Mason et al. [15], which says that residual material from past impulsive SEP events may provide a source population for further acceleration by CME-driven shocks associated with gradual events. Experimental observations of SEP composition during large gradual events [14, 15, 16, 17] and during times of low solar activity [18, 19] have supported this theory.

LOW SOLAR ACTIVITY SPECTRA

The contributions to the small SEP event spectra from galactic cosmic rays (GCR) and anomalous cosmic rays (ACR) [20] have been estimated from SIS measurements during 241 days of low solar activity between 9 April, 1998 and 25 December, 2000. The 241 days were identified by examining the proton fluxes from the Electron, Proton, and Alpha Monitor (EPAM) instrument on board ACE, and requiring that the daily averaged 1.06-4.75 MeV proton flux be less than 0.16 (cm^2 sr s MeV/nuc)$^{-1}$. Next, the 241 days were grouped chronologically into three time periods of relatively constant solar modulation, based on inspection of SIS ∼7-10 MeV/nucleon O fluxes. These time periods were 9 April, 1998–25 November, 1998, 26 November, 1998–14 January, 2000, and 14 January, 2000–25 December, 2000. For each of the three time periods, the average heavy element spectra were extracted from the daily measurements. These average heavy element spectra were weighted with the temporal fraction of the 30 small SEP events which occurred during each time period, and were subsequently summed for subtraction

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from the small SEP event spectra.

HEAVY ELEMENT MEASUREMENTS

The average energy spectra for the elements C, O, Ne, Na, Mg, Al, Si, and Fe were measured for the 30 small SEP events, as well as for the "^{3}He-rich" and "^{3}He-poor" subsets. These spectra were derived by taking the raw number of nuclei for each species detected during all of the SEP events combined, and dividing that number by the total amount of instrument livetime. Finally, the GCR and ACR components of the spectra were subtracted as described above to yield the SEP fluxes for each element. Figure 1 depicts the relative abundances of nine heavy element ratios in the energy range ~11–22 MeV/nucleon, normalized to coronal abundances [21], for both the ^{3}He-rich and ^{3}He-poor SEP event data sets.

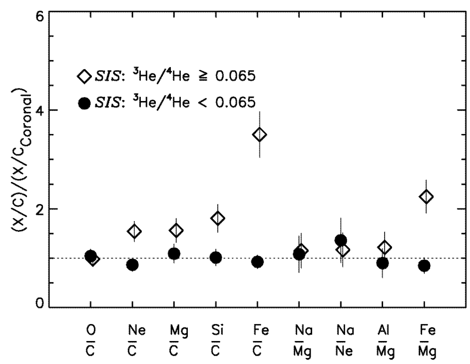

FIGURE 1. 11.0–21.8 MeV/nucleon abundances of O, Ne, Mg, Si, and Fe with respect to C, as well as the Na/Mg, Na/Ne, Al/Mg, and Fe/Mg ratios, normalized to coronal abundances [21], for the ^{3}He–rich (open diamonds) and ^{3}He–poor (filled circles) data sets.

From the figure, it is apparent that while the composition of the ^{3}He-poor data set generally reflects that of the corona, the ^{3}He-rich data set contains an average enhancement in Fe with respect to C of ~4×, as well as more modest enhancements in Ne, Mg, and Si of ~2×. The uncertainties shown in the plot are statistical in nature, and do not reflect any contribution from a possible non-statistical population spread in the events. This trend in the heavy element abundances is in agreement with past studies, which associate large ^{3}He/^{4}He ratios in SEP events with Fe, Ne, Mg, and Si enhancements at ~MeV energies [7, 8], although the magnitude of the enhancements are smaller in the above SIS data. Also of note is that since the coronal values chosen for normalization in this figure were derived from large gradual SEP events, it is likely that the ^{3}He-poor events consist primarily of small "gradual" events.

NEON AND MAGNESIUM ISOTOPE RATIOS

The isotope ratios of ~15-24 MeV/nucleon Ne and ~16-26 MeV/nucleon Mg have been extracted from the SIS data using a superposition of Gaussian fits to the derived charge histograms. Figure 2 shows the two charge histograms of Ne and Mg in these energy ranges. With the iterative charge calculation used, different isotopes of an element are assigned charges differing by ~0.1 charge units for each 1 amu mass difference. Thus the five peaks representing ^{20}Ne, ^{22}Ne, ^{24}Mg, ^{25}Mg, and ^{26}Mg are shown in the figure, and have been fit with a function composed of five Gaussian curves of identical width and uniformly spaced isotopes. Because the ^{25}Mg peak was not well-constrained by the data in the energy range ~16-26 MeV/nucleon, its height was fixed at 12.7% of the ^{24}Mg peak height in accordance with

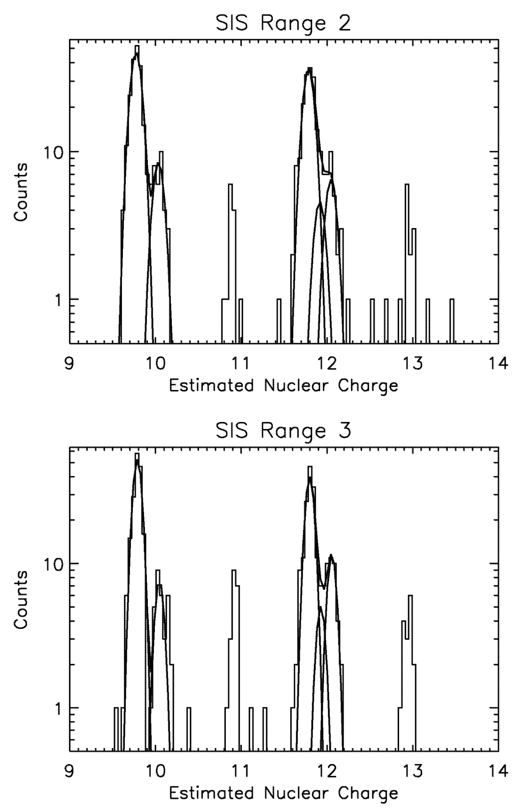

FIGURE 2. Estimated nuclear charge in the energy range 14.7–19.3 MeV/nucleon (top panel) and 17.6–24.1 MeV/nucleon (bottom panel) measured using SIS during the 30 small SEP events. The ^{20}Ne, ^{22}Ne, ^{24}Mg, ^{25}Mg, and ^{26}Mg peaks have been fit with a superposition of five Gaussian curves of identical width and uniformly spaced isotopes. The ^{25}Mg/^{24}Mg ratio of peak heights has been fixed at the average solar system value of 0.127 [22]

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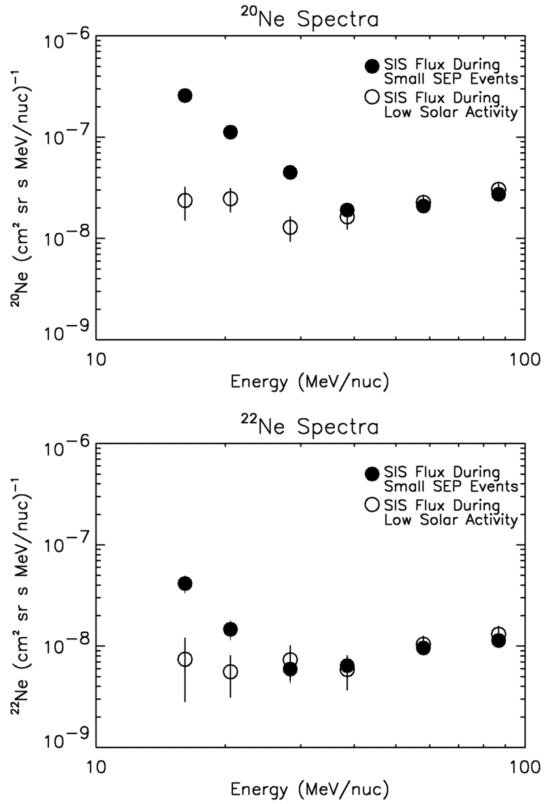

FIGURE 3. Average ^{20}Ne and ^{22}Ne energy spectra for the 30 small SEP events contained in this study (solid circles), and for the days of low solar activity over the same time period (open circles).

the average solar system value reported by Anders and Grevesse [22]. It is important to note that a factor of two variation about the assumed abundance of ^{25}Mg changes the ^{26}Mg/^{24}Mg result less than the statistical uncertainty in that ratio.

The measurements of the Ne and Mg isotope spectra are shown in Figures 3 and 4. The filled circles represent SIS data during the 30 small SEP events, while the open circles show the SIS measurements during periods of low solar activity between the small SEP events (see above). Because the ^{26}Mg quiet-time spectrum was difficult to extract below $\sim$40 MeV/nucleon due to statistical limitations, the higher energy data points were fit with a power-law function which was extrapolated down to $\sim$20 MeV/nucleon. Conversely, the Ne quiet-time spectrum contains a contribution from the ACRs which results in the beginning of a turn-up in the quiet-time spectrum at about 20-30 MeV/nucleon. All of the isotope spectra show clear low-energy ($<$30 MeV/nucleon) turn-ups in the SEP event spectra, which is evidence for the presence of solar particles in numbers well above the low solar activity background.

With the event spectra and low solar activity spectra shown in Figures 3–4, one can derive the small SEP event (with GCR and ACR components subtracted) ^{22}Ne/^{20}Ne and ^{26}Mg/^{24}Mg isotope ratios. This has been done for both the ^{3}He-rich and ^{3}He-poor event data sets. Figure 5 shows the results of the isotope ratio measurements below $\sim$30 MeV/nucleon for each data set. On each plot, the average of the two data points, with one standard deviation of statistical uncertainty, is represented by the grey shaded area.

From the two top panels in Figure 5, it is apparent that the average SEP ^{22}Ne/^{20}Ne ratio is at least slightly enhanced over the solar wind value of 0.073 [23] for both the ^{3}He-rich and ^{3}He-poor event data sets. In the data set with ^{3}He/^{4}He$\geq$0.065, the ^{22}Ne/^{20}Ne ratio is found to be enhanced over the solar wind value by a factor of $\sim$2.4$\times$, with significance at the 2σ level, while in the ^{3}He-poor data set the ratio is only enhanced by 1σ. Similarly, in the bottom panels the ^{26}Mg/^{24}Mg ratio in the ^{3}He-rich

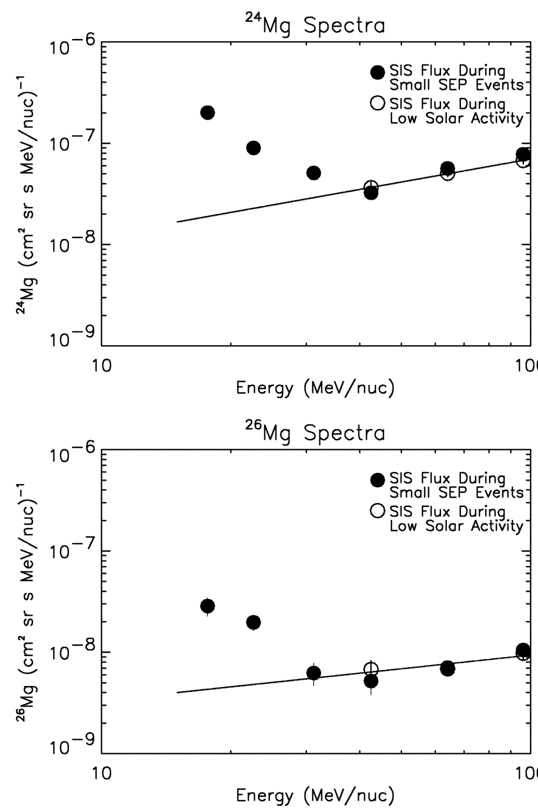

FIGURE 4. Average ^{24}Mg and ^{26}Mg energy spectra for the 30 small SEP events contained in this study (solid circles), and for the days of low solar activity over the same time period (open circles). The solid line represents the extrapolated galactic cosmic ray (GCR) spectrum from the fit with a power–law function to the three highest energy low solar activity data points on the plot.

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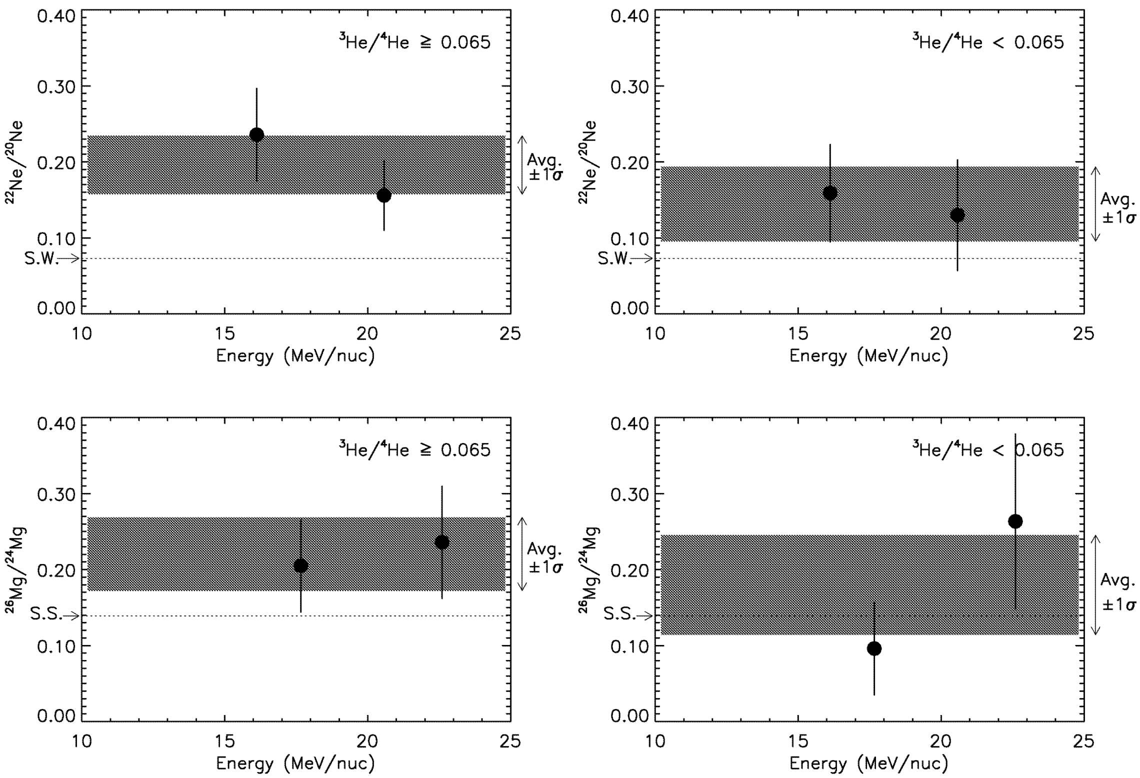

FIGURE 5. Top panels: ^{22}Ne/^{20}Ne ratios for the ^{3}He–rich and ^{3}He–poor data sets. The horizontal dotted line respresents the solar wind value of 0.073 [23]. Bottom panels: ^{26}Mg/^{24}Mg ratios for the ^{3}He–rich and ^{3}He–poor data sets. The horizontal dotted line respresents the average solar system value of 0.127 [22]. The shaded regions in each plot denote the average value of the two data points, with an uncertainty of one standard deviation.

SEP events shows an enhancement over the solar system value of 0.127 [22] by a factor of $\sim 2\times$, at a significance level of 2.5σ. The data set with ^{3}He/^{4}He<0.065 yields a measurement of ^{26}Mg/^{24}Mg which is consistent with the solar system value.

While the ^{3}He–rich events have significant enhancements of neutron–rich heavy isotopes of Ne and Mg, it is important to note again that our definition of "^{3}He–rich" is less restrictive than the widely–accepted requirement that ^{3}He–rich SEP events have ^{3}He/^{4}He>0.1. For this reason, our "^{3}He–rich" subset of events may contain a smaller fraction of impulsive SEP material than it would have had with a more stringent cut on the ^{3}He content. It is possible that the heavy isotopic enhancements would have been even larger if statistics had allowed for such a study.

CONCLUSIONS

The average heavy element content of these 30 small SEP events has been shown to change significantly with the event ^{3}He/^{4}He ratio. Of the 30 events selected for the study, the 17 with ^{3}He/^{4}He<0.065 have an average $\sim$11-22 MeV/nucleon heavy element composition which is very similar to the solar corona. The other 13 ^{3}He-rich events contain average enhancements in Fe/C of $\sim$4, and enhancements in Ne/C, Mg/C, and Si/C of $\sim$2. This trend is in qualitative agreement with past studies of ^{3}He-rich events at lower energies [7, 8].

The average $\sim$15-25 MeV/nucleon Ne and Mg isotopic content of these SEP events also changes with the ^{3}He/^{4}He ratio. The ^{22}Ne/^{20}Ne ratio increases from 0.13$\pm$0.06 in the ^{3}He-poor events to 0.17$\pm$0.05 in the ^{3}He-rich data set, which is consistent with past measurements of "^{3}He-rich" events at $\sim$MeV energies (^{22}Ne/^{20}Ne=0.29$\pm$0.10) [24]. Similarly, we find that the ^{26}Mg/^{24}Mg ratio increases to 0.25$\pm$0.05 in the ^{3}He-rich data set, consistent with previous studies (^{26}Mg/^{24}Mg=0.36$\pm$0.21) [24].

The observations of ^{3}He-rich SEP events with enhancements in neutron-rich heavy isotopes is consistent with the model of Miller [12]. This model predicts that in ^{3}He-rich events, isotopes with a lower charge-to-mass

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ratio should be enhanced relative to those with a higher ratio due to interactions with cascading Alfvén wave turbulence. While the exact magnitudes of the expected enhancements have not been determined, we find that the isotopic enhancements reported using SIS data are in qualitative agreement with this model and are quantitatively consistent with those of past measurements.

ACKNOWLEDGMENTS

This research was supported by NASA at Caltech (under grant NAG5–6912), JPL, and GSFC. We thank the EPAM science team for providing the proton fluxes used to define the time periods of low solar activity in this paper.

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