THE COMPOSITION OF HEAVY IONS

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SOLAR ENERGETIC PARTICLE EVENTS

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ABSTRACT

We review recent advances in determining the elemental, charge-state, and isotopic composition of $\lesssim 1$ to $\gtrsim 20$ MeV per nucleon ions in solar energetic particle (SEP) events and outline our current understanding of the nature of solar and interplanetary processes which may explain the observations.

The composition within individual SEP events may vary both with time and energy, and will in general be different from that in other SEP events. Average values of relative abundances measured in a large number of SEP events, however, are found to be roughly energy independent in the ~ 1 to ~ 20 MeV per nucleon range, and show a systematic deviation from photospheric abundances which seems to be organized in terms of the first ionization potential of the ion.

Direct measurements of the charge states of SEPs have revealed the surprisingly common presence of energetic He^{+} along with heavy ions with typically coronal ionization states. High-resolution measurements of isotopic abundance ratios in a small number of SEP events show these to be consistent with the universal composition except for the puzzling overabundance of the SEP $^{22}Ne/^{20}Ne$ relative to this isotopes ratio in the solar wind. The broad spectrum of observed elemental abundance variations, which in their extreme result in composition anomalies characteristic of ^{3}He-rich, heavy-ion rich and carbon-poor SEP events, along with direct measurements of the ionization states of SEPs provide essential information on the physical characteristics of, and conditions in the source regions, as well as important constraints to possible models for SEP production.

It is concluded that SEP acceleration is a two-step process, beginning with plasma-wave heating of the ambient plasma in the lower corona, which may include pockets of cold material, and followed by acceleration to the observed

energies by either flare-generated coronal shocks or Fermi-type processes in the corona. Interplanetary propagation as well as acceleration by interplanetary propagating shocks will often further modify the composition of SEP events, especially at lower energies.

I. Introduction

Solar energetic particles (SEP), broadly defined as particles of energies greater than $\sim$1 MeV, are commonly accelerated in association with solar flare eruptions. The study of these particles has important bearing on a number of problems in solar physics, heliospheric physics, and astrophysics. Knowledge of the elemental and isotopic abundances of the solar atmosphere, which can be inferred from composition measurements of SEP, is essential for constructing models of interiors and atmospheres of the sun and other stars as well as for a better understanding of nucleosynthesis and of the evolution and formation of the solar system. Solar particles observed in interplanetary space are a direct sample of the solar material, which in principal can be measured in arbitrary detail. Before relating the SEP composition measurements to solar abundances one must, however, understand and correct biases which alter the composition of these particles as they undergo heating, acceleration and propagation.

Comprehensive measurements of the elemental, charge state and isotopic composition of SEP over a wide energy range, in a large number of solar flare events, at various phases during such events, and at different locations in the heliosphere give us the means of understanding these compositional biases. Equally important, such detailed observations should also lead to refinements of models of particle acceleration and propagation in astrophysical plasmas, and would allow us to determine what fraction of the energy released in flares goes into acceleration of particles, and how this fraction depends on the physical conditions at the flare site.

In this paper we review recent progress in the study of the composition of heavy ions in SEP events. Results prior to 1974 were discussed in an earlier review on this subject (Fan et al. 1975). Various aspects of SEP composition have also been addressed in a number of review papers (e.g., Gloeckler 1975, 1979; Mewaldt, 1980; Klecker, 1981; McGuire, 1983). The material is divided into three major sections: (1) Average elemental, charge state and isotopic compositions of heavy ions in SEP events, (2) Variabilities in the composition of SEPs, and (3) ^{3}He-rich, heavy-ion-rich and carbon-poor SEP events.

II. Average Elemental, Charge State and Isotopic Compositions of Heavy Ions in SEP Events

Since the discovery of nuclei heavier than He in SEP by Fichtel and Guss (1961) numerous measurements of their composition have been made; the most recent ones with high-resolution instruments flown on satellites and space probes. The introduction of thin-window proportional counters (Hovestadt and Vollmer, 1971) and $\sim$2 and 5μ thin solid state detectors (Krimigis et al., 1977) as ΔE elements in dE/dx vs E instruments reduced the low energy limit of the measurements by an order of magnitude to several hundred keV/nucleon. This and the use of large-geometry solid-state telescopes (e.g. Cook et al., 1979) led to a large increase in the number of SEP events whose heavy ion compositions could be determined, permitted studies of the time dependence of elemental abundances during SEP events, and resulted in measurements of rare elements such as Na and Al. At the same time, development of high-voltage electrostatic-deflection techniques (Tums et al., 1974; Hovestadt et al., 1978) provided the first direct measurements of the ionization or charge states of $\lesssim$1 MeV/nucleon ions in SEP events. Use of position-sensitive solid-state detectors to determine individual particle trajectories in dE/dx vs range telescopes (Althouse et al., 1978) allowed for the first time high-resolution measurements of the isotopic composition of SEPs.

Relative abundances are generally measured at equal energy per nucleon and extend in energy from $\lesssim$0.5 MeV/nucleon (Mason et al. 1980, 1983; Hamilton and Gloeckler, 1981) to $\gtrsim$100 MeV/nucleon (Dietrich and Simpson, 1978), although the majority of the recent observations are below $\sim$10 MeV/nucleon (e.g., Hovestadt et al., 1973; Cook et al., 1979, 1980; McGuire et al., 1979, 1981b). Because the injection, acceleration and propagation of SEPs very likely depend on the charge-to-mass ratio of ions which, as we shall see, are generally not fully ionized, the shapes of the differential energy spectra of individual ions may be different, resulting in changes of the abundance ratios with energy. Such variations have indeed been observed. Early measurements using Lexan track detectors flown on sounding rockets (Price et al., 1973; Crawford et al., 1975) indicated that the relative abundance of heavier to lighter ions (i.e., Fe/O or O/He) increased with decreasing energy below ∿15 MeV/nucleon. Gloeckler (1979), however, first pointed out that such variations would generally disappear if abundance ratios were computed at equal magnetic rigidity instead of energy per nucleon. More recently, McGuire et al. (1981b) using model calculations showed that energy dependent variations in abundances may be a natural consequence of the spectral shapes and charge states of SEPs.

As more composition measurements became available, especially from spacecraft experiments which could provide event-averaged abundance ratios, it was found that the average of abundance ratios measured in a number of large SEP events showed no significant variations with energy (Mason et al., 1980). Mewaldt (1980) compared results reported by a number of investigator groups on the O/He, Fe/O, Fe/He and other ratios in ten large SEP events and also concluded that the average of these ratios remains approximately energy independent between ∿1 and $\gtrsim$10 MeV/nucleon, even though in individual SEP events the abundance ratios at equal energy per nucleon may either increase with decreasing energy, decrease with decreasing energy or remain unchanged (e.g. see discussion in Gloeckler, 1979).

1. Average Elemental Abundances of SEPs

It is now well established that the relative elemental abundances vary considerably from one event to the next as well as during a given event as will be discussed in Section III. In its extreme this variability leads to compositions characteristic of so called ^{3}He-rich and heavy-ion-rich events (see Section IV). Nevertheless, it is instructive to compile average SEP abundances and compare these with compositions found in other source materials in our solar system.

In Table 1 we list the average abundances relative to oxygen for 14 elements. Abundance ratios listed in column 2 are averages derived by Meyer (1981a) from 39 observations which represent nearly all available SEP composition data through 1980. They are in agreement with other compilations (e.g., Gloeckler, 1979) and with averages of ratios at 8.7-15 MeV per nucleon in 7 SEP events as reported by Cook et al., (1979, 1980). For comparison, ratios at low energies (∿1 MeV/nucleon) reported by Mason et al. (1980) and at high energies (>10 MeV/nucleon) as given in Webber (1975) are listed in columns 3 and 4 respectively. The last column shows local galactic abundances compiled by Meyer (1979a,b) which are taken to represent the composition of the photosphere. We note in passing that the local galactic ratios of Meyer (1979a, b) for the 14 elements listed in Table 1 generally agree within the quoted uncertainties with other recent compilations of universal abundances (e.g. Withbroe, 1971; Cameron, 1973; Malinovsky and Heroux, 1973; and Ross and Aller, 1976).

In examining the data in Table 1 we note first that, the SEP abundances at low and high energies are in reasonable agreement, indicating, as we stated earlier, the absence of significant energy dependence in the averaged ratios (Mason et al. 1980). The low Fe/O ratio at >10 MeV/nucleon may be attributed to the relatively small number of SEP events in the compilation of Webber (1975) and the fact that the Fe/O ratio shows large event-to-event variability. In fact, had more recent observations at >10 MeV/nucleon (von Rosenvinge et al. 1975; Dietrich and Simpson, 1978) been included the average high-energy Fe/O ratio would increase to a value consistent with those in columns 2 and 3.

Second, while the SEP composition for C, N, O, Ne, S and Ar are in good agreement (within ~50%) with the local galactic (LG) abundances, the SEP He is underabundant by a factor of about two, and SEP Na, Mg, Al, Si, Ca, Cr, Fe and Ni are overabundant by factors of 3 to 5. This systematic deviation of SEP from photospheric (or LG) abundances is best organized in terms of the first ionization potential, I, of the chemical element as first discussed by Crawford et al. (1972) and Hovestadt (1974). Their work was motivated by a similar correlation of the overabundance factor, F, with the first ionization potential first discovered by Havnes (1971)(see also Casse and Goret, 1978, and references therein) for the elemental abundances of galactic cosmic rays. The correlation of F with I for SEPs has been examined in more detail by Webber (1975), McGuire et al. (1979), Cook et al. (1979) and most recently by Meyer (1981a, b). In Fig. 1 (from Meyer, 1981a) the overabundance factor F of a given element in the SEP composition (normalized to oxygen) with respect to the LG composition (also normalized to oxygen) is plotted as a function of the first ionization potential, I, of that element. It is evident from this figure that F decreases monotonically (within the uncertainties inherent in the values of F) with increasing first ionization potential. While elements with I $\lesssim$ 8 eV are overabundant by factors of 3 to 5, elements (except He) with I $\gtrsim$ 10 eV have about the same relative abundance in the SEPs as they do in the photosphere (LG).

The enrichment of elements with low ($\lesssim$8 eV) first ionization potential in SEPs would seem to indicate that the source of SEPs lies in the inner transition region between the photosphere and chromosphere where the temperature is appropriately low to preferentially ionize elements with lower I, and thus make these ions accessable to electromagnetic interactions. It is, however, unlikely for several reasons that the acceleration process, which takes ions heated above some energy threshold to the observed high energies, occurs at such low altitudes. First, the high densities in the lower transition region would require that SEPs pass through considerable amount of material resulting in severe energy losses and significant nuclear spallation. In fact, most studies show that both energy loss (Mason et al. 1983) and spallation (McGuire et al. 1979, Cook et al. 1980) are small, leading to upper limits for pathlength of $\lesssim 3$ mg/cm^2 and 50 mg/cm^2, respectively. Second, the observed charge states (see below) of heavy ions in SEP are high and typically coronal (~ 1 to $2 \cdot 10^6$K). Based on this evidence one may conclude, and it is so generally accepted, that acceleration of SEPs takes place in the corona.

Meyer (1981b) has investigated where acceleration takes place and what source material is accelerated by comparing SEP compositions with coronal and solar wind abundances as shown in Fig. 2 (from Meyer 1981b). The upper panel of Fig. 2 reproduces data of Fig. 1 except that both the SEP and LG abundances are now normalized to Mg. The middle (lower) panel shows the abundance of elements in SEPs compared to coronal (solar wind) compositions, all normalized to Mg. Except for He, the results are consistent with identical SEP, coronal and solar wind compositions, a conclusion also arrived at by Cook et al. (1980). More definitive comparison between SEP and solar wind abundances should be possible in the near future with the launch of the solar wind ion composition instrument on the International Solar Polar Mission.

2. Charge States of SEPs

Because various electromagnetic processes (plasma heating, acceleration, propagation) which produce SEPs depend on the mass-to-charge ratio of the ions, knowledge of the ionization or charge states of SEPs is essential for understanding and modelling these processes. Furthermore, detailed measurements of the charge states of SEPs can be related to tne ionization state of the source material thus providing essential information on the temperature characteristics of the plasma in the source regions.

(a) Average Charge States of Heavy Ions

Significant advances have been made recently in measuring directly the charge states of SEPs below ~3 MeV/nucleon. The first direct evidence that SEPs below ~1 MeV/charge are not fully stripped was obtained by Gloeckler et al. (1973, 1975a, 1976), and Sciambi et al. (1977). They found that the mean charge states of C, O and Fe in equal energy per charge intervals (a) are consistent with charge states of these elements in a ~$1\text{-}2 \cdot 10^6$K corona and in the solar wind (i.e. C^{+6}, $O^{+6,7}$, Fe^{+10-13}); (b) do not vary substantially from one SEP event to the next, and (c) are energy independent in the range 50 to 1000 keV/charge.

These first direct determinations of the mean charge states of SEPs have been obtained using data from both the EECA (Electrostatic-Energy vs Charge-Analyzer) described by Tums et al. (1974), and the ULET (Ultra Low Energy Telescope) sensor (Hovestadt and Vollmer, 1971) of the University of Maryland/Max-Planck-Institut experiments on the IMP 7 and 8 satellites. EECA, a high-voltage electrostatic deflection system placed in front of five solid state detectors at different fixed deflection angles, is used to measure the charge spectrum of the incoming ions below 1.2 MeV/charge. ULET, a dE/dx vs E telescope utilizing a thin-window proportional counter as the ΔE element is used to determine the elemental composition from ~0.5 to ~10 MeV/nucleon. A typical energy histogram derived from the EECA pulse-height data summed over 15 SEP events is shown in Fig. 3a (from Ma Sung et al. 1981b) along with a background distribution obtained during inactive periods. In a given energy per charge range, fixed by the width and position of one of the rectangular solid-state detectors and the deflection system analyzer constant, the energy histogram corresponds to the composite charge state distributions of incoming ions in that energy per charge interval. The three peaks seen in the figure correspond to charge Q = 1 (protons), Q = 2 (He^{+2}) and $4 \lesssim Q \lesssim 20$ ($Z \geq 6$) ions respectively. Because of the large energy/charge windows of the EECA instrument neither individual heavy ions ($Z \geq 4$) nor their charge states can be resolved in the broad, $Q \gtrsim 4$ peak. Thus the following procedure was adopted to make charge state determinations: (a) Determine the relative elemental abundances and energy spectra of the elements in a SEP event using data from the ULET sensor. (b) Assuming a reasonable coronal temperature determine the charge states of the elements using tables published in Jordon (1969). (c) Construct a predicted pulse-height profile of the EECA sensor using the instrument response, the measured elemental composition and energy spectra, and the assumed charge state distribution for each element. (d) Compare the predicted pulse-height profile with the observed histogram. (e) Vary the coronal temperature until the predicted pulse-height profile best fits the observed distribution.

Applying this fitting technique to the EECA data along with abundance measurements from the ULET sensor, Ma Sung et al. (1981b) examined the charge states of heavy ions between 0.16-0.24 MeV/Q in the decay phase of 15 flare-associated events from November 1973 to April 1980. Using a background corrected distribution for heavy ions ($Q \gtrsim 4$ peak) summed over all events in their survey to improve statistics as shown in Fig. 3b (from Ma Sung et al., 1981b), they found that no single source temperature was consistent with their 15-flare averaged data. To explain the excess of both low charge states (e.g., C^{+4}, C^{+5}, or O^{+5}) as well as high charge states (e.g., Fe^{+16-18}) they proposed a wide range in the equilibrium temperature of the source material, from $\sim 5\cdot 10^5$K to $\sim 5\cdot 10^6$K.

Improved measurements of the charge states have been made more recently by Hovestadt et al. (1981b) and Gloeckler et al. (1981) using the Max-Planck-Institut/University of Maryland ULEZEQ sensor on the ISEE-3 spacecraft. In ULEZEQ, techniques used separately in ULET and EECA are combined in one sensor which consists of a high-voltage, small-angle deflection analyzer, a position-sensitive solid-state detector and a thin-window proportional counter between the deflection system and solid state detector. The mass (or atomic number) of a particle is first determined using the energy loss and residual energy signals from the proportional counter and solid-state detector, respectively. The charge is then obtained from the amount of deflection in the analyzer (indicated by the position signal) and the energy signal of the solid-state detector (Hovestadt et al. 1978).

The charge histograms using the ULEZEQ data for the June 6-9, 1979 event are shown in Fig. 4 (from Gloeckler et al., 1981) for He, C, O, and Fe in the indicated energy per nucleon intervals, and are typical of all SEP events surveyed. The charge resolution is sufficient to separate the two charge states of He (left-most panel) although not the individual ionization states of heavier ions. The surprisingly large abundance of SEP He^+ ($He^+/He^{++} \sim 0.1$) is a common feature of all events surveyed as will be discussed below. From the charge distributions of the heavy ions, it is evident that (a) the mean charge states for C, O and Fe are about 5.7, 7 and 12.5 respectively, (b) several ionization states are present, especially for Fe (e.g. Q $\sim$ 10 to 15 for Fe), and (c) no measurable abundances of low charge-state heavy ions (i.e., $C^{+1\text{ to }+3}$, $O^{+1\text{ to }+4}$, $Fe^{+1\text{ to }+5}$) are observed (Gloeckler et al., 1981).

The mean ionization states of C, O and Fe, based on event-averaged ULEZEQ data have been measured by Gloeckler et al. (1981) for each of ten SEP events observed between Sept. 1978 and Sept. 1979, and are listed in the last three columns of Table 2 (adopted from Gloeckler et al. 1981). In four cases (March 28-29, April 23-25, May 28-30, and September 15-26) the fluence of Fe was below the level required to yield measurements of the iron charge states in their preliminary analysis. The variations in the mean charge states of the three heavy elements are seen to be reasonably small. The 10-flare averages (6 flares for Fe) of the mean values for C, O and Fe are 5.8, 7.1 and 13.5 respectively (see also Hovestadt et al., 1981a), being roughly consistent with, although somewhat higher than, values reported earlier using the EECA data. There may be several reasons for this discrepancy. First, mean charge states, which are measured by ULEZEQ at equal energy per nucleon may be energy dependent. Second, the mean charge states may change during the SEP event due to rigidity-dependent propagation effects as discussed recently by Mason et al. (1983). The EECA measurements being confined to the decay phase of events because of instrumental background problems at other times, could thus be seeing slightly higher mean charge states. Finally, in ULEZEQ the detection of high-rigidity (or low charge states) ions is likely to be suppressed, as was pointed out by Gloeckler et al. (1981) and will be discussed further below.

Direct observations of charge states of heavy ions in SEP events show them to be consistent with values for corresponding ions in the solar wind (e.g., Bame et al., 1975,1979) and in the $\sim$1 to $2 \cdot 10^6$K corona (Jordan, 1969). This provides further evidence that the acceleration takes place in the corona and that the bulk of the accelerated ions come from coronal material.

(b) Singly Ionized Helium

High charge states observed for heavy ions in SEPs as discussed in the previous section are all consistent with a source material at an equilibrium temperature above about $5 \cdot 10^5$K. At such high temperatures helium would be nearly fully stripped. The discovery of substantial amounts of He^+ (~10% of He^{++}) in several large flares by Hovestadt et al. (1981a, 1981b) came therefore as a surprise since it would indicate that at least some of the source material came from substantially colder ($T \lesssim 10^5$K) temperature regions.

Gloeckler et al. (1981) studied the abundance of He^+ in SEP events in more detail using ULEZEQ measurements in ten solar flare associated particle events listed in Table 2 (1st column). They found that He^+ was present in all ten events and that the average (for all 10 events) He^+/He^{++} ratio was 0.09 at equal energy per nucleon, with a range of values between 0.06 and 0.13 (see column 6).

Fitting the differential energy spectra, j, for He^+, He^{++} (and in the larger events also for C, O and Fe) in the energy range of ~0.3-2.4 MeV/nucleon to power laws ($j \propto E^{-\gamma}$) in kinetic energy per nucleon, E, they found that in all of the 10 SEP events surveyed, the spectra of higher rigidity (higher mass-to-charge ratio) ions were steeper (larger γ) than those of lower rigidity (lower mass-to-charge ratio) ions as illustrated in Fig. 5a (from Gloeckler et al., 1981) for the June 6-9, 1979 event. This is also evident by examining the ratios of spectral indices of He^+ to He^{++}, $\gamma_{He^+}/\gamma_{He^{++}}$, as listed in column 3 of Table 2, where the average $\gamma_{He^+}/\gamma_{He^{++}}$ ratio is about 1.2 The He^+/He^{++} ratio in the energy range 0.3 to 2.4 MeV per nucleon is thus energy dependent if computed at equal energy per nucleon. In order to find a spectral representation in which the energy dependence of He^+/He^{++} (and also C/He^{++}, O/He^{++}, Fe/He^{++}) is eliminated, Gloeckler et al. (1981) suggested a dependence of the distribution function f on the velocity, v, and rigidity R of the particles of the form

$$f \equiv j/v^2 = f_0 \exp(-vR^n/\eta_0)$$

where n and η_0 are two parameters which are adjusted to minimize the energy dependence of the ion abundance ratios. As an example, we show in Fig. 5b (from Gloeckler et al., 1981) a plot of the distribution functions of He^+, He^{++}, $C^{+5.7}$, O^{+7} and $Fe^{+12.5}$ vs $\eta \equiv vR^n$ for the June 6-9, 1979 event with n = 0.35 and η_0 = 0.42 for all five species. The values of n and η_0 used in this SEP event are seen to be roughly representative of all flares in the survey (see columns 4 and 5 of Table 2).

We note that in the limited energy range of the measurements the distribution functions of all 5 species shown have, within the uncertainties of the data points, identical exponential shapes in the $\eta \equiv vR^n$ representation, making the ratio of He^+/He^{++} of 0.25 (as well as the ratios of He/O, C/O, and Fe/O) independent of energy, or more accurately η. Assuming that the $\eta \equiv vR^n$ dependence of the distribution function is also valid over a broader energy range (say 0.1 to 10 MeV/nucleon), Gloeckler et al. (1981) derived density ratios for the 5 species by integrating f over velocity space. For the June 1979 event they obtained density ratios for He^+/He^{++} of 0.14 and for He^{++}/O, C/O and Fe/O of 55, 0.6, and 0.16 respectively which are consistent with the average SEP composition listed in Table 1. The He^+/He^{++} density ratios for the 10 SEP events, listed in column 8 of Table 2, range from 0.08 to 0.29 with an overall average of 0.15.

The fact that energetic He^+ is seen consistently and at surprisingly large relative abundances in every SEP event studied to date argues for the presence of cold ($T < 10^5$K) regions in the source material at the time of acceleration as suggested by Hovestadt et al. (1981a, b) and Gloeckler et al. (1981). This being the case, why then are low-ionization states of heavy ions not observed? The reason suggested by Gloeckler et al. (1981) is that in the limited energy per nucleon range of the ULEZEQ instrument, and with the observed dependence of the distribution function on vR^n, the abundance of low charge state (high rigidity) heavy ions would be significantly reduced compared to that of the high charge state (lower rigidity) ions, and would thus be beyond the detection limit of the instrument. This same effect would also tend to raise somewhat the mean charge state values of heavy ions above their actual values, accounting in part for the discrepancy between the ULEZEQ and EECA mean charge state measurements mentioned earlier.

The effect of suppressing abundances of low charge states compared to high charge state ions of the same element has also been examined by Hovestadt et al. (1983). In Fig. 6 (from Hovestadt et al., 1983) is shown the dependence of the measured distribution functions for O^{+7} and Fe^{+14} on the rigidity of these ions for a He^{+}-rich period (He^{+}/He^{++} = 0.3) in March of 1979. In this representation (which is similar to that of Gloeckler et al. (1981) with n = 1) the distribution functions fall off rapidly with increasing rigidity, and the Fe/O ratio appears independent of rigidity. If we now assume that at equal rigidities the abundance of a low charge-state ion (e.g. O^{+1}) is equal to that of a high charge-state ion of the same element (e.g., O^{+7}), and that this ratio (i.e. O^{+1}/O^{+7}) is independent of rigidity, then at equal energy per nucleon the abundance of O^{+1}, whose rigidity is seven times larger than that of O^{+7}, as indicated in the upper portion of the figure, would be many orders of magnitude lower than the abundance of O^{+7}. Given the measured energy spectra it is clear that low charge state ions are essentially excluded from charge state distributions at equal energy per nucleon, as measured by ULEZEQ.

We may therefore conclude that the absence of low ionization states in charge state distributions of heavy ions measured at equal energy per nucleon is not inconsistent with the presence of pockets of cold material, and low charge state heavy ions, in the acceleration region as indicated by the large He^{+}/He^{++} ratios, provided that the distribution functions of SEPs depend on the ion charge-to-mass ratio (e.g., vR^{n}), or rigidity as first suggested by Freier and Webber (1963). It should be emphasized, however, that the acceleration process is unlikely to take place in the transition region, where the temperature is sufficiently low for He^{+} to be present, because the high densities in this region would lead to charge exchange processes which would alter the He^{+}/He^{++} ratio. Far more plausible is the rapid transport of confined regions of cold material (e.g., as coronal mass ejections) to beyond $\sim 1.5\ R_{\odot}$ where acceleration is most likely to occur.

(c) Isotopic Abundances of Heavy Elements

Knowledge of the isotopic composition of the sun is important for studies of the origin of the elements and of the formation of the solar system. Solar energetic particles and the solar wind provide direct samples of the solar atmosphere. Although isotopic ratios of helium in SEPs have been measured as early as 1960 (Schaeffer and Zahringer, 1962), isotopic abundances of elements heavier than He, all determined from data obtained with spacecraft instrumentation, have only recently been reported (Dietrich and Simpson, 1979a, b, 1981; Mewaldt et al., 1979, 1981a, b). The excellent mass resolution of the Caltech experiment on ISEE-3 (Althouse et al., 1978), by far the most impressive to date, is achieved using position-sensitive elements in an all solid-state detector multiple dE/dx vs range telescope to determine the trajectory of individual particles. Fig. 7 (from Mewaldt et al., 1979, 1981a, b) shows mass histograms of C, N, O, Ne and Mg in the indicated energy per nucleon intervals measured with the Caltech instrument during the September 23, 1978 SEP event. For the first time individual isotopes such as ^{13}C and ^{12}C are clearly resolved.

In Table 3 we list isotope ratios reported by Mewaldt et al. (1981b) and compare these with respective ratios in the solar system (Cameron, 1980). Note the excellent agreement of the SEP isotope ratios with the Cameron solar system abundances as is also evident in Fig. 8 (from Mewaldt et al., 1981b). The earlier results at higher energies (35-55 MeV/nucleon) of Dietrich and Simpson (1979a, b, 1981) for the SEP $^{22}Ne/^{20}Ne$ and $^{26}Mg/^{24}Mg$ ratios, also listed in Table 3 and plotted in Fig. 8, are in good agreement with the Caltech results. The Dietrich and Simpson measurements are based on data obtained with the University of Chicago solid-state, multi-element particle telescope on the IMP-8 satellite (Garcia-Munoz et al., 1977) and are averaged over seven SEP events for Ne and ten events for Mg.

Measurements of the isotopic abundances in the solar wind are restricted at this time to noble gases (e.g., Ne, Ar). The solar wind $^{21}Ne/^{20}Ne$ and $^{22}Ne/^{20}Ne$ ratios reported by Geiss et al. (1970), and also plotted in Fig. 8, are seen to be below SEP values. In particular, the $^{22}Ne/^{20}Ne$ ratio of 0.13 in the SEP appears to be about a factor of 2 higher than the $^{22}Ne/^{20}Ne$ ratio of 0.076 in the solar wind. Other than the direct determination of the $^{22}Ne/^{20}Ne$ ratio in the SEP and the solar wind, there are also measurements of the Ne isotopes trapped in meteorites and the lunar soil. In meteorites, the abundances occur in two characteristic patterns which were designated by Signer and Suess (1963) as the solar component, neon B, with a value $^{22}Ne/^{20}Ne = 0.08$, and the planetary component, neon A, with $^{22}Ne/^{20}Ne = 0.12$. Since the solar wind ratio is 0.076 ± 0.003, neon B is generally regarded as the result of direct implantation of solar wind neon into meteoritic material. A similar component is found in lunar samples. The SEP abundance ratio appears to be consistent with neon A. The basic question is how can the sun emit two different components of neon?

No satisfactory resolution of this puzzle has as yet been proposed. If the ^{22}Ne abundance in the SEP is enhanced by similar processes as ^{3}He and heavy ions in ^{3}He-rich and heavy ion-rich SEP events (see Section IV) then one would expect some correlation between the $^{22}Ne/^{20}Ne$ ratio and e.g., Fe/O. Dietrich and Simpson (1979b) separated their seven-flare data set into two groups on the basis of the value of the Fe/O ratio ("normal" and iron-rich) and computed the neon isotope ratio for each group. Within their 30% overall statistical uncertainty they found no significant difference in the two $^{22}Ne/^{20}Ne$ ratios. Mewaldt et al. (1981b) investigated a simple mass dependent selection effect in SEP by plotting normalized (with respect to solar system abundances) isotope abundance ratios as a function of the isotope mass ratio. Their results are consistent with an absence of any significant mass fractionation in the SEP from origin to observation, and they suggested that solar neon may be neon A, with the fractionation occuring in the solar wind acceleration process. The problem with this suggestion is that it would imply that all of the SEP Ne is accelerated deep in the corona, which, as we discussed previously, is contrary to most observations.

There is finally the remote possibility that the recent satellite observations (1974-1978) of the SEP neon isotope ratio may be short-term departures from a ratio which is consistent with the solar wind value or may be biased since they include only a relatively small sample of flares. (It should be recalled that early observations of the high-energy Fe/O ratio in flares, e.g. Webber (1975), indicated a Fe/O ratio lower than that indicated by recent observations.) Rao et al. (1981) analyzed the Ne content in lunar soil after removing the solar wind contamination at the surface by selective chemical etching. The mineral residues, containing mostly the noble gases, were analyzed by step-wise gas release mass spectrometric methods. The SEP neon isotopes thus obtained indicate that the long-term average solar flare Ne is neon B, consistent with the measured solar wind value. It should be noted, however, that the integrated record measured in the lunar soil is dominated by occasional big SEP events, and that these results may thus be strongly biased (Rao et al., 1981).

III. Variabilities in the Composition of SEPs

Early composition measurements at energies above ∿10 MeV/nucleon in eight major SEP events, carried out by the Goddard Group (e.g., Bertsch et al., 1969; Biswas and Fichtel, 1963, 1965) with rocket-borne emulsion stacks, seemed to indicate that the relative elemental abundances remained fairly constant from flare to flare and reflected the photospheric composition. Satellite observations, generally sampling lower enrgies, showed, however, that the SEP composition was far more variable than the earlier results had indicated (Armstrong and Krimigis, 1971, 1973, 1975; Teegarden et al., 1973; Van Allen et al., 1974; Armstrong et al., 1976). There is now abundant evidence that the SEP composition at all energies measured varies not only from one event to the next but also during any given SEP event.

1. Overall Variability of Elemental Abundance Ratios

A comprehensive survey of ∿1 MeV per nucleon SEP abundances of the major elements from hydrogen to iron during the Nov. 1973-Dec. 1977 solar minimum period has been carried out by Mason et al. (1980). In order to study compositional variations, they constructed two-dimensional plots of daily fluxes for selected pairs of elements as shown in Fig. 9a-c (from Mason et al., 1980) for He vs Fe, C vs O, and O vs Fe, respectively. Each point in each of the plots represents a 24-hour average of the fluxes for each of the pair of elements measured between 0.6 and 1.6 MeV/nucleon with the University of Maryland/Max-Planck-Institut ULET sensor on the IMP-8 satellite. Only points above an intensity threshold 10-100 times higher than for moderately quiet time periods (Mason et al., 1979d) are plotted. Similar plots have been used earlier by Anglin et al. (1977) in their study of the variation of relative elemental abundances.

Several characteristic features are apparent from the scatter plots shown in Fig. 9: (1) The overall variation in the abundance ratio of any pair of elements is typically 10 to 100. (2) There is a systematic tendency for the ratio variation for all species to increase with decreasing intensity (Mason et al., 1980, 1981; also noted by Zwickl et al., 1978). These variations are far larger than would be expected based on counting statistics alone. The ratio variations in the large flares, which may be represented by several points in the plots, are typically 10 times less than variations in the smaller, lower intensity SEP increases, although part of this may be due to the smaller sample of large intensity increases. (3) In several instances, indicated by special symbols, the ratios of heavier-to-lighter elements are systematically large. These low-intensity SEP events strongly enriched in heavy elements (and often ^3He as well) will be discussed in Section IV.

2. Variability in the He^+/He^{++} Ratio

Hovestadt et al. (1983) have recently reported results of their systematic study of daily averages of the 0.5 to 0.67 MeV/nucleon He^+/He^{++} ratio over a 420 day period in 1978 and 1979. A plot of the He^+/He^{++} ratio for this period is shown in the bottom panel of Fig. 10 (from Hovestadt et al., 1983). The range of He^+/He^{++} values is typically from $\sim$0.03 to $\sim$0.3 with the highest values (above 1) associated with modest intensity increases in the 0.4-0.6 MeV/nucleon He flux (top panel of Fig. 10). As is evident from Fig. 10, and as we noted previously, the variation in the He^+/He^{++} ratio among the 10 larger SEP events (He rate $\gtrsim 2 \cdot 10^{-2}$ counts/sec) is not as pronounced as for the whole data set. Among these larger events the ratio ranges between $\sim$0.06 and $\sim$0.13. We may thus conclude that the variability in the He^+ flux is similar to the variabilities observed for other element species discussed above.

3. Systematic Deviations from the Average SEP Abundance

Mason et al. (1980) examined the variability in the daily-average fluxes in large SEP increases which they defined as 24-hour periods during which the average flux of 1.0-4.6 MeV/nucleon Oxygen exceeded 50 particles/(m^2 sr MeV/nuc). The average values of the relative elemental abundances of this more restricted data set of 37 days are listed in column 3 of Table 1.

The normalized width, S(Z), of the distribution of values of the relative abundance ratio of a given element of atomic number Z, (e.g., Fe/O or C/O) may be estimated by taking a pseudo 1-standard deviation limit (which excludes one-sixth of both the high and low side of the distribution), and dividing this by the average abundance ratio for that element. Following this procedure for their 37 daily average abundance ratios of H, He, C, Ne, Mg, Si, S-Ca, and Fe relative to oxygen in the 12 large SEP events of their survey, Mason et al. (1980) found a surprisingly smooth dependence of S(Z) on Z of the form $S(Z) = 1.3|Z^{1/3} - Z_0^{1/3}|$, where $Z_0 = 8$ (oxygen), as shown in Fig. 11 (from Mason et al., 1980). They also observed that there is a correlation between the abundance of an element relative to oxygen and the Fe/O ratio. This correlation is positive for Ne/O, Mg/O, Si/O and (S-Ca)/O and becomes progressively stronger as the atomic number of the element approaches that of iron. The C/O ratio, however, has a negative correlation with Fe/O, especially for Fe/O $\gtrsim$ 0.1, and no correlation is evident for H/He vs He/O or for He/O vs Fe/O.

Similar correlations have also been reported by others (Dietrich and Simpson, 1978; McGuire et al., 1979; Cook et al. 1979, 1980; Meyer, 1981a). Meyer (1981a), for example, compiled all then available observations of abundance ratios in the ~1 to ~20 MeV/nucleon range in non-^{3}He-rich SEP events during some 20 active periods, and sorted these data into five groups according to the values of the Fe/O ratios: 1.5-0.5 (Fe-richest), 0.5-0.15 (Fe-rich), 0.15-0.07 (Fe-medium), 0.07-0.05 (Fe-poor), and <0.05 (Fe-poorest). Fig. 12 (from Meyer, 1981a) shows the spread of abundances relative to the average SEP composition listed in column 2 of Table 1. For each element, the five vertical bars corresponds sequentially to the range of values in the Fe-richest class (left-most) to the Fe-poorest class (right-most). The trends in the variation in the ratios reported by Mason et al. (1980) are clearly evident here for the larger data set: (a) a smooth, mass (or Z) dependent spread which is greatest for the iron group (Cr-Ni) elements, (b) a systematically increasing enhancement (depletion) of $Z > 8$ elements compared to the average SEP values correlated with the over (under) abundance of Fe/O, (c) a modest anti-correlation of the C/O ratio with respect to the e.g. Fe/O ratio, and (d) no simple correlation in the He/O or N/O ratios with Fe/O.

4. Temporal Variations in the Abundance Ratios Within Individual SEP Events

Significant variations in the relative abundances are frequently observed during individual SEP events. Such compositional changes, which are generally most pronounced at low energies, have often been interpreted in terms of rigidity-dependent interplanetary propagation effects, where it was assumed that energetic heavy ions were not fully ionized (Van Allen et al., 1974; O'Gallagher et al., 1976; Scholer et al., 1978; von Rosenvinge and Reames, 1979). Some of the observed variations, such as abundance differences observed between closely spaced spacecraft (Armstrong et al., 1976), or extremely large and long-term systematic changes (Klecker et al., 1981a), cannot, however, be readily explained by interplanetary propagation effects alone.

As an example of temporal abundance variations observed within individual SEP events we show in Fig. 13 (from Hamilton and Gloeckler, 1981) plots of the 6-hour averaged flux ratios (0.6 - 0.95 MeV/nucleon) for He/H, O/He, O/C and Fe/He as a function of time for the November 22-28, 1977 SEP event observed with the LECP telescope (Krimigis et al., 1977) on Voyager 2 at ~1.55 AU. It is seen that all ratios show similar trends: maximum values of the abundance ratio of heavier-to-lighter species are observed near flare onset late on day 326 (except for He/H, which after a large decrease reaches its maximum value about one day later); the ratios then decline fairly rapidly until about the time of maximum intensity (middle of day 328), after which the decline is much slower with short-term variations during the decay phase. An interplanetary shock on day 330 produced in this particular case no noticeable changes in the ratios. The largest change occurs in the Fe/He ratio showing a decrease of ~factor of 4; next is the O/He with a decrease of ~factor of 3. The O/C ratio decreased the least, about 30%.

Mason et al. (1981, 1983) have recently examined in some detail temporal variations in the relative abundances of ~1 MeV/nucleon H, He, C, O and Fe in large SEP events observed in the four-year time period 1973-1977 using the ULET sensor on IMP-8. To simplify their analysis they selected events with a clear parent flare identification in the well-connected region of the solar disc (W20-W80 heliolongitude), single-injection profiles, and absence of interplanetary disturbance. This selection process eliminated all but two flares, the Nov. 22, 1977 (shown in Fig. 13 and discussed above) and the Sept. 19, 1974 events, indicating that "clean" SEP events near ~1 MeV/nucleon are very rare. For these two flares Mason et al. (1983) found that the choice of spectral representation did not simplify or organize the temporal variations, and that ionization energy losses in the solar atmosphere could not reproduce the observed systematic ratio changes. The abundance ratio variations in these "clean" SEP events were found to consist of two components: (a) rise-phase related systematic changes which were well correlated with spectral index changes, as shown also by Hamilton and Gloeckler (1981), and(b) short-term fluctuations on the order of a factor of 2 in the decay phase which were uncorrelated with spectral index changes. Such more or less random fluctuations in abundance ratios by factors of ∿2 to 3 seem in fact to be common in the typical, more complex SEP events, and may be due to inhomogeneities in composition of coronal material as suggested by Gloeckler et al. (1975b) and Zwickl et al. (1978).

Rise-phase related abundance ratio changes may be modelled in terms of conventional interplanetary propagation with rigidity dependent diffusion coefficients (e.g., Englade, 1971; Scholer, 1976; Scholer et al., 1979; Witte et al., 1979). Mason et al. (1983) were able to fit closely the intensity as well as ratio changes of H, He, C, O and Fe for each of the two clean SEP events using a numerical model of solar particle propagation based on a spherically symmetric Fokker-Planck equation including convection and adiabatic energy loss. Their results, shown in Fig. 14 (from Mason et al., 1983) for 0.6 to 1 MeV/nucleon particles in the September 19, 1974 event, indicate excellent fits to all the data from time of onset through the time of shock passage at ∿1200 on September 21. From detailed fits (such as shown in Fig. 14) in several different energy/nucleon intervals, they found the dependence of the interplanetary mean free path, λ, on particle rigidity, R, to be $\lambda \propto R^{0.61\pm0.18}$, from which they deduced mass-to-charge ratios for C, O, and Fe which were consistent with direct measurements by Gloeckler et al. (1981) in 10 other SEP events (see Section II.2)

Finally, we note that large (factor ~5 to 10) decreases in the ratios of higher-to-lower rigidity ions are often observed during energetic storm particle (ESP) enhancements preceding passage of flare-associated interplanetary shocks (Hovestadt et al., 1981c; Klecker et al., 1981b). Such compositional variations may be understood in terms of rigidity dependent acceleration by interplanetary shocks which changes the spectral shapes and intensities of the locally accelerated ions.

IV. ^{3}He-rich, Heavy Ion-rich, and Carbon-poor SEP Events

The first attempt to measure the ^{3}He abundance of SEPs was made by Schaeffer and Zahringer (1962) who found for the November 12, 1960 event a surprisingly large $^3He/^4He$ ratio of about 0.2 at about 70 MeV/n. Subsequent measurements (Hsieh and Simpson, 1970; Anglin et al., 1973; Dietrich, 1973; Garrard et al., 1973; Balasubrahmanyan and Serlemitsos, 1974) have revealed the existence of a class of SEP events in which the $^3He/^4He$ ratio is orders of magnitude larger than its value of about 10^{-4} in the ambient solar atmosphere (Geiss and Reeves, 1972; Hall, 1975).

^{3}He-rich SEP events are a subset of a larger class of solar flare associated increases whose composition is anomalous as summarized below (see also Gloeckler 1975, 1979; Ramaty et al., 1979, 1980).

(a) The $^3He/^4He$ ratio is highly variable, ranging from 10^{-2} to 1.

(b) The large enhancement of ^{3}He is not accompanied by a similar enhancement in ^{2}H and ^{3}H. For instance, for the July 30, 1970 ^{3}He-rich event, $^3He/^4He = 0.45 \pm 0.09$ in the energy range from 10.5 to 22.1 MeV/nucleon while $^2H/^4He \leq 0.05$ (Anglin, 1975).

(c) ^{3}He-rich events are generally associated with the enhancement of heavy nuclei such as Fe. The range of variations of $Fe/^4He$ is similar to that of $^3He/^4He$, and $^3He/^4He$ is strongly correlated with the $Fe/^4He$ ratio (e.g., Hurford et al., 1975b; Mobius et al., 1981).

(d) The enrichment of heavy ions such as Fe is not necessarily accompanied by an overabundance of ^{3}He (Anglin et al., 1977; Zwickl et el., 1978; Mobius et al., 1980; Mason et al., 1980; Reames and von Rosenvinge, 1981).

(e) Carbon is often significantly depleted in Fe-rich, ^{3}He-rich events (Mason et al., 1979c; 1980).

(f) There are ^{3}He-rich events which are not overabundant in heavy ions (Mason et al., 1980).

(g) Large enhancements of ^{3}He are usually associated with small SEP events in which the proton intensity is low, and which cannot always be identified with reported solar flares (Ramaty et al., 1980; Pesses, 1981).

The early explanations of the large ^{3}He enrichment (^{3}He/^{4}He $\sim$ 0.1-0.2) invoked nuclear interaction of solar energetic ^{4}He in the solar atmosphere (Garrard et al., 1973; Ramaty and Kozlovsky, 1974; Rothwell, 1976). The absence of ^{2}H in these events was believed to be the result of the kinematic properties of the ^{2}H and ^{3}He producing reactions. Since ^{2}H is preferentially emitted in the direction of the primary projectile, and assuming that the energetic α-particles are beamed, fractionation effects among ^{3}He and ^{2}H could arise. But under most favorable conditions the maximum value of ^{3}He/^{2}H was only 30. In order to explain ^{3}He/^{2}H ratios at least as large as 600 reported by Serlemitsos and Balasubrahmanyan (1975), Colgate et al., (1977a, b), proposed special conditions in the flare region whereby ^{2}H and ^{3}H would be selectively destroyed by nuclear reactions. Aside from the inability of nuclear reaction models to account convincingly for the absence of spallation products other than ^{3}He, such models fail to explain the other compositional anomalies (e.g., large heavy ion enhancement, carbon depletion) associated with ^{3}He-rich events. Therefore, the general validity of nuclear reaction models is doubtful.

More successful explanations of ^{3}He-rich and heavy-ion-rich events are based on preferential injection or heating models as proposed by Ibragimov and Kocharov (1977), Fisk (1978), Ibragimov et al. (1978) and most recently by Varvoglis and Papadopoulos (1983). In all these models a two-stage process is assumed: first injection of ions by preferential heating, which is then followed by acceleration. In the model by Ibragimov et al. (1978) the ambient medium is heated during the injection phase by Langmuir turbulence generated by a beam of high-energy electrons of energies $\sim$10 keV within the flare site. (Recently Kocharov and Kocharov (1981) were able to show the dominance of ion acoustic turbulence over Langmuir turbulence under plausible coronal conditions.) The heating rate varies as

$$\frac{dT}{dt} \sim \frac{Q^4}{A^2} \qquad (2)$$

where Q is the charge state and A, the atomic mass of the ion. From this expression, it is seen that $^3He^{+2}$ gains energy at a rate about twice that of $^4He^{+2}$. Highly ionized heavier ions such as C^{+6}, O^{+8}, etc. are even more efficiently heated. If the second stage acceleration process requires an injection energy threshold, so that only particles in the high energy tail of the energy distribution are accelerated (see for instance Sturrock,(1980);or Trivedi and Biswas, 1981), the acceleration of the $^3He^{+2}$ and heavier ions is thus favored. The heating process requires a large electron to proton temperature ratio ($T_e/T_i \gg 1$), a condition which probably can only be maintained during nonstationary conditions.

In the model by Ibragimov et al. (1978) the heating of ^3He is not a resonant phenomenon,and the relative efficiency of heating ^3He compared to that of ^4He differs only by a factor of two. It is thus hard to imagine that this difference can alter the $^3He/^4He$ ratio from 10^{-4} for the ambient medium to $\sim$1 in ^3He-rich events. Furthermore, according to Eq. (2), the heating rates for C, N and O are even higher than the rate for ^3He. Thus for a ^3He-rich event, there would be correspondingly higher enrichments of $Q \geq 6$ ions. Yet, for the six events studied by Hurford et al. (1975a; 1975b), $^3He/^4He$ was enriched by 10^4 compared to an enhancement by a factor of 3-30 of the $(Z \geq 6)/^4He$ ratio. For these reasons, the preferential injection model of Ibragimov et al. (1978)

may be inadequate in explaining the full range of compositional anomalies including the carbon depletion often associated with ^3He-rich events, unless additional conditions are imposed for variable injection energy thresholds for different ion species.

In contrast to the model of Ibragimov et al. (1978), Fisk (1978) proposed a resonant heating model in which a current-driven instability may excite electrostatic ion cyclotron waves near the $^4He^{++}$ cyclotron frequency which could then resonantly heat ^3He to a temperature higher than that of the ambient ^4He. This selective pre-acceleration heating brings a far larger fraction of ^3He compared to ^4He above some injection energy threshold for subsequent acceleration to higher energies (e.g., Pesses, 1981). In neither of the two plasma-wave heating models (Fisk, 1978; Ibragimov et al., 1978) discussed are ^2H or ^3H preferentially heated, consistent with the observations.

The special but not implausible requirements of Fisk's model are that (a) the β of the plasma be less than 10^{-3} (low ratio of thermal to magnetic field energy), (b) the electron-to-ion temperature ratio, T_e/T_i, be high enough to excite the plasma instability but less than 10; under these conditions the excitation of electrostatic ion cyclotron waves becomes dominant, and (c) the $^4He/^1H$ ratio be high ($\sim$0.25), a condition required for the wave frequency to fall close to the cyclotron frequency of $^4He^{+2}$.

To examine the degree to which the physical conditions required by Fisk's model may be realized, Ramaty et al. (1979, 1980) compiled data on all known ^3He-rich events observed in 1968-1976 and examined the characteristics of the 36 ^3He-rich events in their sample. They found that high ($^3He/^4He$) ratios are associated most frequently with small proton-intensity events. For these events, the $^4He/^1H$ ratio is also, in general, large. This correlation may be regarded as the confirmation of requirement (c) in Fisk's model. The association of ^3He-rich events with the enrichment of heavier elements such as Fe may indicate that the source of the particles is in the lower corona where thermal diffusion enriches the heavier elements. This would satisfy requirement (a) in Fisk's model. As to the requirement (b) of $T_e/T_i \lesssim 10$, Ramaty et al. (1979, 1980) found that many of the ^3He-rich events are not clearly associated with identified flares. This may be interpreted as the indication of low electron temperature.

One of the basic differences between Fisk's model and that of Ibragimov et al. (1978) is that in Fisk's model, the heating of the ^3He ions is by waves at resonance with the gyrofrequency of the preferentially heated ion. For the enhancement of heavy ions, Fisk (1978) suggested that partially stripped ions having a mass-to-charge ratio, A/Z of $\sim$3, such as $^{12}C^{+4}$, $^{16}O^{+5}$, and $^{56}Fe^{+17}$, may be heated by waves of frequencies at the cyclotron second harmonic. Such ions could exist in the corona where the temperature may range between $5 \cdot 10^5$ and $5 \cdot 10^6$K.

Indeed, Ma Sung et al. (1979, 1981a) reported the existence of such A/Z $\sim$ 3 ions in the May 14-15, 1974 ^3He-rich event, using data taken by the Electrostatic Energy Versus Charge Analyzer (EECA) on the IMP-8 satellite (see Section II.2). Since the instrument does not have sufficient resolution to separate individual charges, they relied on the computer fitting procedure to the observed pulse-height profile as described in Section II.2. Figure 15 (from Ma Sung et al., 1979) summarizes their result and indicates the presence of $^{16}O^{+5}$ and $^{56}Fe^{+18}$. As emphasized by Ma Sung et al. (1979, 1981a), the coexistence of $^{16}O^{+5}$, $^{56}Fe^{+11,12,13}$ and $^{56}Fe^{+16,17,18}$ they observed requires a range of different coronal equilibrium temperatures from $\sim 4 \cdot 10^5$K to $5 \cdot 10^6$K, consistent with the results of Mason et al. (1979b), 1980) and Ma Sung et al. (1981b).

Recently Varvoglis and Papadopoulos (1983) have extended Fisk's (1978) model by including non-linear physics of particle energization by electrostatic ion cyclotron waves. They have shown that $^{3}He^{++}$ can also be preferentially heated by hydrogen (rather than $^{4}He^{++}$) cyclotron waves when the wave amplitude exceeds a threshold located within the normally expected amplitude range. Just as the model of Fisk (1978), this non-resonant heating by hodrogen cyclotron waves can also account for the other compositional anomalies found in SEP events and listed at the beginning of this section.

Reames and von Rosenvinge (1981) studied ^{3}He-rich events in the period of August 1978 through August 1980 in order to search for the resonance effect suggested by Fisk's model. Assuming that in a $1.5\text{-}2 \cdot 10^{6}$K corona the charge states of heavy ions are typically $Q = Z - 1$ for N and O, $Q = Z - 2$ for Ne-Si and $Q = 10$ for S and heavier ions, they plot the overabundance factor, F, of ^{3}He and major heavy elements relative to ^{4}He as a function of the mass-to-charge ratio A/Q for the October 3, 1979 and January 14, 1980 events as shown in Fig. 16 (from Reames and von Rosenvinge, 1981). In neither of the two events is there a resonance peak at $A/Q \sim 3$. The absence of a resonance peak at $A/Q \sim 3$ (corresponding to resonance with the 2nd harmonic of the wave) should not, however, be regarded as a contradiction to Fisk's model, since as pointed out by Ma Sung et al. (1979, 1981a), resonance heating at higher harmonics ($A/Q \sim 9/2$, $A/Q = 6$) may also be possible. It should also be noted that a reliable test of Fisk's resonance heating model would require measured rather than assumed charge states based on a single coronal temperature.

The full range of compositional anomalies in a number of smaller SEP events has been explored by Mason et al. (1980). In addition to the more common ^{3}He-rich events with heavy ion enrichment for O-Fe, they found (a) carbon-poor flares with simultaneous enrichment of ^{3}He and heavy ions discovered previously by Mason et al. (1979c), (b) an event with ^{3}He enrichment and no heavy ion enhancement, and (c) a ^{3}He-rich event with only Si-Fe enriched. Mason et al. (1980) were able to explain this wide range of compositional anomalies in terms of Fisk's model assuming, however, differing initial plasma temperatures and temperature changes during the injection phase.

V. Conclusion

Detailed measurements of the composition of energetic particles associated with solar flares carried out in recent years primarily with satellite and space-probe instruments have revealed a complexity and numerous surprises not anticipated by the early observation of heavy nucleon abundances. Although a number of puzzling questions are still outstanding and many details need to be filled in, this new knowledge on the elemental, charge states and isotopic composition of SEPs gives us a rough indication where the acceleration may take place, what the physical conditions and characteristics of the source region may be, and by what means material, which initially must originate in the photosphere, is heated and then accelerated to the observed $\gtrsim 1$ MeV per nucleon energies of SEPs. Because these processes produce compositional biases, it is as yet not possible to obtain reliable and accurate solar system abundances from SEP composition measurements.

Solar particles are most likely accelerated in a two-step process. After initial heating, ions in the high-energy tails of the broadened plasma distribution, and hence above some given energy threshold, may be efficiently accelerated to high energies. We have not discussed here the nature of these acceleration mechanisms (see e.g., McGuire, 1983) which could, for example, involve strong, flare-generated coronal shocks or stochastic Fermi-type processes similar to those believed to be responsible for the acceleration of ions upstream of the earth's bow shock. Abundant experimental evidence, discussed in this paper, supports the idea that the second-stage acceleration takes place in the low-density outer corona and that nuclear processes and energy losses by ionization are not important at this stage. Before we observe SEPs, generally at heliocentric distances ≳1 AU, interplanetary propagation and acceleration by interplanetary propagating shocks produce systematic compositional distortions, and may also be responsible for some of the more random fluctuations in the abundances of particularly the low energy ions.

The source material is transported from the cold photosphere to the acceleration region in the hot corona either rapidly in isolated pockets (e.g. coronal mass ejections) without significant heating, or more gradually, in the more conventional sense, leading to the formation and acceleration of the solar wind. This later mechanism is most likely to introduce systematic biases in the composition, whereby ions with low first ionization potential, I, are overabundant compared to those with a high I, and heavier ions may be systematically depleted compared to lighter ions due to gravitational settling (Geiss, 1972). Thus the source plasma probably contains some pockets of cold plasma imbedded in the hot corona in variable proportions.

The source plasma is likely to be inhomogeneous in both composition and temperature on a scale on the order of one solar radius. Aside from the discrete cold regions, the temperature could range from $\lesssim 10^5$ to $\gtrsim 10^7$K. Given these conditions in the source region, probably the lower corona, a variety of plasma processes could then be invoked to locally heat the ion population thereby taking a fraction of these ions above the energy threshold for efficient second-phase acceleration. At this injection stage certain ions could, under favorable coronal conditions, be preferentially heated leading to the various types of compositional anomalies discussed in Section IV. It is also conceivable that such preferential mechanisms operating in localized regions along with the more ordinary plasma heating, could be responsible for the less pronounced mass-dependent enhancements of heavy ions in the large SEP events, and could also produce some of the observed short-term temporal compositional variabilities.

Significant advances in our understanding of compositional biases in SEPs will come with detailed comparison between SEP abundances and the solar wind composition, the two direct samples of solar material. Although the first step in this direction has been taken with the neon isotopes measurements in the SEP and the solar wind, extensive comparison will be possible only after the planned launch of advanced solar wind composition instruments in the near future. The discrepancy between the SEP and solar wind $^{22}Ne/^{20}Ne$ ratio remains a puzzle. It may be, however, that more extensive SEP isotope measurements, especially at lower energies, will reveal variabilities similar to those seen in the elemental composition of SEPs, resulting in an average value more consistent with that in the solar wind.

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Table 1

Elemental Abundances Relative to Oxygen

Element	Averages of ratios in SEP events (1 ~ 20 MeV/n)[(a)]	Near 1 MeV/n[(b)]	Above 10 MeV/n[(c)]	Local Galactic Abundances[(d)] (Photosphere)
He	56	68	41-88	117±26
C	0.43	0.50	0.49	0.57±0.13
N	0.13	--	0.13	0.10±0.04
O	≡1	≡1	≡1	≡1
Ne	0.13	0.16	0.14	0.12±0.08
Na	0.014	--	0.019	0.0024±0.0004
Mg	0.19	0.15	0.19	0.0457±0.0013
Al	0.015	--	0.024	0.0037±0.0002
Si	0.15	0.12	0.12	0.0435±0.0013
S	0.032		0.025	0.020±0.006
Ar	0.006	0.08 (S, Ar, Ca)	--	0.004±0.003
Ca	0.011		--	0.0027±0.0004
Cr	0.003			0.0006±0.0001
Fe	0.14	0.14 (Cr, Fe, Ni)	0.03-0.06 (Cr, Fe, Ni)	0.038±0.0026
Ni	0.007			0.0021±0.0003

(a) compiled by Meyer (1981a)

(b) from Mason (1980)

(c) compiled by Webber (1975)

(d) from Meyer (1979a, b)

Table 2

Spectral Characteristics and Ionization States of 0.3 to 2.4 MeV/nuc He, C, O and Fe in Solar Flare Particle Events

Date	Spectral Characteristics				Ionization States: He^+/He^{++}			Mean Charge States $<Q>^{(d)}$		
	$\gamma_{He^{++}}$ (a)	$\gamma_{He^+}/\gamma_{He^{++}}$ (a)	η	η_0	$r_{E/A}^{(a)}$	$r_{\eta}^{(b)}$	$r_{\rho}^{(c)}$	$C^{(e)}$	$O^{(e)}$	$Fe^{(f)}$
1978										
25-27 Sept	1.54	1.05	0.50	0.55	0.06	0.22	0.11	5.7	7.2	13
10-12 Nov	1.82	1.15	0.53	0.33	0.06	0.17	0.08	6.0	7.2	14
1979										
18-22 Feb	2.36	1.06	0.38	0.33	0.06	0.18	0.10	5.7	7.3	15
28-29 Mar	2.25	1.16	0.45	0.37	0.13	0.55	0.29	5.6	6.9	--
3-6 Apr	1.78	1.23	0.47	0.47	0.06	0.17	0.09	5.8	7.2	13
23-25 Apr	2.55	1.27	0.71	0.48	0.09	0.50	0.21	6.0	7.2	--
28-30 May	2.42	1.05	-0.05	0.15	0.12	0.09	0.10	5.9	7.2	--
6-9 June	1.66	1.21	0.35	0.42	0.09	0.25	0.14[g]	5.7	7.0	12.5
6-10 July	1.72	1.25	0.42	0.44	0.10	0.33	0.18	5.7	6.9	13
15-26 Sept	1.12	1.30	0.60	0.82	0.13	0.50	0.23	5.5	6.7	--
FLARE AVERAGE	1.92	1.17	0.44	0.44	0.09	0.30	0.15	5.8	7.1	13.5

(a) energy dependent, averaged over 0.3 to 2.4 MeV/nucleon
(b) ratio at equal $\eta = vR^{\eta}$ (v = velocity, R = rigidity)
(c) density ratio assuming $f = A\exp(-\eta/E_0)$ holds from $E \lesssim 0.1$ to $E \gtrsim 10$ MeV/nuc
(d) possibly energy dependent; ratio averaged over 0.4 to 2.4 MeV/nucleon; values subject to systematic error of 0.05<Q>.
(e) one sigma error is ~ 0.15 charge units
(f) one sigma error is ~1.0 charge units
(g) density ratios $He^{++}:He^+:O:C:Fe$ are 55:7:1:0.6:0.16

Table 3

Isotope Ratios of Solar Energetic Particles

9/23/78 SEP Event(a)			Observed Isotope Ratio at 35-55 MeV/nuc (Averages of 7 (Ne) & 10 (Mg) SEP events)	Solar System (Cameron, 1980)
Isotope Ratio	Energy Interval (MeV/nuc)	Observed Ratio		
$^{13}C/^{12}C$	6-38	$0.010^{+.003}_{-.004}$		0.0112
$^{14}C/^{12}C$	6-38	<0.0014		radioactive
$^{15}N/^{14}N$	9-42	$0.008^{+.010}_{-.005}$		0.0037
$^{17}O/^{16}O$	7-45	<0.0019		0.00037
$^{18}O/^{16}O$	7-45	$0.0018^{+.0007}_{-.0008}$		0.00204
$^{21}Ne/^{20}Ne$	11-26	<0.016		0.0030
$^{22}Ne/^{20}Ne$	11-26	$0.13^{+.04}_{-.03}$	0.13 ± 0.04 (b)	0.122
$^{25}Mg/^{24}Mg$	12-36	$0.14^{+.05}_{-.02}$		0.129
$^{26}Mg/^{24}Mg$	12-36	$0.15^{+.04}_{-.03}$	$0.13^{+0.04}_{-0.03}$ (c)	0.142

(a) from Mewaldt *et al*. 1981b

(b) Dietrich and Simpson 1979a

(c) Dietrich and Simpson 1981

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Figure Captions

Fig. 1 Variations of the ratios of the relative (normalized to oxygen) abundances of different elements in the SEP composition (listed in column 2 of Table 1) to their respective relative abundances (also normalized to oxygen) in the local galactic (photospheric) composition (listed in column 5 of Table 1) versus the first ionization potential of these elements. The boxes indicate the errors in the local galactic abundances (from Meyer, 1981a).

Fig. 2 Variations of the ratios of the relative abundances of different elements in the SEP composition (listed in column 2 of Table 1) to their respective relative abundances in the photospheric or local galactic composition (top panel), coronal composition (middle panel), and solar wind composition (lower panel), versus the first ionization potential of these elements. All four compositions have been normalized to magnesium. "Best" horizontal lines have been drawn through all data points only to guide the eye (from Meyer, 1981b).

Fig. 3 (a) Energy histogram for 163-238 keV/charge ions derived from the Electrostatic-Energy vs Charge-Analyzer pulse-height data summed over 15 SEP events (upper histogram), and during quiet time periods (lower histogram).

(b) Energy histograms showing the heavy ion portion of the 15 flare sum data after subtraction of background (solid histogram), and predicted distributions for an ion population with an average SEP abundance, average power law spectral index of 1.5 and at equilibrium coronal temperature of 10^6K (dashed histogram) and $2 \cdot 10^6$K (dotted histogram). See text for explanation (from Ma Sung et al., 1981b).

Fig. 4 Ionization state histograms for He, carbon, oxygen and iron for the June 6-9, 1979 SEP event derived from data obtained with the ULEZEQ instrument (from Gloeckler et al., 1981).

Fig. 5 (a) Energy spectra and (b) distribution functions of He^{++}, He^{+}, O, C and Fe in the June 6-9, 1979 SEP event (from Gloeckler et al., 1981).

Fig. 6 Measured distribution functions of O^{+7} and Fe^{+14} vs rigidity for the March 14-18, 1979 He^{+}-rich period (from Hovestadt et al., 1983).

Fig. 7 Mass histograms of C, N, O, Ne and Mg in the energy ranges 6-38, 9-42, 7-45, 11-26 and 12-36 MeV/nucleon respectively (for ^{20}Ne, the energies are 6% higher), for the 9/23/78 SEP event (from Mewaldt et al., 1979, 1981a, 1981b).

Fig. 8 Solar isotopic abundance ratios (from Mewaldt et al., 1979, 1981a, b).

Fig. 9 Daily average flux values for enhanced periods between October 31, 1973 and December 1, 1977 for the following species and energy intervals: (a) He versus Fe, 0.6-1.6 MeV/nucleon, (b) C versus O, 0.6-1.6 MeV/nucleon, and (c) O versus Fe, 1.0-4.6 MeV/nucleon (from Mason et al., 1980).

Fig. 10 Daily averages of the counting rate of 0.4 to 0.6 MeV/nucleon He (upper panel), and of the He^{+}/He^{++} ratio in the 0.5 to 0.67 MeV/nucleon energy interval (lower panel) during a 420 day period from September 2, 1978 to October 27, 1979 (from Hovestadt et al., 1983).

Fig. 11 Normalized widths (pseudo one-standard deviations) of the distributions of measured abundances of different elements relative to oxygen (filled circles), and a fit to the observed variations using the empirical expression $1.3|Z^{1/3} - 8^{1/3}|$ (open circles). See text for details. (from Mason et al., 1980).

Fig. 12 Observed deviations of the relative abundances (normalized to oxygen) of elements in each of five classes of SEP events from the average relative SEP abundances (column 2 of Table 1) versus the atomic number Z of the element. The five vertical bars for each of the elements represent in sequential order from left to right the range of deviations found in SEP events with Fe/O ratios of 1.5-0.5, 0.5-0.15, 0.15-0.07, 0.07-0.05, and <0.05, respectively. Elements with first ionization potential, $I \gtrsim 10$ are indicated by arrows at the top of the figure (from Meyer, 1981a).

Fig. 13 Six-hour averages of abundance ratios of 0.6-0.95 MeV/nucleon He/H, O/He, O/C and Fe/He during the November 1977 SEP event observed on Voyager 2 at 1.55 AU (from Hamilton and Gloeckler, 1981).

Fig. 14 Model fits (solid curves) to observed intensities (upper panel) and ratios (lower panel) of 0.6-1.0 MeV/nucleon H, He, C, O, and Fe during the September 19, 1974 SEP event. Arrow on top left of figure marks time of the optical flare. Dashed curves represent calculated Fe/O and O/He ratios using a value for the interplanetary diffusion coefficient for oxygen ±20% from the best fit value (from Mason *et al.*, 1983).

Fig. 15 Observed energy histograms for (a) 163-238 keV/charge and (b) 692-1000 keV/charge ions derived from the Electrostatic-Energy *vs* Charge-Analyzer pulse-height data during the May 14, 15 ^{3}He-rich SEP event. The instrument response (dashed curve) is calculated assuming indicated power-law spectral indices for H^+, He^{++}, O to S and Fe ions, measured relative abundances of major heavy elements (C through Fe) and charge-states of heavy ions predicted by Fisk's (1978) plasma heating model.

Fig. 16 Observed enhancements of the relative abundances (normalized to ^4He) of 2 to 3 MeV/nucleon ^3He, ^4He, C, N, O, Ne, Mg, Si, S, Ca, and Fe during the (a) October 3, 1979 and (b) January 14, 1980 ^3He-rich SEP events compared to the average relative abundances in SEP events (column 2 of Table 1) versus the mass-to-charge ratio of the ion. The charge states Q were assumed to be as follows: Q = Z-1 for N and O, Q = Z-2 for Ne-Si and Q $\sim$ 10 for S, Ca and Fe (from Reames and von Rosenvinge, 1981).

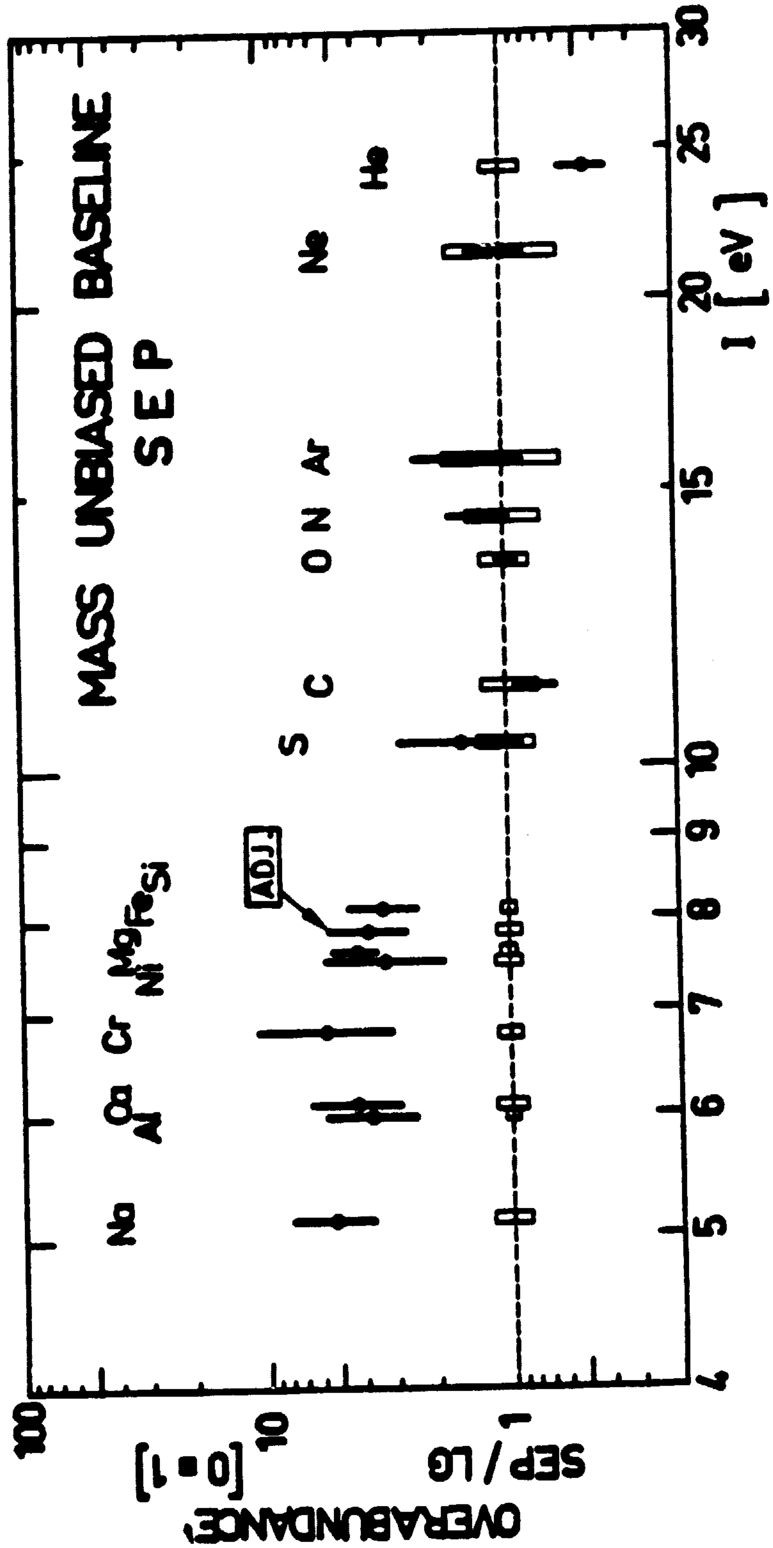
MASS UNBIASED BASELINE
SEP
Na Al Ca Cr Ni Mg Fe Si
S C O N Ar Ne He
ADJ.
OVERABUNDANCE, SEP / LG [O = 1]
I [eV]

Figure 1

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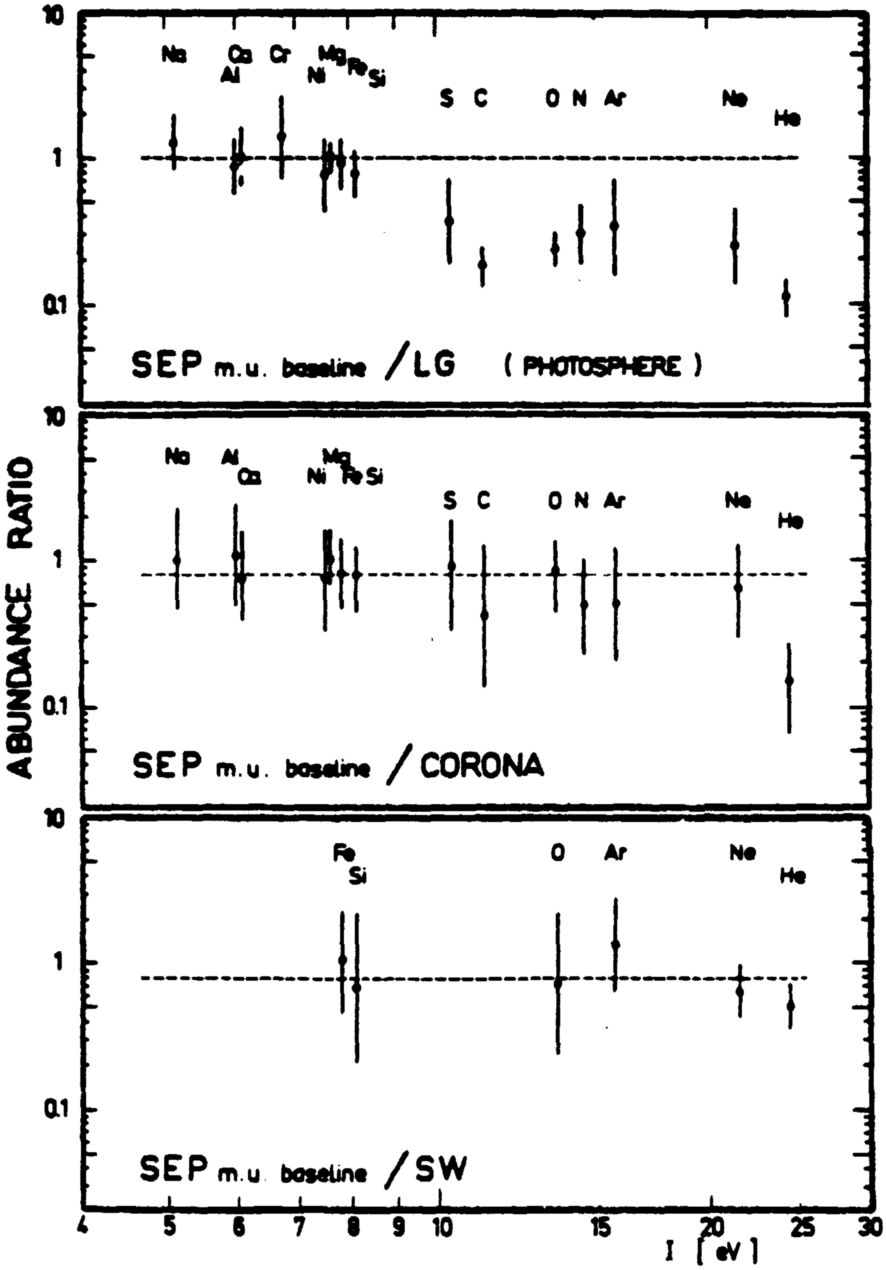

Figure 2

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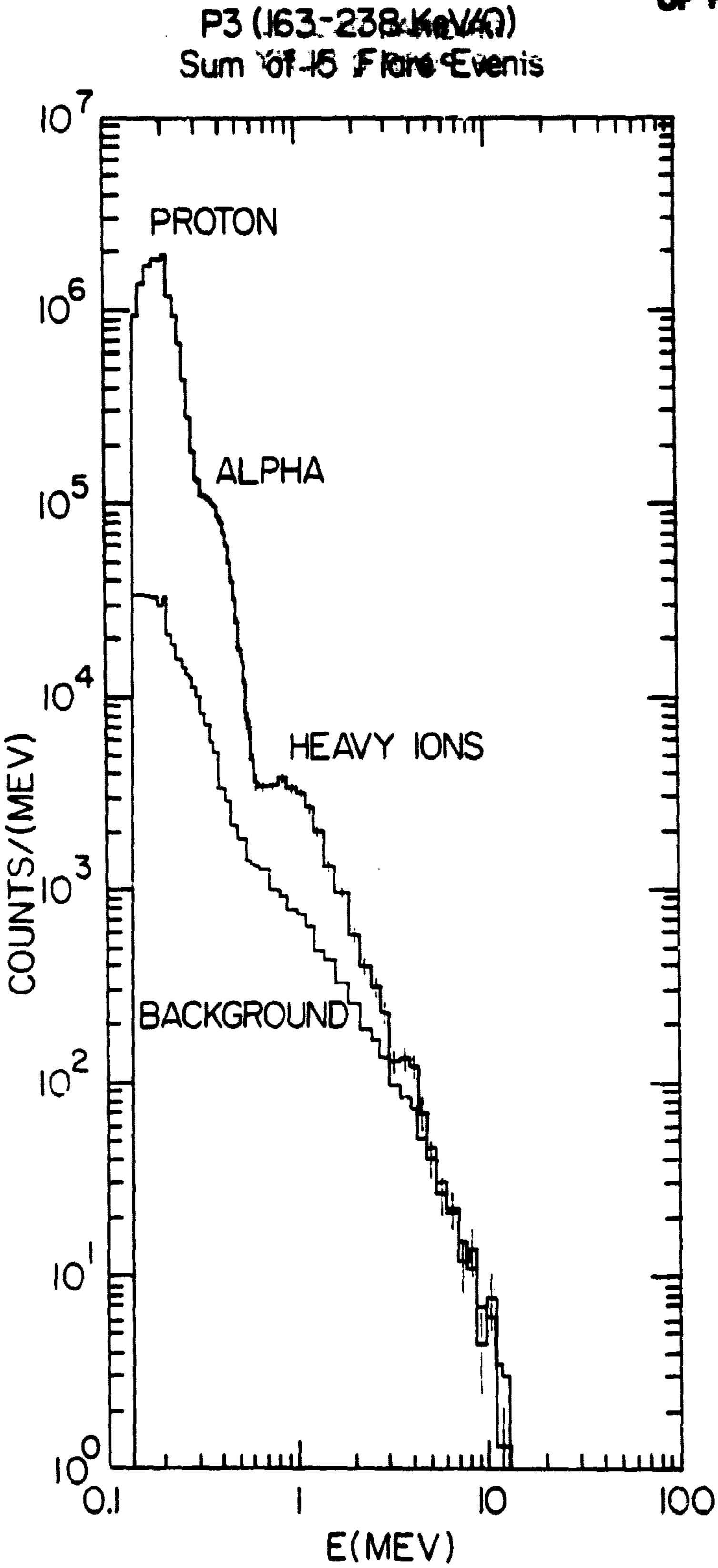
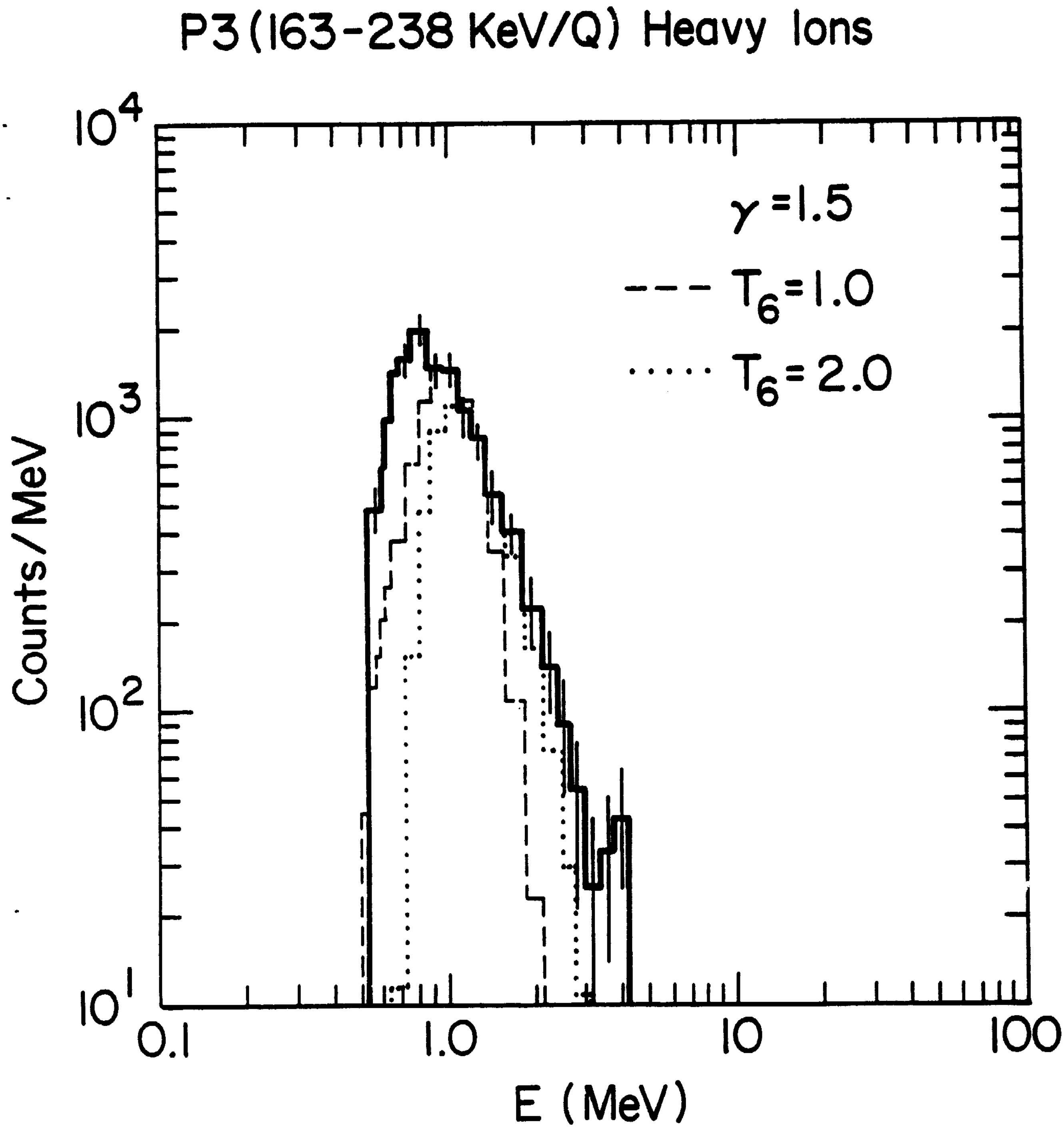
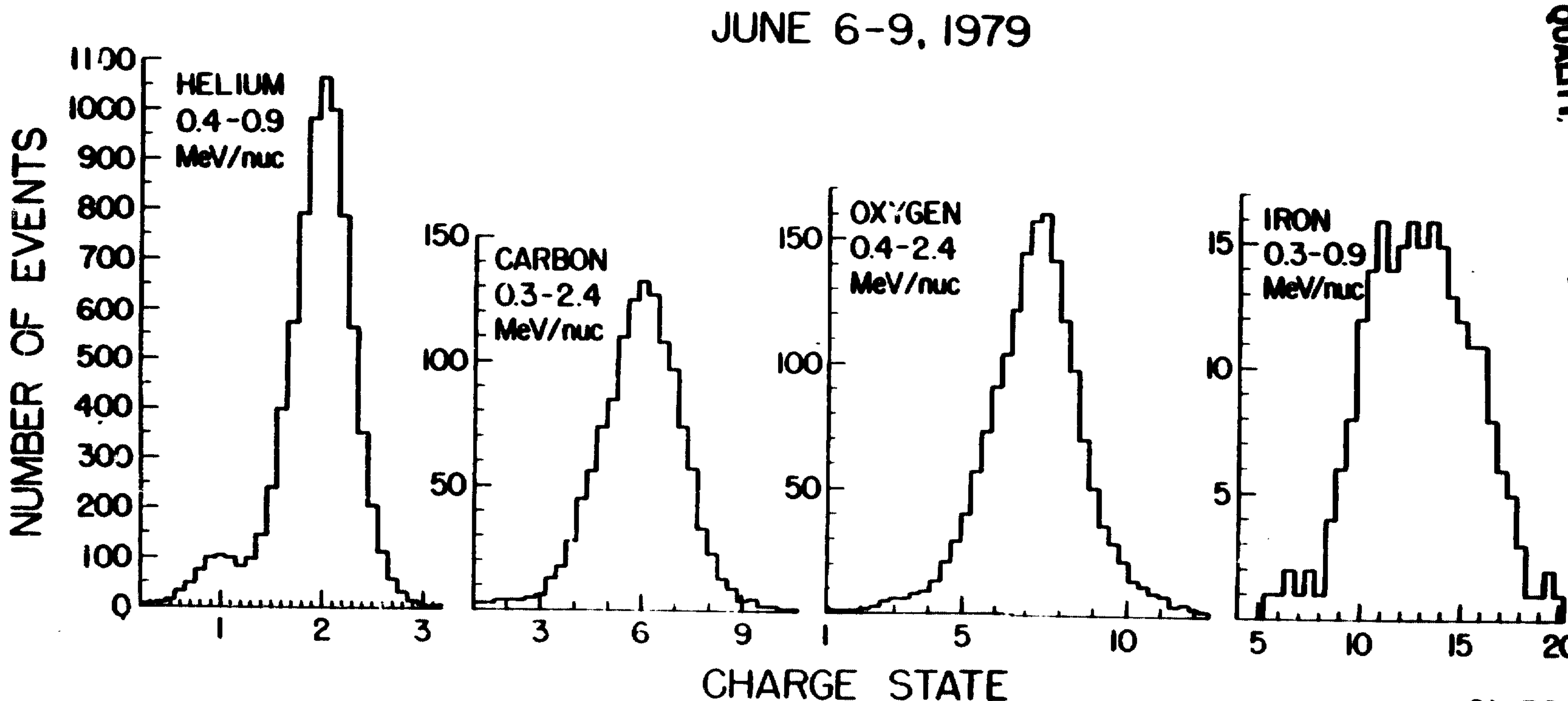


Figure 3a



81-58

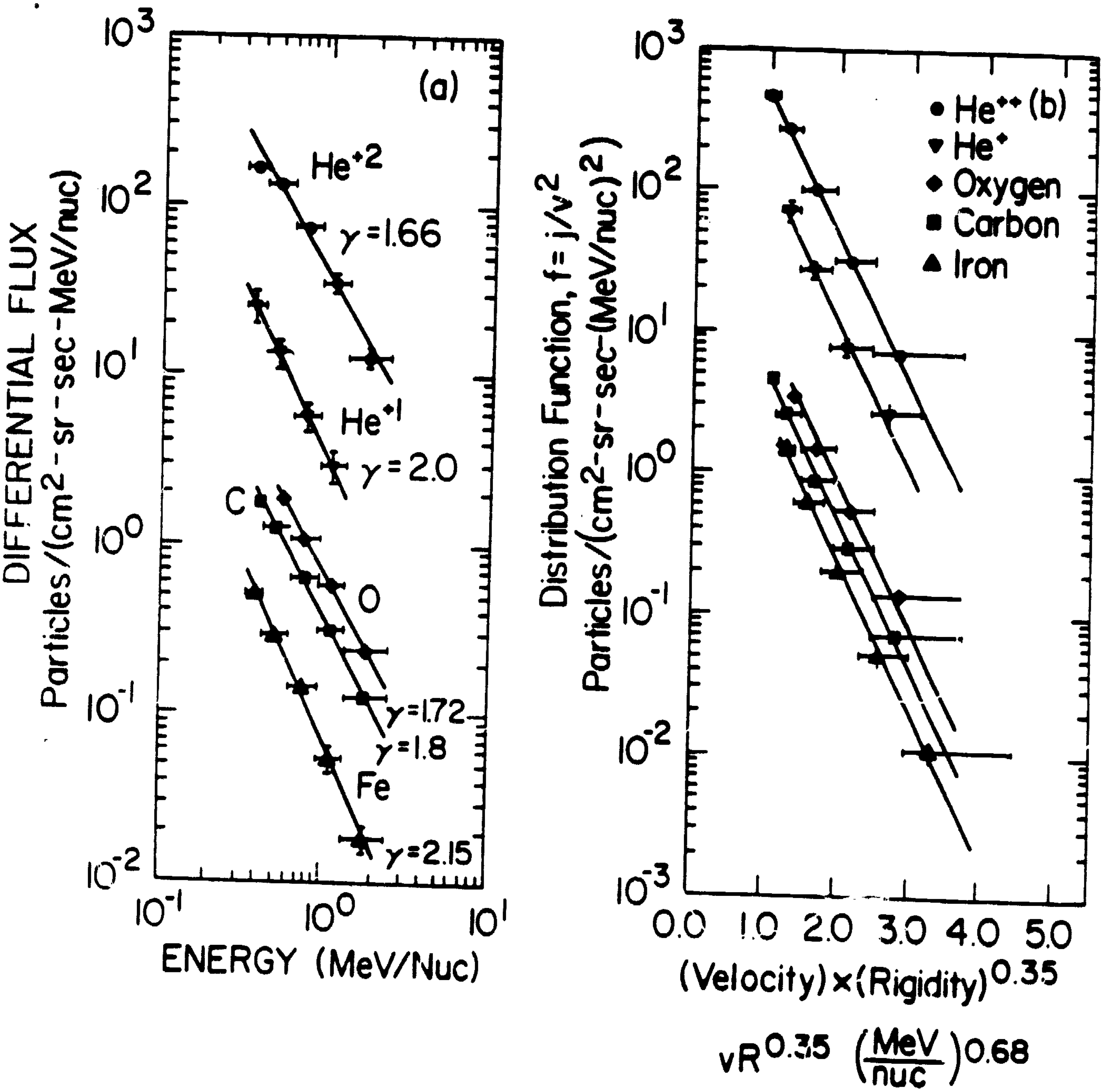
Figure 3b



JUNE 6-9, 1979
NUMBER OF EVENTS
HELIUM
0.4-0.9
MeV/nuc
CARBON
0.3-2.4
MeV/nuc
OXYGEN
0.4-2.4
MeV/nuc
IRON
0.3-0.9
MeV/nuc
CHARGE STATE

81-32

JUNE 6-9, 1979
ULEZEQ SENSOR on ISEE-3
Max-Planck-Institute/
University of Maryland Experiment



81-34

Figure 5

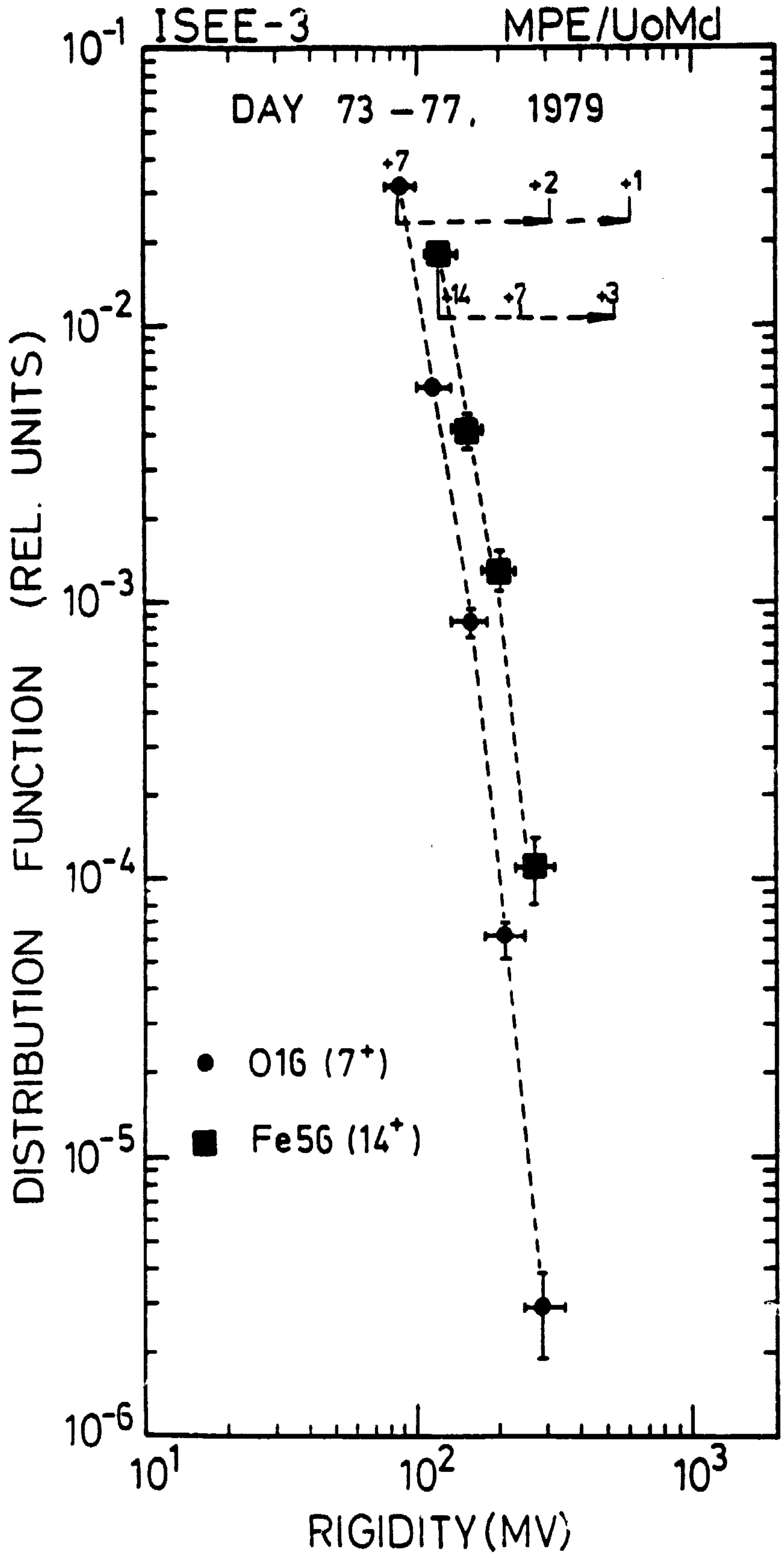

ISEE-3
MPE/UoMd
DAY 73 – 77, 1979
+7
+2
+1
+14
+7
+3
O16 (7+)
Fe56 (14+)
DISTRIBUTION FUNCTION (REL. UNITS)
RIGIDITY (MV)
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^1
10^2
10^3

Figure 6

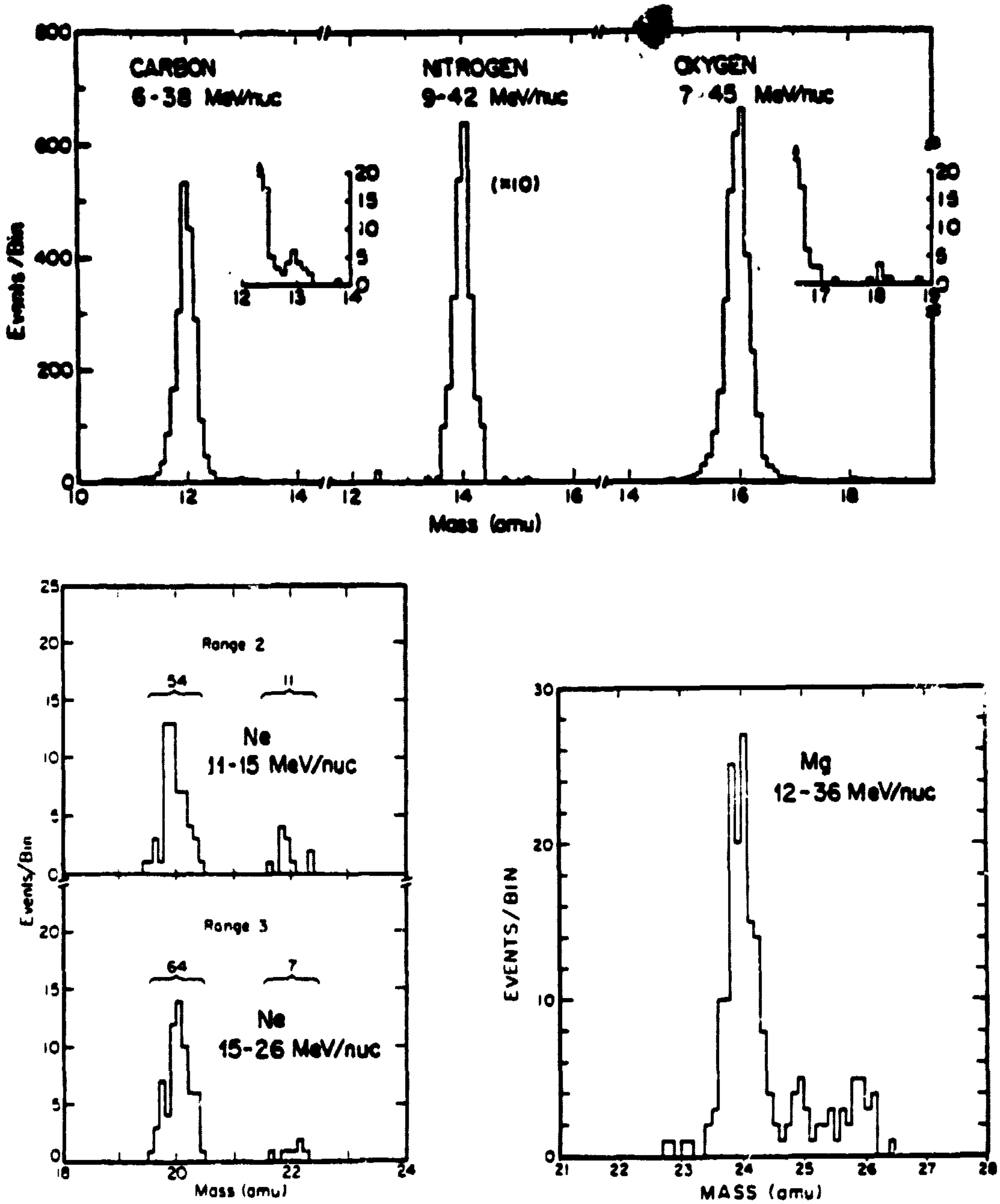

CARBON
6-38 MeV/nuc
NITROGEN
9-42 MeV/nuc
OXYGEN
7-45 MeV/nuc
(x10)
Events/Bin
Mass (amu)
Range 2
54
11
Ne
11-15 MeV/nuc
Range 3
64
7
Ne
15-26 MeV/nuc
Events/Bin
Mass (amu)
Mg
12-36 MeV/nuc
EVENTS/BIN
MASS (amu)

Figure 7

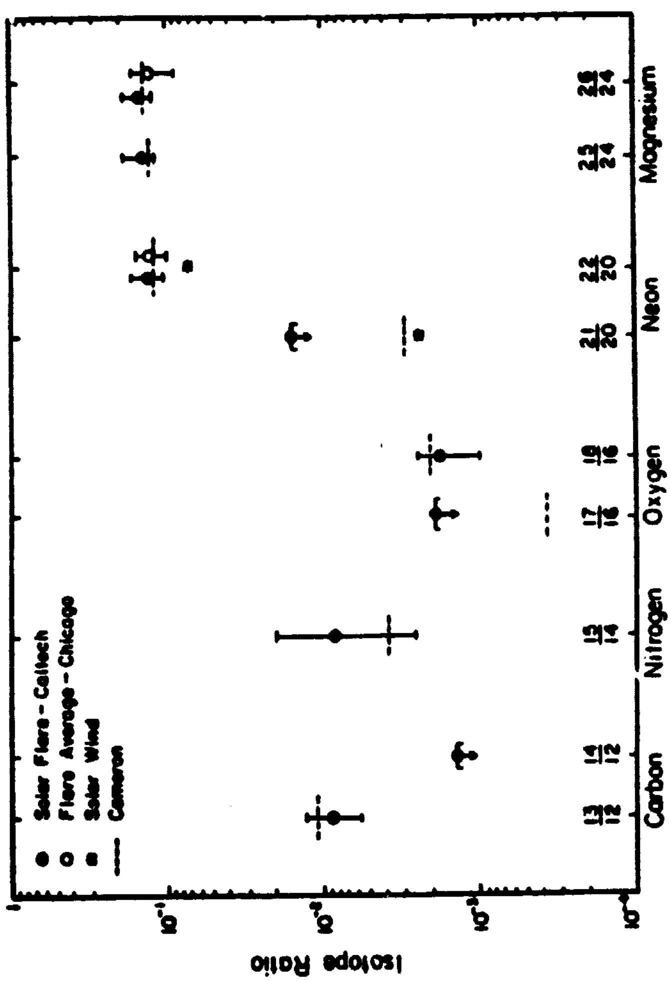

Solar Flare - Caltech
Flare Average - Chicago
Solar Wind
Cameron
Isotope Ratio
Carbon
Nitrogen
Oxygen
Neon
Magnesium

Figure 8

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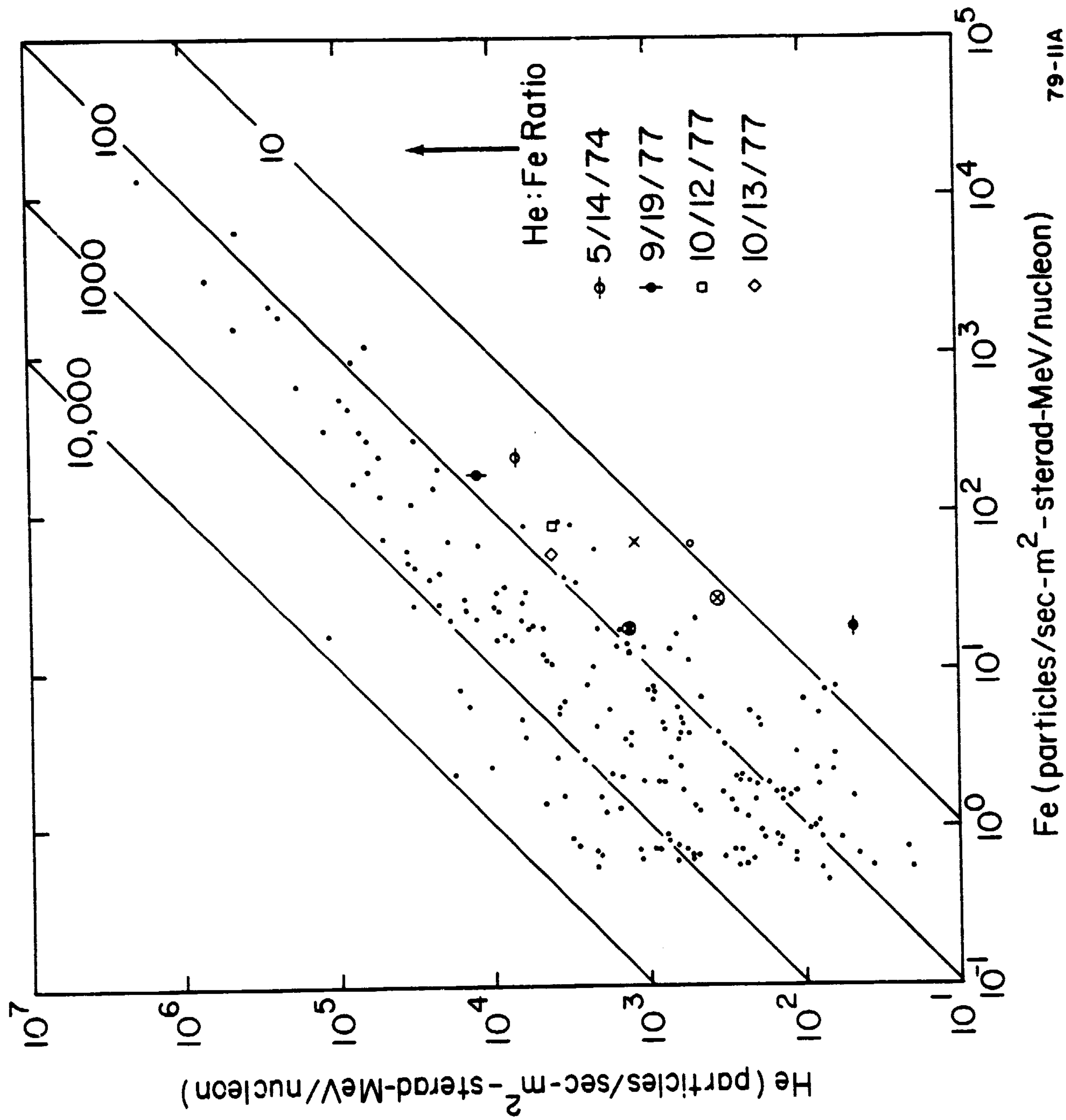

Figure 9 a

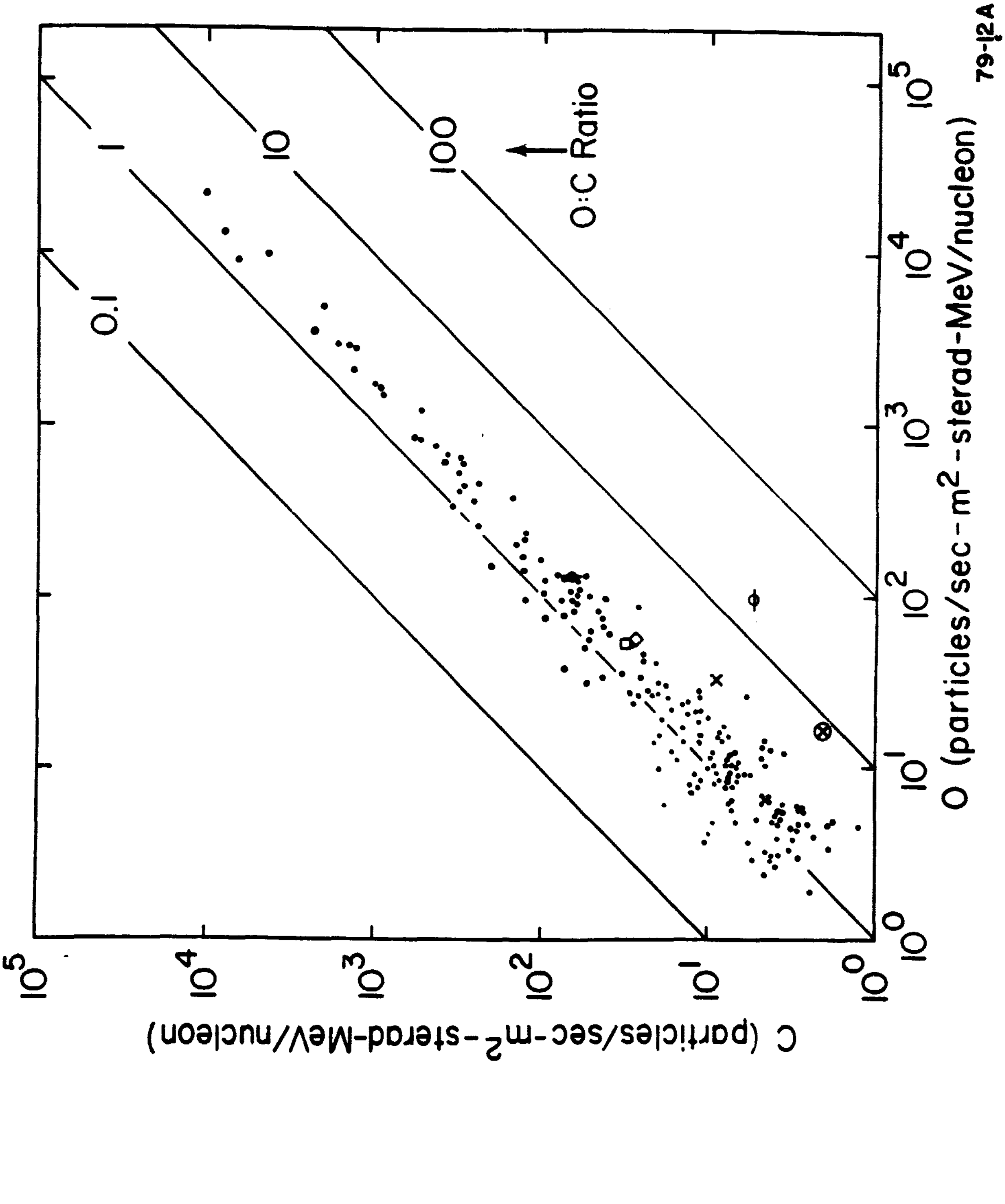
O (particles/sec-m^2-sterad-MeV/nucleon)
C (particles/sec-m^2-sterad-MeV/nucleon)
10^0
10^1
10^2
10^3
10^4
10^5
0.1
1
10
100
O:C Ratio
79-12A

Figure 9b

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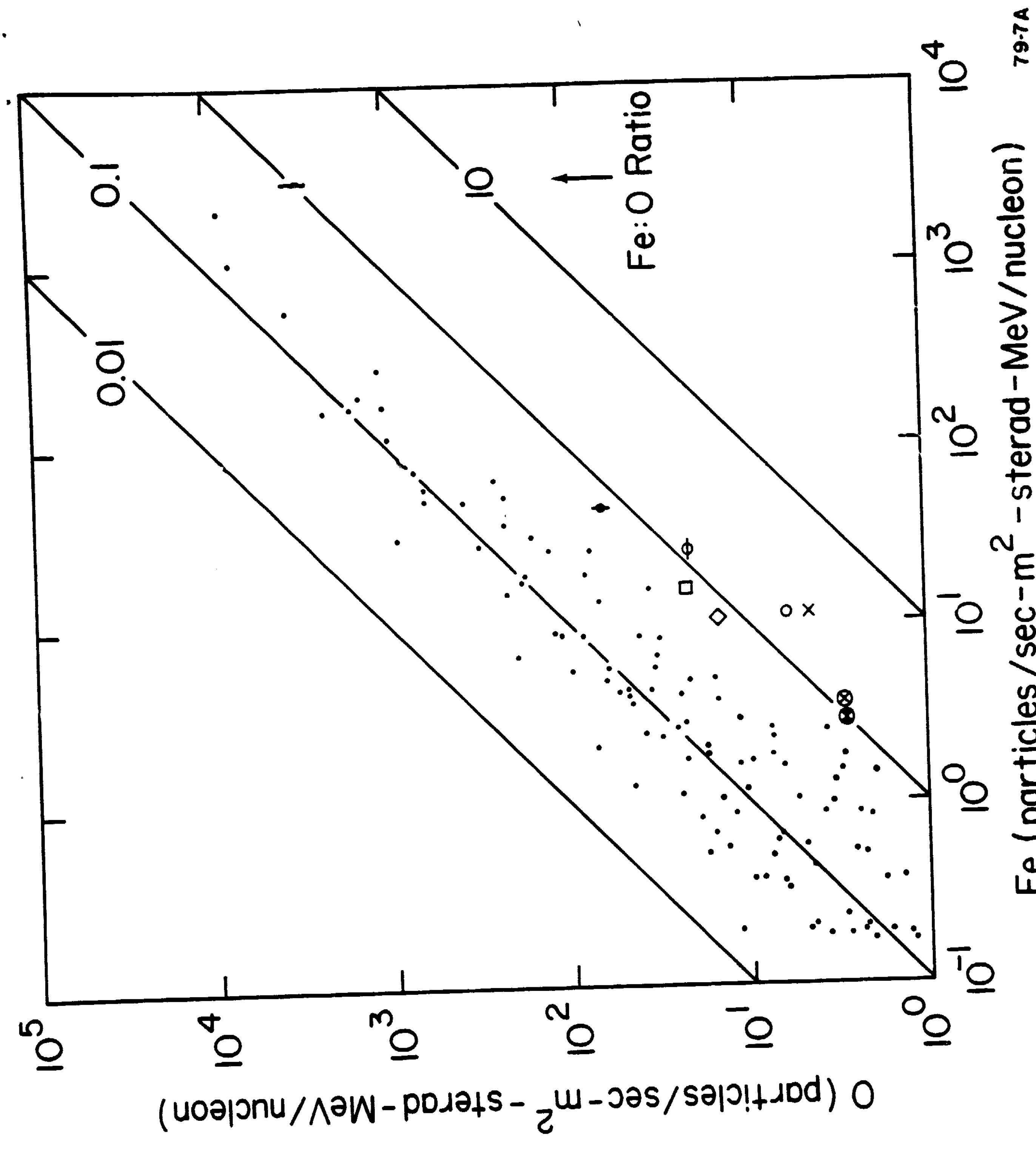

Figure 9c

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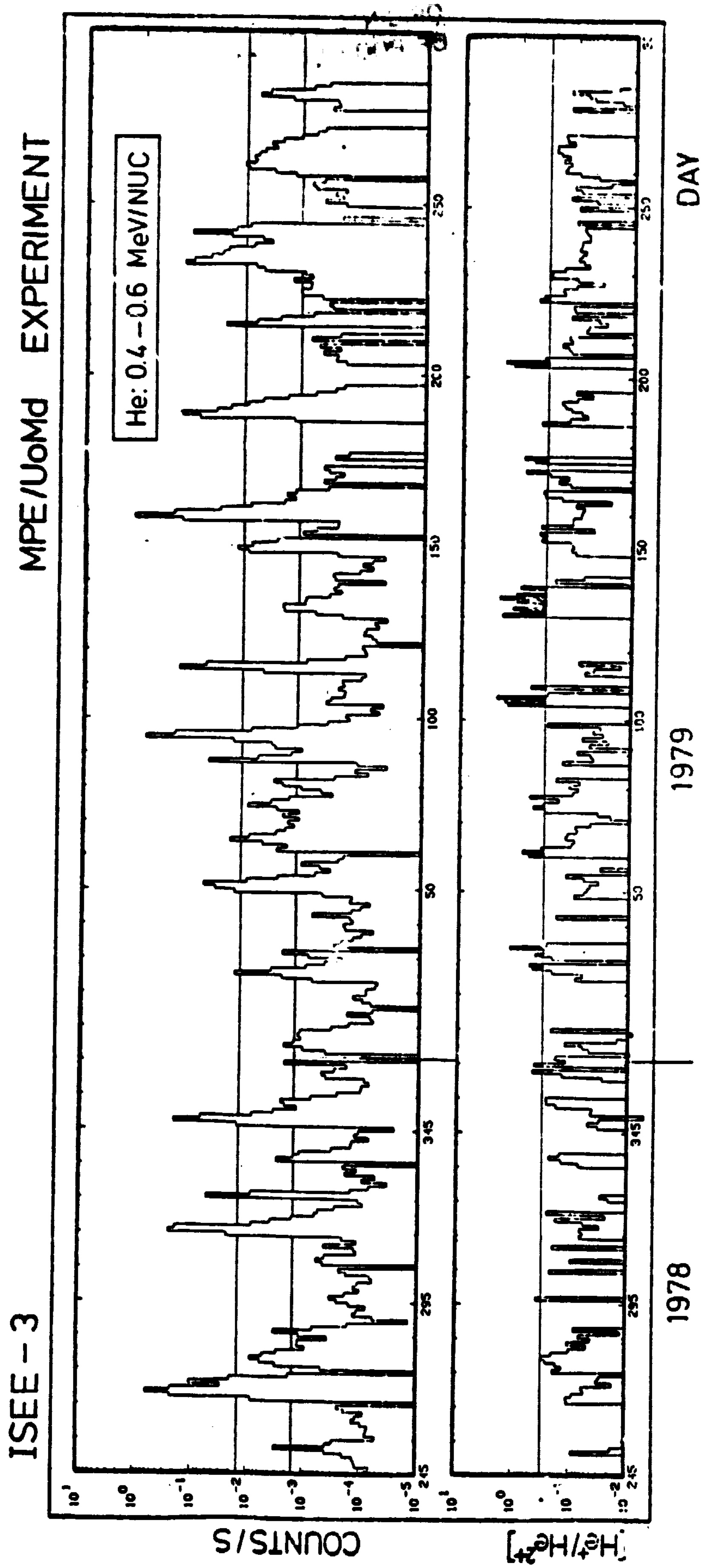


Figure 10

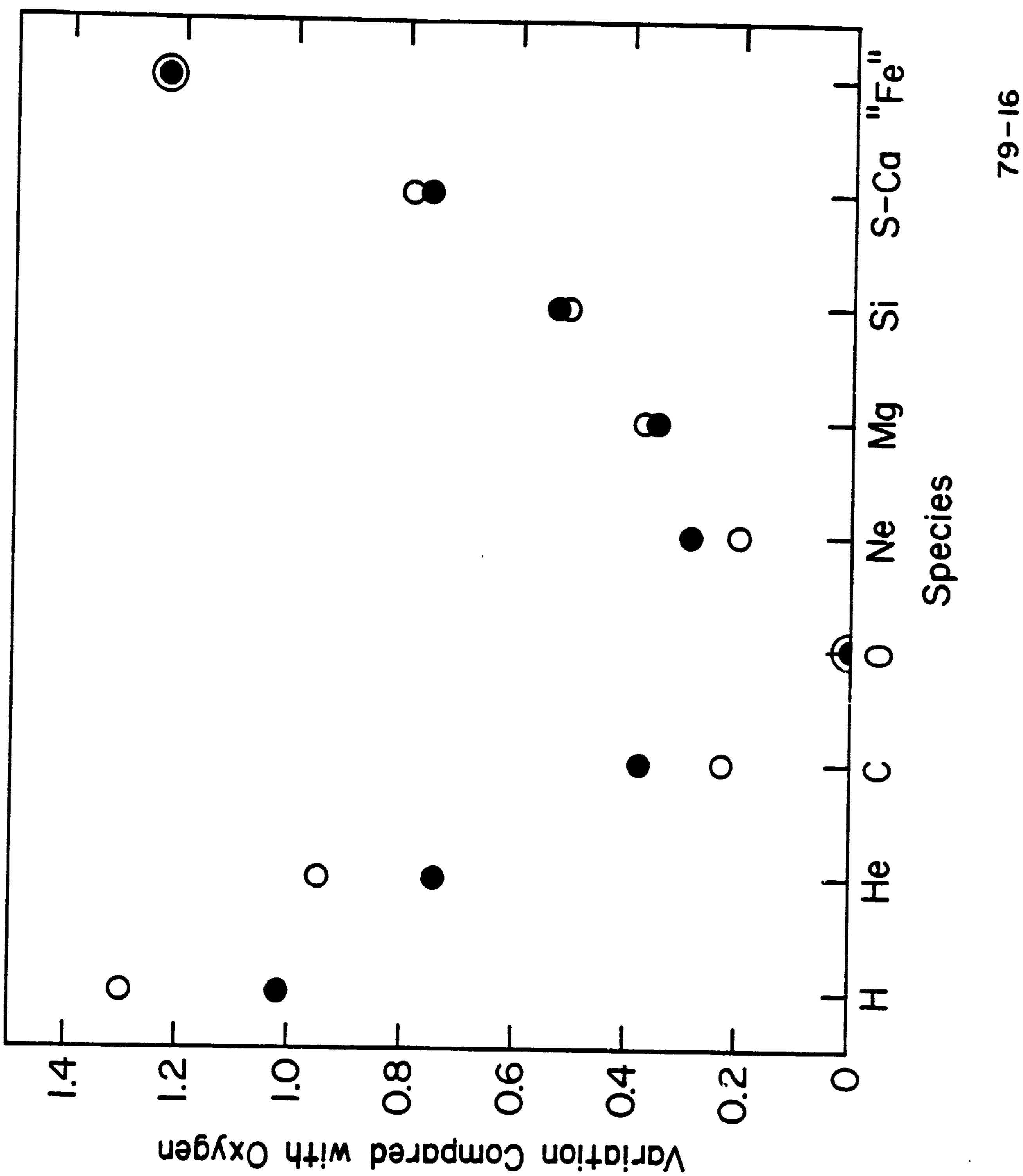

Variation Compared with Oxygen
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Species
H
He
C
O
Ne
Mg
Si
S-Ca
"Fe"
79-16

Figure 11

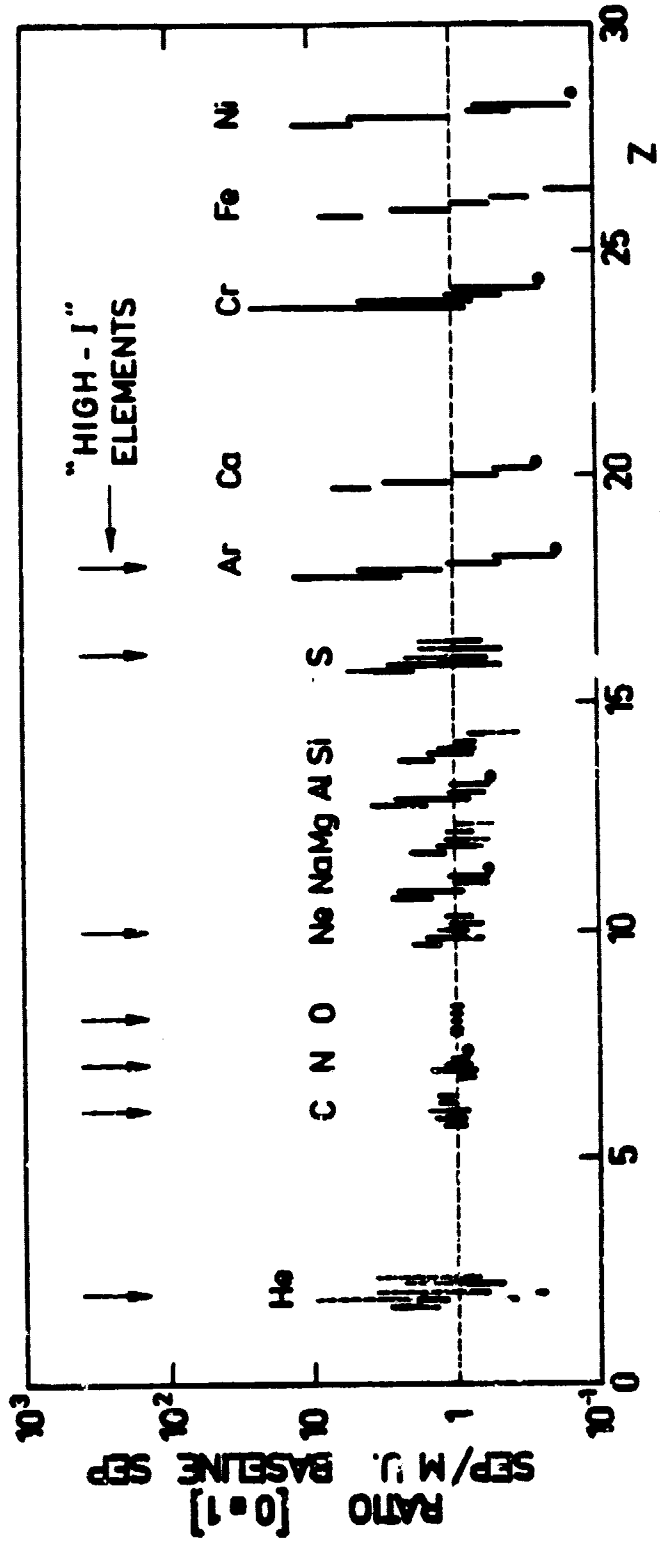
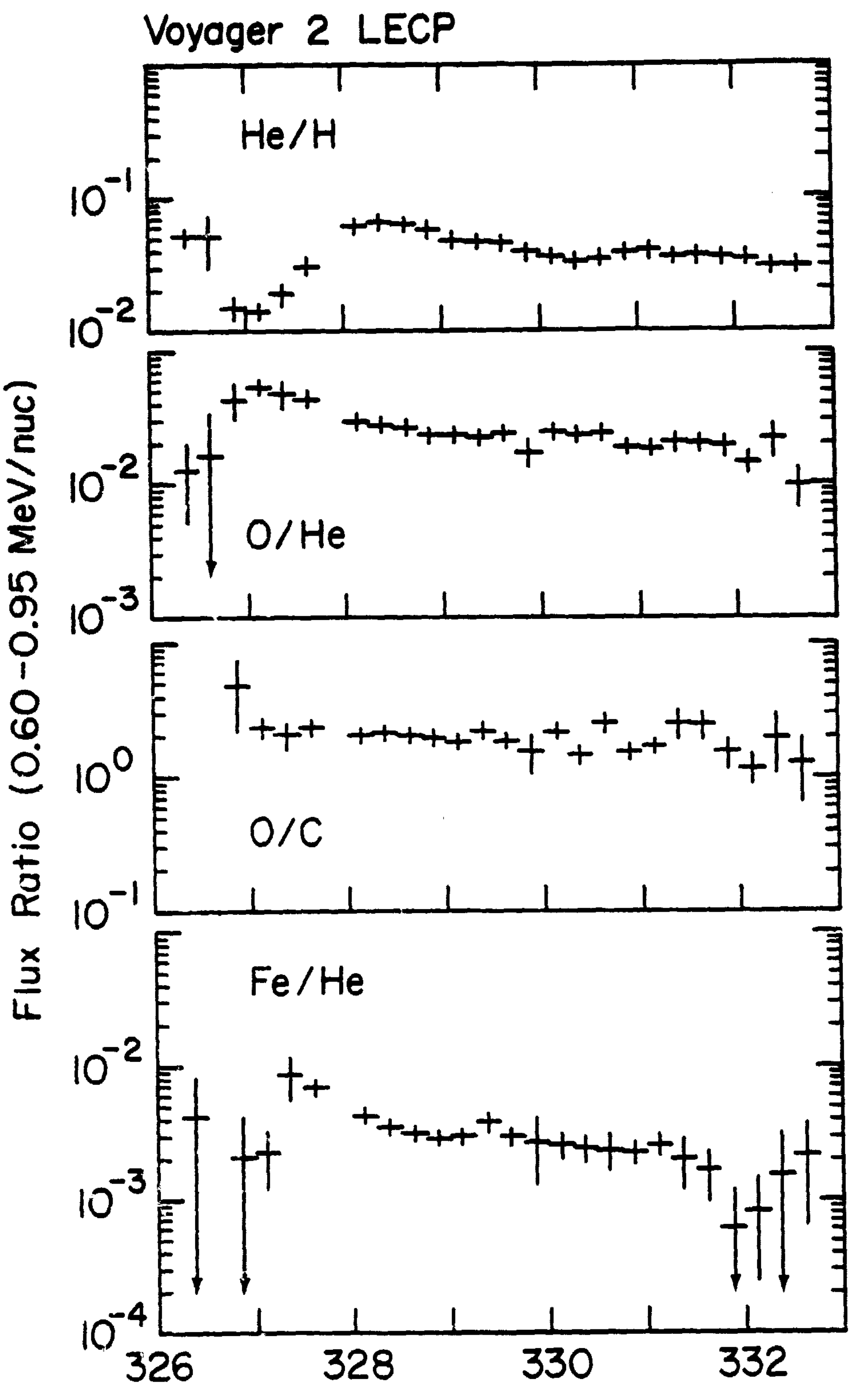
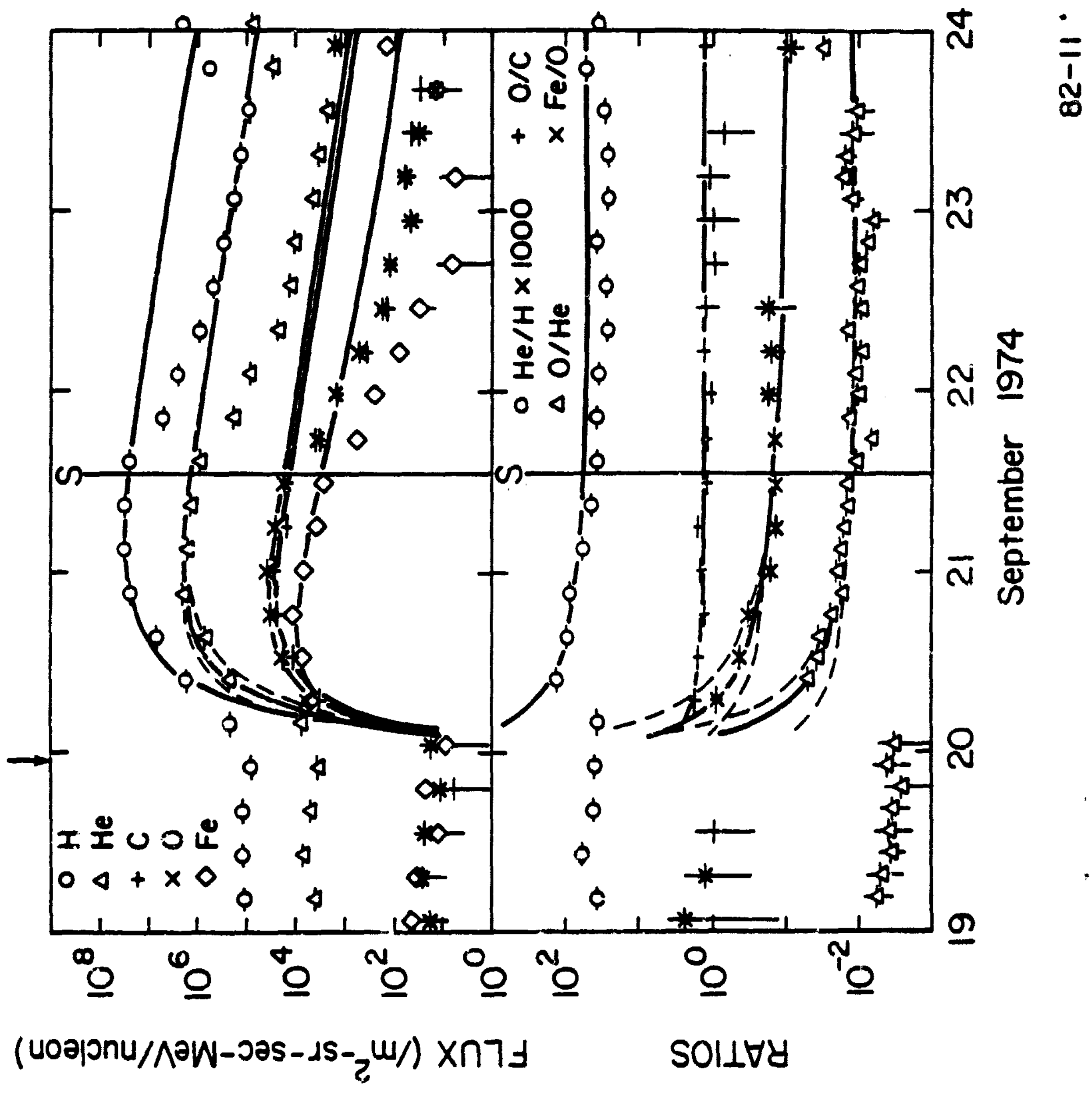

"HIGH - Z"
ELEMENTS
He
C N O
Ne NaMg Al Si
S
Ar Ca
Cr
Fe
Ni
Z
0
5
10
15
20
25
30
SEP/M.U. BASELINE SEP
RATIO [0=1]
10^3
10^2
10
1
10^-1

Figure 12


Voyager 2 LECP
He/H
O/He
O/C
Fe/He
Flux Ratio (0.60-0.95 MeV/nuc)
10^{-1}
10^{-2}
10^{-3}
10^{0}
10^{-4}
326
328
330
332
Day of 1977

81-64

ORIGINAL PAGE IS OF POOR QUALITY



82-11

Figure 14

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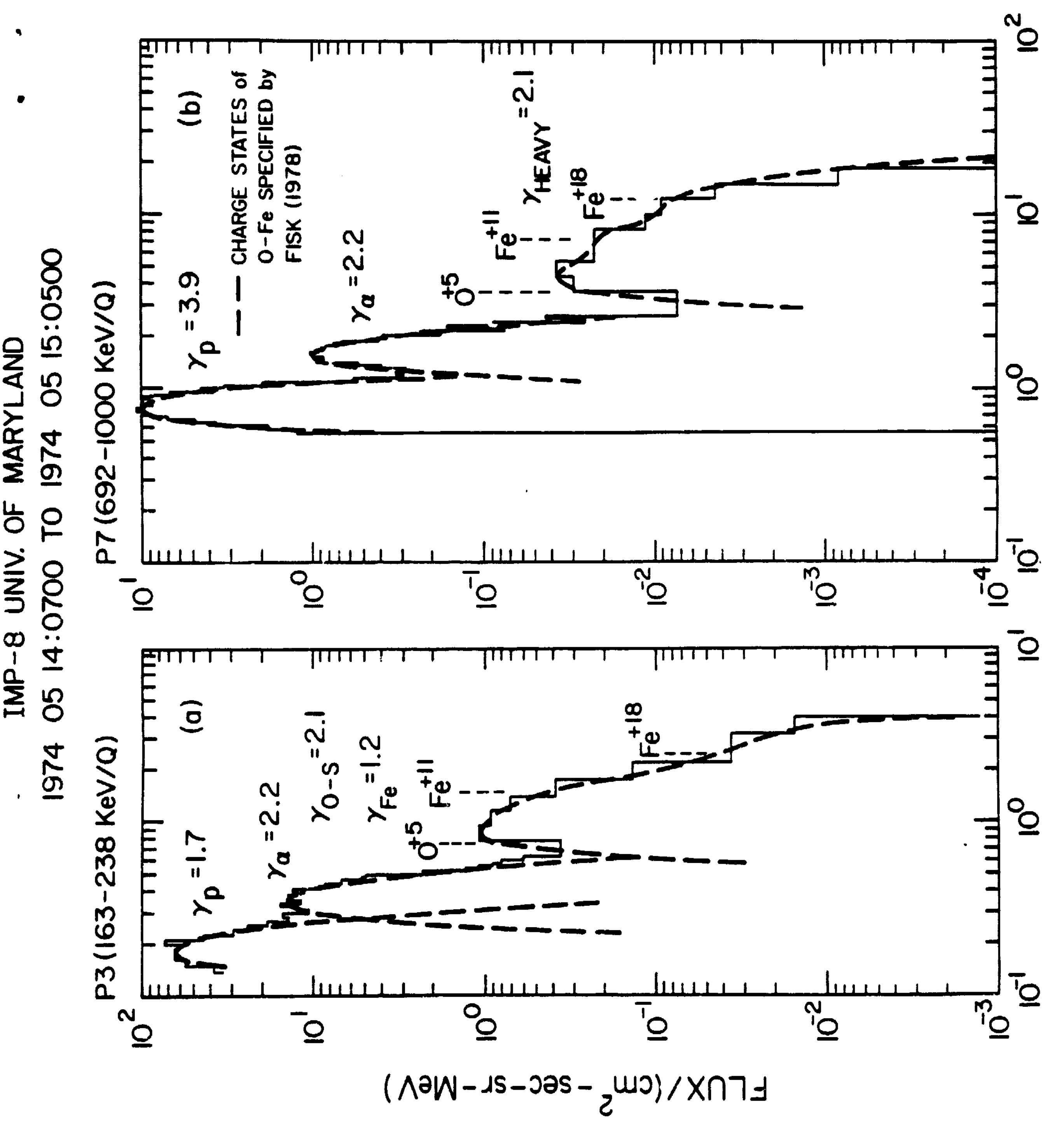

Figure 15

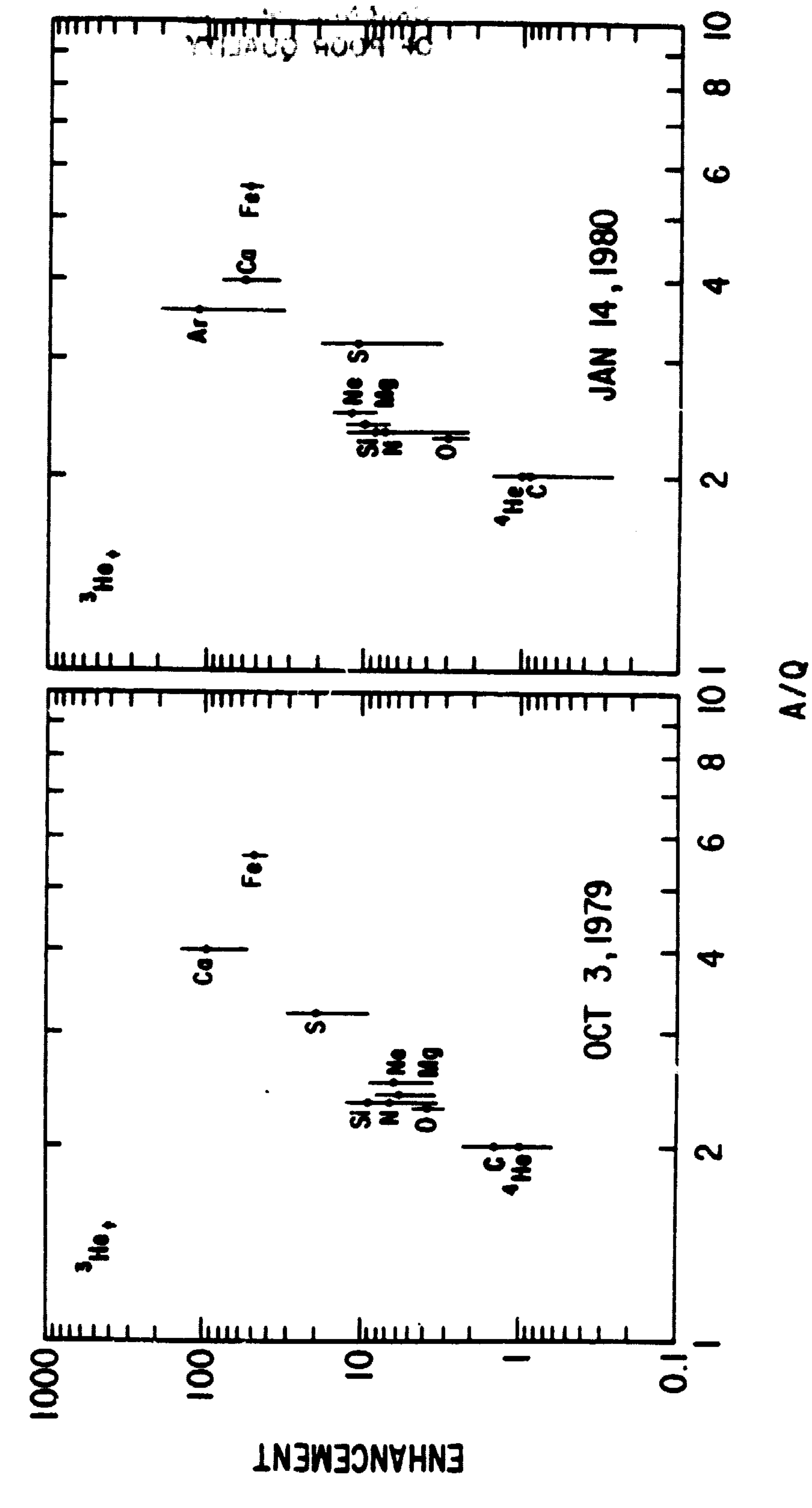
ENHANCEMENT
A/Q
JAN 14, 1980
OCT 3, 1979
1000
100
10
1
0.1
1
2
4
6
8
10
^{3}He
^{4}He
C
N
O
Ne
Mg
Si
S
Ar
Ca
Fe

Figure 16