A Study of ^{3}He Spectra and Abundances in Impulsive Solar Energetic Particle Events - Results from Measurements with ACE/SEPICA, ACE/SIS and SOHO/HSTOF

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Abstract

Energy spectra of the He isotopes and the energy dependence of the $^3He/^4He$ ratio during a number of impulsive solar energetic particle events (SEP) observed between September 1997 and December 1998 are analyzed. Data covering the energy range from 0.1 to 10 MeV/amu were supplied by three instruments with complementary energy ranges: the Solar Energetic Particle Ionic Charge Analyzer (SEPICA) and the Solar Isotope Spectrometer (SIS) on ACE, and the time-of-flight mass spectrometer HSTOF on SOHO. We confirm the trend of a monotonic increase of the ^{3}He abundance with energy up to a maximum in the region of a few MeV/amu found in previous ISEE studies and extend the analysis to events of intermediate ^{3}He enrichment. We briefly discuss the observational data and their relation to existing theoretical work on selection and acceleration mechanisms in impulsive flares.

1 Motivation

A set of particle instruments on the ACE and SOHO missions offer possibilities for new insights into the physics of impulsive SEP events and by gaining new and more complete data on their spectra and time evolution, a chance for better understanding their connection to impulsive solar flares (Reames, 1990). To understand how our results relate to already existing knowledge one must be aware of the present state of the problem - below is a concise summary of the picture of the physics of impulsive SEP events. The material emerging out of the flare region is enriched in ions of ^3He so that 1000-fold and even higher enhancements of the $^3He/^4He$ ratio above its level in the quiet corona are observed. Furthermore, the following features of ^{3}He-rich SEP events must be accounted for by any theory claiming to tackle the problem: preferential acceleration of ^{3}He occurring in impulsive flares; the correlation of the ion acceleration mechanism(s) to the electron beams generated during such flares; coronal plasma enrichments in heavy ions (Fe) also appear to be a prerequisite for the ^{3}He-rich events; increase in the average charge states of the energetic heavy ion components.

In theories attempting to explain the extremely high ^{3}He/^{4}He ratios from impulsive SEP events different mechanisms of selective heating out of the thermal component of ^{3}He by wave-particle interactions occurring in impulsive flares have been invoked. To mention only the most popular of them: resonant interaction with electromagnetic ion-cyclotron waves produced between the H and ^4He gyrofrequences by streaming electrons in the flare plasma - Temerin & Roth (1992), and mechanisms of preferential acceleration of ^{3}He up to MeV-energies by stochastic Fermi acceleration of preheated particles in an environment of Alfven turbulence ($\omega_A < \Omega_c$) - Barbosa (1979), Möbius et al. (1982); the ion acceleration takes place on open field lines near the flare site in stochastic interactions with waves generated in the nearby flare - Reames (1990).

2 Observations

Data from three different instruments of complementary energy ranges have been used for the present analysis. The energy range between 0.5 and 10. MeV/amu is covered by two sensors onboard ACE whereas the lowest energy interval (0.1 - 1.0 MeV/amu) is measured by one of the particle telescopes on SOHO. Only the most substantial parameters of the instruments are mentioned below.

The Solar Energetic Particle Ionic Charge Analyzer (SEPICA/ACE) is designed to measure the ionic charge state, the kinetic energy, and the nuclear charge of energetic ions from ~ 0.4 to ~ 4 MeV/amu (for He). It is a dE/dx - E telescope with a proportional counter - solid state detector combined with a collimator - electrostatic analyzer assembly. The combined geometry factor of the entrance aperture of the three fans of the instrument is 0.23 $cm^2 sr$ - Möbius et al. (1998).

The Solar Isotope Spectrometer (SIS/ACE), Stone et al. (1998), provides high resolution measurements of the isotopic composition of energetic nuclei from He to Ni (Z=2 to 28). For He its energy range is ~ 3.5 to ~ 45 MeV/amu. SIS has a geometry factor of $\sim 40 cm^2 sr$, which is significantly larger than previous satellite solar particle isotope spectrometers.

The Suprathermal TOF sensor HSTOF is an ion telescope with a geometry factor of $0.22 cm^2 sr$ and an energy range from 0.1 to 1.0 MeV/amu achieved by employing an electrostatic deflection system with flat deflection plates, time-of-flight section and SSD detector for the residual energy of the incident particles - Hovestadt et al. (1995).

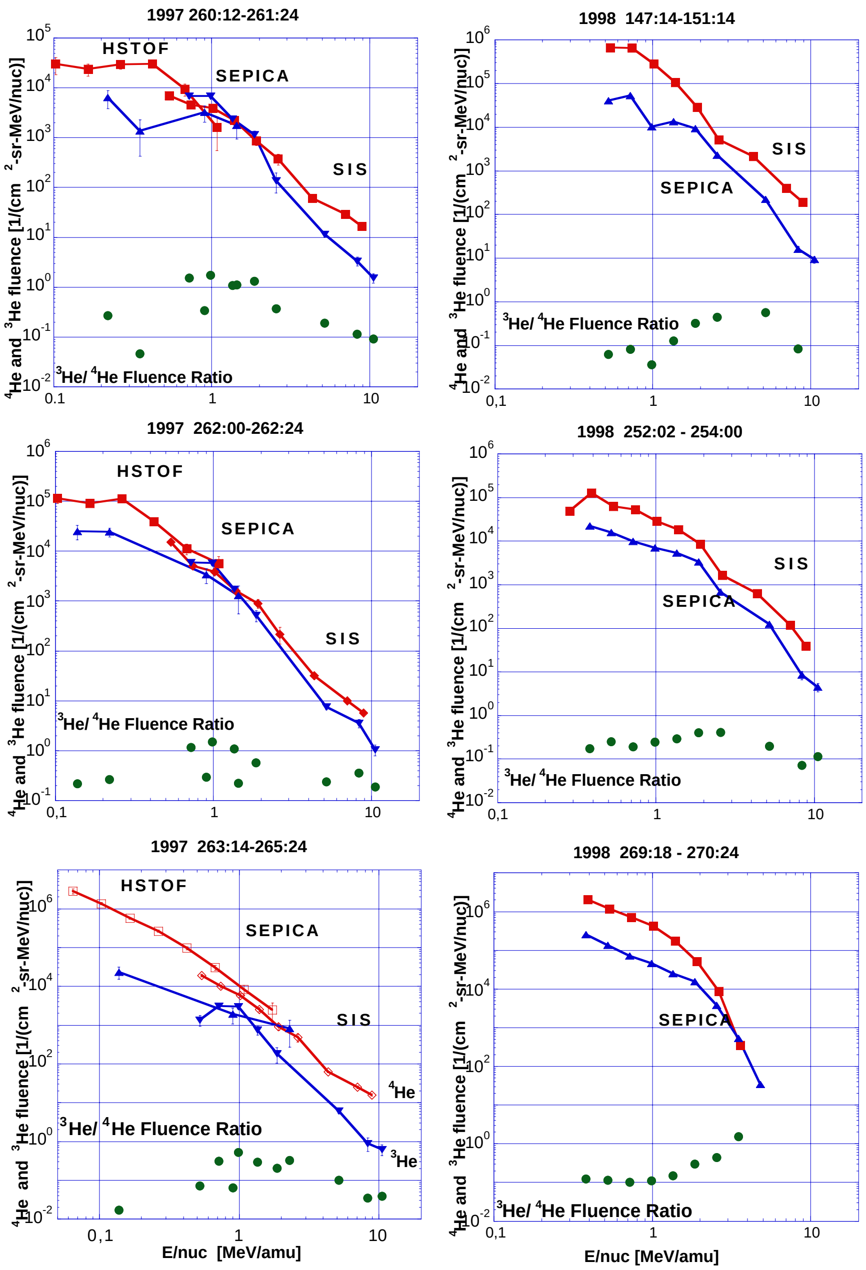

Figure 1: Fluence vs. Energy spectra for ^4He and ^3He. The ratio of both isotopes is given by circles

Four periods in 1997 and 1998 have been chosen for the analysis. The observed events have been identified as belonging to the impulsive class by various characteristics such as the peaks of non-relativistic electron beam injections seen in the ACE/EPAM electron data and by the specific heavy ion enrichments and charge state signatures. Covering about two orders of magnitude in energy makes velocity dispersion an important factor which renders the direct comparison of flux spectra impossible. For this reason we use instead the fluences over the full periods of the respective events. Below is a table of the time intervals used for integrating the fluxes:

97:260	260.5 - 262.0	98:147	147.6 - 151.6
97:262	262.0 - 263.0	98:252	252.1 - 254.0
97:263	263.6 - 266.0	98:270	270.0 - 271.0

The first three periods belong to the same active period in September 1997. For them we use the full set of three instruments and for the three events in 1998 only the ACE instruments contribute to the data. Because of the overlap of the energy intervals covered by SEPICA and HSTOF the fluences for these two sensors have been presented separately, while SIS and SEPICA data are represented by a single curve.

3 Discussion

Let us now see how our results compare to those obtained in earlier experiments on ^{3}He and ^{4}He spectra in impulsive ^{3}He-rich events - Möbius (1982), Reames et al. (1997). Dealing here primarily with the data on He isotopes we are going to concentrate our attention on the energy dependence of the spectra. In particular the existence of a local maximum in the $^3He/^4He$ ratio is of interest because it is one of the primary indicators for the possible energization and enrichment mechanisms of ^3He in impulsive solar flares. The position of this peak in energy, which is more or less pronounced and varies within the range of $\approx 1.$ to $\approx 6.$ MeV/amu, could be a decisive clue for understanding the levels of wave turbulence and other parameters of the flare and near flare regions in view of existing theoretical work on the influence of Coulomb losses as a limiting agent on the acceleration mechanisms, Litvinenko (1996).

The spectral form is compatible obviously with neither a power law, nor an exponential in energy; furthermore a substantial flattening of the spectra of both isotopes toward low energies in the range of $E < 0.35$ MeV/amu can be seen, most pronounced in the first two events of 1997, while the spectra of both isotopes are generally steepening with increasing energy.

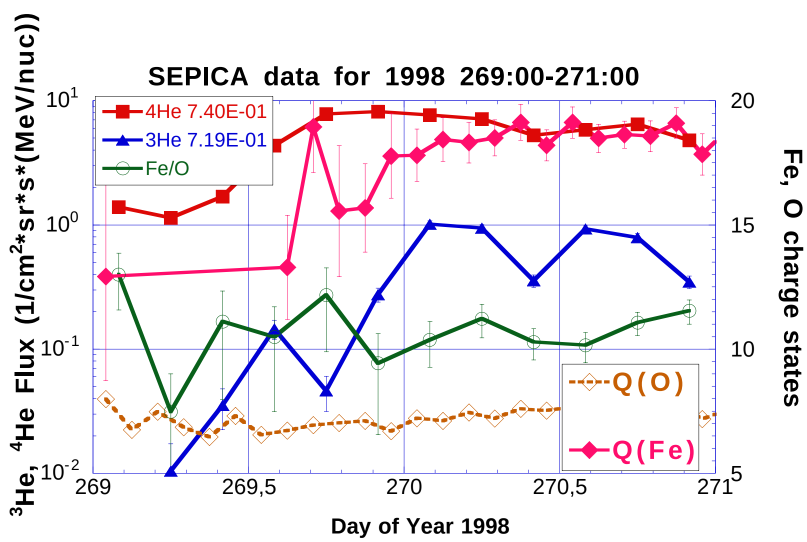

Figure 2: ^4He and ^3He fluxes, the Fe/O ratio and the Fe and O charge states vs time for the last of the events whose spectra are on Fig. 1

The divergence of the spectra of the two isotopes for energies above $\approx$ 5 - 6 MeV/amu in the events of 97:260, 97:263 and 98:147 is the result of the acceleration processes and is not due to contamination by ^{4}He coming from the anomalous cosmic ray component. With a background level of ACR ^{4}He flux of $\sim 0.2/(m^2 - sr - (MeV/nuc))$ (Reames, 1999) the ^{4}He fluences observed here in the upper energy range (the SIS points) are by order of magnitude too high to be affected.

An interesting topic is the correlation between the ^{3}He enrichment and the heavy ion charge states. Figure 2 shows that the mean ionic charge of Fe in the energy range 0.2 to 0.5 MeV/amu increases significantly with the onset of the ^{3}He-rich event, as typically observed for impulsive SEPs (see also Möbius et al., 1999).

The correlation of the properties of the He isotope spectra with the specific features of the charge state variations from event to event will be a topic for future studies.

4 Conclusions

No simple approximation for the spectra of ^{3}He and ^{4}He can be given. Both spectra steepen at higher energies and the ^{3}He spectrum tends to flatten below few hundred keV/amu; The average slope of the spectra varies substantially from event to event, indicating various acceleration conditions;

The time evolution of the ^{3}He abundance can be traced, indicating that within the series of impulsive events studied here the first and second one have the highest degree of ^{3}He enrichment;

Earlier observations on the existence of a maximum of the ^{3}He/^{4}He ratio at an energy E_0 of a few MeV/amu are substantiated by this study;

The observations reported here, along with earlier results by Reames et al. (1997) extend ^{3}He and ^{4}He spectra from impulsive events to energies as low as 0.1 MeV/amu and thus provide additional constraints for existing models.

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