SURVEY OF He^+/He^{2+} ABUNDANCE RATIOS IN ENERGETIC PARTICLE EVENTS

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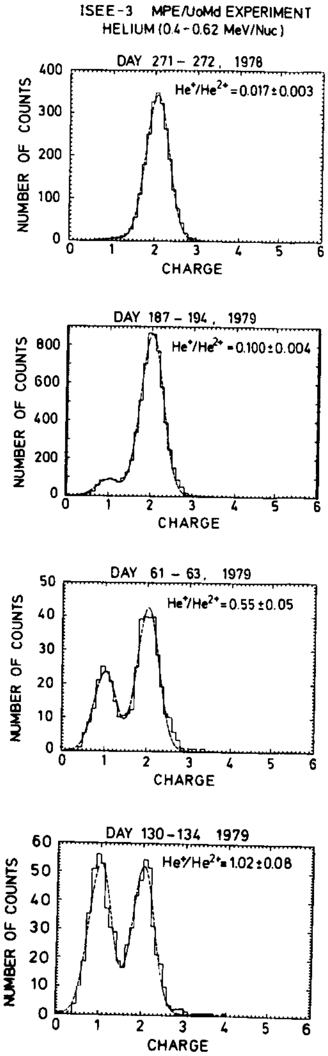
A B S T R A C T

We report first results of a systematic study of the helium charge distribution in the energy range 0.4 - 0.62 MeV/nucleon in energetic particle events. The data have been obtained during the time period September 1978 to November 1979 with the Max-Planck-Institut/University of Maryland experiment on ISEE-3. We found an average He^+/He^{2+} ratio of 0.12 ± 0.04 with ratios exceeding 0.3 for 41 out of 420 days analyzed. No obvious association with optical flare events could be observed for the events richest in He^+. We did not find significant differences of the proton energy spectra, and the abundance of helium relative to protons and heavy ions for He^+-rich events ($He^+/He^{2+} > 0.3$) and for events with $He^+/He^{2+} < 0.3$, respectively. However, it has been found that He^+-rich events are predominantly low in energetic particle intensity.

Introduction

The measurement of the ionization states of solar energetic particles is of fundamental importance in two respects. Firstly, it provides information about the temperature of the source region at the sun. Secondly, it is essential for the investigation of acceleration and propagation processes at the Sun and in interplanetary space, because these processes will generally depend on the particle velocity and rigidity (i.e. mass per charge ratio). A direct determination of both the nuclear and ionic charge of heavy ions has been beyond experimental capabilities until recently. The first direct ionic charge measurements for solar flare particles in the MeV/nucleon energy range with simultaneous element identification have been reported by Hovestadt et al. (1981a, b) and Gloeckler et al. (1981). The most surprising feature of their measurements was the observation of large abundances of singly ionized helium in the energy range 0.4 - 1.5 MeV/nucleon. For 10 solar energetic particle events studied until now, the mean charge states of C, O, and Fe turned out to be consistent with "freezing-in" temperatures in the range $2 - 3 \cdot 10^6$ K, whereas for He^+/He^{2+} a ratio of $\sim 0.06 - 0.2$ had been found, indicative of significant contributions of cold material with $T \leq 5 \cdot 10^4$ K. In this paper we report the results of a systematic study of the helium charge state distribution during the time period September 1978 to November 1979.



Instrumentation and Satellite

The data have been obtained with the Ultra-Low-Energy-Z-E-Q analyzer (ULEZEQ) of the Max-Planck-Institut/Universi-ty of Maryland experiment on ISEE-3. During the time period investigated ISEE-3 was stationed in the interplanetary medium at the Langrangian point L_1 between the Earth and the Sun, at a distance of $\sim$ 230 R_E from the Earth. The instrument represents the combination of an electrostatic analyzer with a dE/dx versus E sensor system, thus providing the determination of the nuclear charge, the energy, and the ionic charge independently for each particle. More datails of the principle of operation and of the data analysis may be found elsewhere (Hovestadt et al., 1978, 1981a).

Figure 1 shows typical helium charge histograms obtained for the energy range 0.4 - 0.62 MeV/nucleon during 4 energetic particle events in 1978 and 1979. The He^+/He^{2+} ratios are derived from gaussian fits of the histograms as indicated by dashed lines. Figure 1 demonstrates the variety of the He^+/He^{2+} ratios, it shows that variations by almost two orders of magnitude ($He^+/He^{2+} \sim 0.02 - 1.0$) can be observed.

Figure 1: Helium charge histograms for four typical energetic particle events showing the variability of the He^+/He^{2+} abundance ratios. The dashed lines are least square fits to the data.

Observations

For our survey of He^+ and He^{2+} abundances we computed daily averages of the He^+/He^{2+} ratio and of the helium flux in the energy range 0.40 - 0.62 MeV/nucleon. The survey covers the time period September 1978 to December 1979 (420 days). From this total number of 420 days we excluded days with less than 20 helium counts per day from our analysis. Figure 2 shows daily averages of the helium counting rate (upper panel) and of the He^+/He^{2+} ratio (lower panel) in the energy range 0.40 - 0.62 MeV/nucleon. It can be seen that the He^+/He^{2+} ratio is less than 0.3 for the majority of days analyzed. However, large He^+/He^{2+} abundance ratios exceeding 0.3 are observed for 41 days. Figure 2 shows also that large abundances of singly ionized helium seem to be correlated with low intensity energetic particle events.

This can be seen more clearly in Figure 3, where we correlated the daily averages of the He^+/He^{2+} ratio with the helium counting rate. The crosses in Figure 3 (and in the following Figures) indicate that for the He^+/He^{2+} ratio only upper limits could be computed. It should be noted that due to the selection criterion ($\geq$ 20 cts/day) with the averaging period (1 day) no data are available in the shaded area of the scatter plot. It is evident from Figure 3 that large abundances of He^+

occur only at small helium fluxes; e.g. $He^+/He^{2+} > 1$ is observed only for $< 3 \cdot 10^{-3}$ c/s. The contrary, however, is not true: small values of He^+/He^{2+} are observed for a large range of helium fluxes. It is possible that the spread in the charge abundance ratios increases with decreasing helium-fluxes similarly to observations of Mason et al. (1980), who observe an increasing spread in elemental abundance ratios of interplanetary radiation with decreasing absolute flux values.

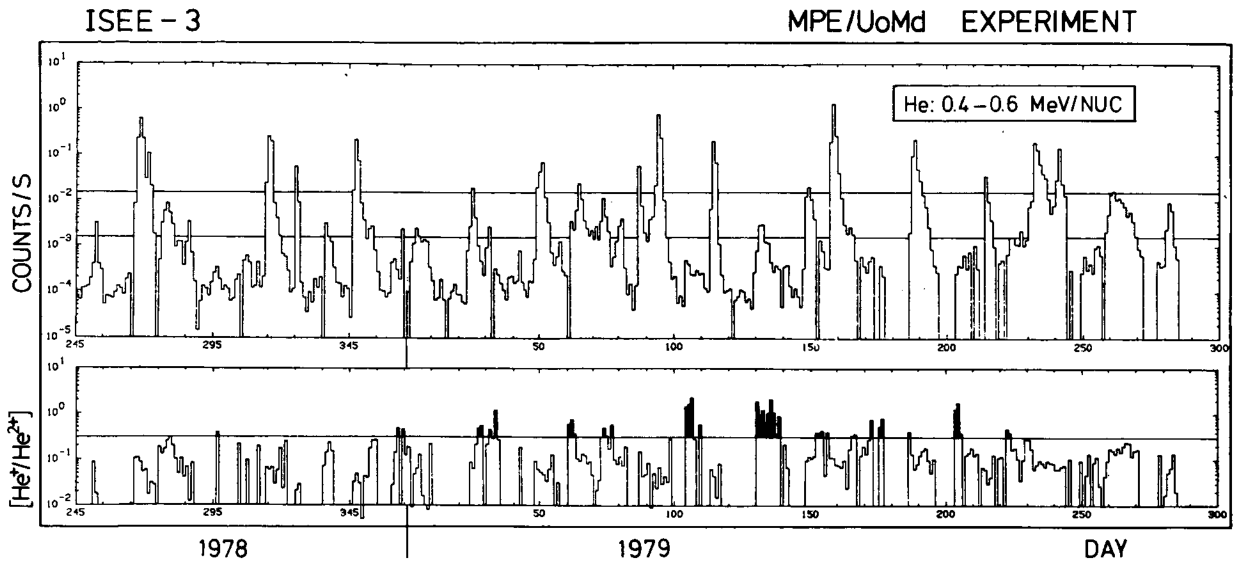


Figure 2: Helium flux (upper panel) and He^+/He^{2+} ratio for the time period September 1978 to November 1979. He^+-rich time periods ($He^+/He^{2+} > 0.3$) are marked by vertical bars.

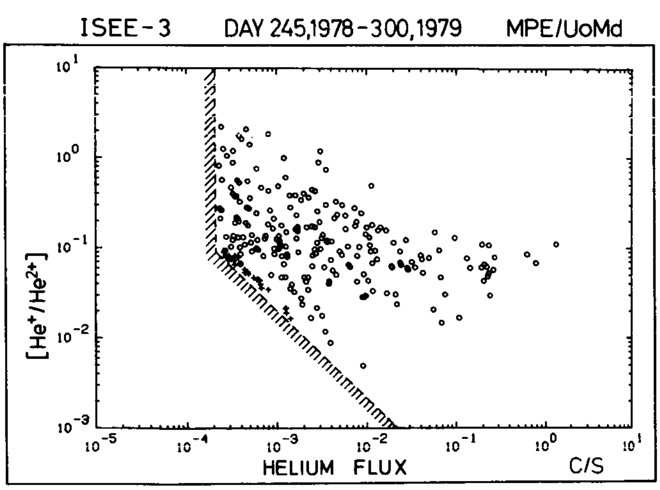


Figure 3: Correlation of the He^+/He^{2+} ratio with the helium flux in the energy range 0.4 - 0.62 MeV/nucleon.

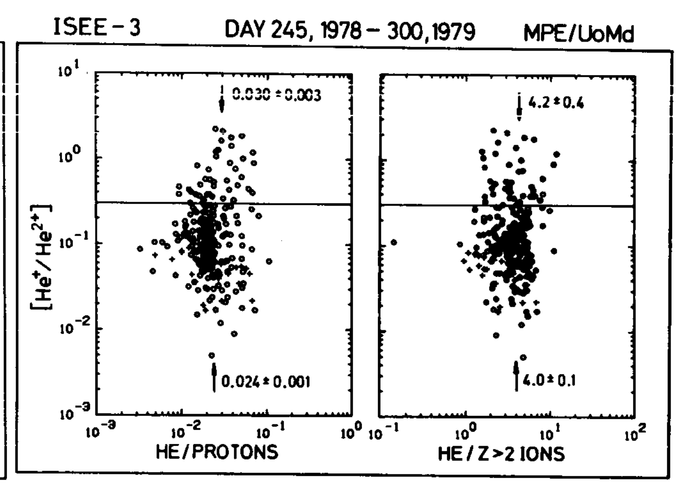


Figure 4: Correlation of the He^+/He^{2+} ratio with helium abundances relative to protons (left panel) and $Z > 2$ ions (right panel). The abundances are given in relative units, not normalized to the same energy range.

In Figure 4 we correlated the He^+/He^{2+} ratio with the abundance of helium ($He^+ + He^{2+}$) relative to protons (left panel) and relative to $Z > 2$ ions (right panel).

The energy range is 0.45 - 1.2 MeV for protons and > 0.3 MeV/nucleon for Z > 2 ions (oxygen). The He/p and He/Z > 2 abundance ratios are given in relative units, not normalized to the different energy ranges of the measurement. The scatter plots show only a very weak correlation of the He^+/He^{2+} ratio with the He/p ratio and no significant correlation with the He/Z > 2 ratio. This can be seen more quantitatively from the mean values of He/p and He/Z > 2, which differ less than 2 sigma for time periods with $He^+/He^{2+} < 0.3$ and $He^+/He^{2+} > 0.3$, as shown in Figure 4.

A possible correlation of the He^+/He^{2+} ratio with the spectral index γ of the proton energy spectra at low energies has been investigated in Figure 5. The spectral index has been calculated from proton fluxes in the energy ranges 0.45 - 1.2 MeV, and 1.2- 3.0 MeV as measured with the same experiment, assuming $j_p \propto T^{\gamma}$. Figure 5 shows that the mean value of γ is not significantly different for events with $He^+/He^{2+} > 0.3$, and $He^+/He^{2+} < 0.3$ respectively. The large spread of γ for time periods with $He^+/He^{2+} < 0.3$ is partly due to time dispersion effects. These time periods include large solar energetic particle events where flat ($\gamma \sim 0$) energy spectra during the onset phase of the event are frequently observed.

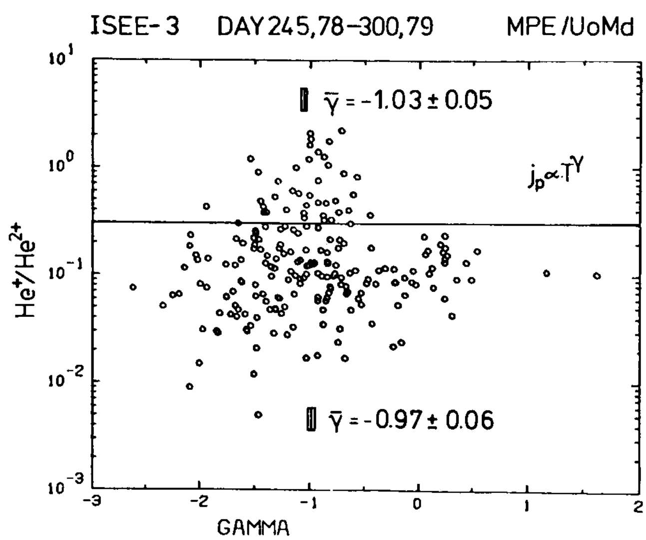


Figure 5: Correlation of the He^+/He^{2+} ratio with the spectral index of protons assuming $j_p \propto T^{\gamma}$. T is the kinetic energy.

Discussion and Summary

The results of our survey of He^+/He^{2+} abundance ratios can be summarized as follows:

(1) Small but finite abundances of singly ionized helium in energetic particle events are very common.

(2) The mean value of the He^+/He^{2+} ratio for time periods with high helium fluxes $> 1.5 \cdot 10^{-2}$ c/s corresponding to > 4 particles/cm^2 sr sec MeV/nuc has been obtained as $He^+/He^{2+} = 0.067 \pm 004$. These periods usually can be correlated with solar flares.

(3) High He^+/He^{2+} ratios are less frequently observed. However, for 41 out of 420 days $He^+/He^{2+} > 0.3$ has been measured and $He^+/He^{2+} > 1$ has been observed for 11 days.

(4) We find no correlation of the He^+/He^{2+} ratio with
- the helium/$Z > 2$ ratio
- the spectral slope of protons at low energies (0.45-3.0 MeV) and
- only a very weak one if at all with the helium/proton ratio

(5) We do find a correlation of the He^+/He^{2+} abundance ratios with the helium flux in the sense that large He^+/He^{2+} abundance ratios are only observed for periods with small helium fluxes, but not vice versa. At small fluxes the apparent spread of the charge abundance ratio may be simply larger to include large ratios.

Our survey of the helium charge state composition in energetic particle events clearly shows that significant abundances of He^+ represent a common feature of the low energy particle population in interplanetary space. These large abundances of He^+ are certainly not compatible with the charge state of helium in a hot coronal gas, which has usually been considered as the source of energetic flare particles. At coronal temperatures above 10^6 K the fraction of singly ionized helium is expected to be much less than 10^{-4} (e.g. House, (1964)). Therefore we conclude that significant contributions of cold material are accelerated, not only in large solar particle events (discussed by Hovestadt et al., (1981a), and Gloeckler et al., (1981)), but also in small events with low particle intensities in interplanetary space.

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