Charge States and Energy-Dependent Composition of Solar-Flare Particles*

D. Braddy, J. Chan, and P. B. Price†
Department of Physics, University of California, Berkeley, California 94720
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During a weak solar flare, energy spectra of He, O, and Fe from 0.2 to ~30 MeV per nucleon were measured with glass and plastic detectors exposed on the Apollo 16 spacecraft. The spectra were very steep and the abundance ratios Fe/O and O/He decreased rapidly with energy, approaching solar atmospheric ratios at energies above ~5 MeV per nucleon. The shapes of the rigidity spectra suggest that the ions were completely stripped while being accelerated.

Results of several recent experiments have indicated that heavy nuclei are present in higher than solar proportions in low-energy solar-flare particles.[1-6] Until now the regime of charge or energy studied with a given detector has been limited, and various assumptions have had to be made in order to infer a heavy-element enhancement.[7] Further, it has not been possible with electronic detectors on satellites to identify heavy particles at energies below a few MeV per nucleon. This is a region where interesting peculiarities in composition might be expected, because at low energies ions in charge equilibrium should have charge/mass ratios that vary with charge and velocity.

In the lunar-surface cosmic-ray experiment[8] on Apollo 16 we have been able to measure fluxes of solar particles covering 9 orders of magnitude of intensity and to identify major elements from He to Fe at energies down to 0.2 MeV per nucleon that originated in the flare on 17 April 1972. Our results provide decisive evidence that the composition of solar-flare particles changes with energy, with the Fe/O and O/He ratios smoothly decreasing with energy.

Silica glass was used to record tracks of nuclei with $Z \gtrsim 18$, about 90% of which were left by Fe nuclei. The glass was etched sequentially from 1 to 12 h in a 5%-HF solution. Plastic replicas of the surface were made after each hour and examined by optical and scanning electron microscopy. For calibration, control samples were bombarded with Ar, Ti, Fe, and Kr ions of 2 to 10 MeV per nucleon and processed together with the actual detector. Atomic numbers and energies were determined from shapes and sizes of replicated etch pits.

Multilayer stacks of Lexan were used to record tracks of nuclei with $Z > 1$. A three-stage process consisting of a NaOH etch, ultraviolet irradiation, and a re-etch[9] produced tracks whose geometry allowed atomic numbers and energies to be determined. To permit a continuous sampling of He tracks at energies below 1 MeV per

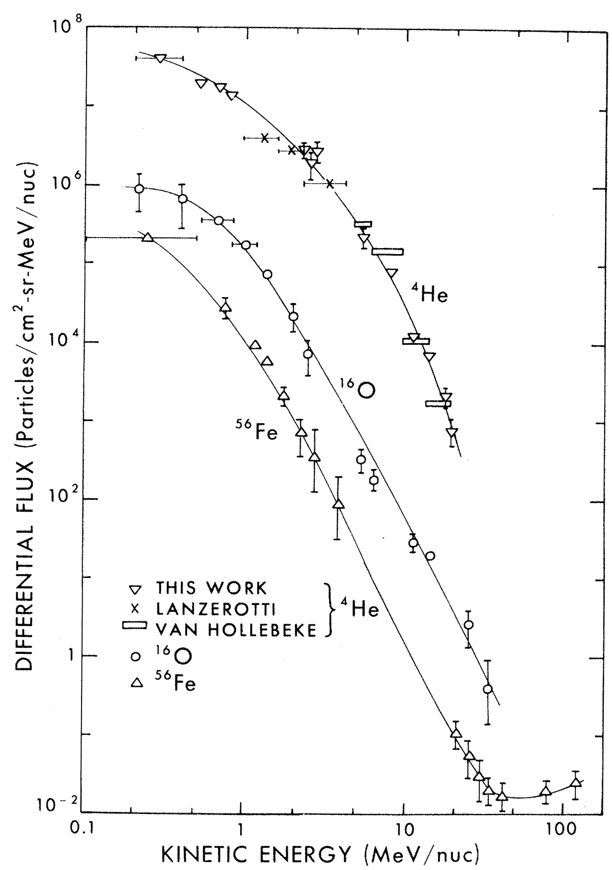

FIG. 1. Energy spectra of He, O, and Fe summed over the week of 16 to 23 April 1972 during which a weak flare occurred. The α particle data of Lanzerotti and of van Hollebeke were obtained with electronic detectors on satellites. To get the average flux per second for the flare particles, divide the ordinate by 8×10^4 sec. (The flare lasted about 1 day.) To get the flux per second for the Fe nuclei of energy greater than ~40 MeV per nucleon, divide the ordinate by 6×10^5 sec. (Being galactic in origin, they entered the detector during the entire collecting interval of 167 h.)

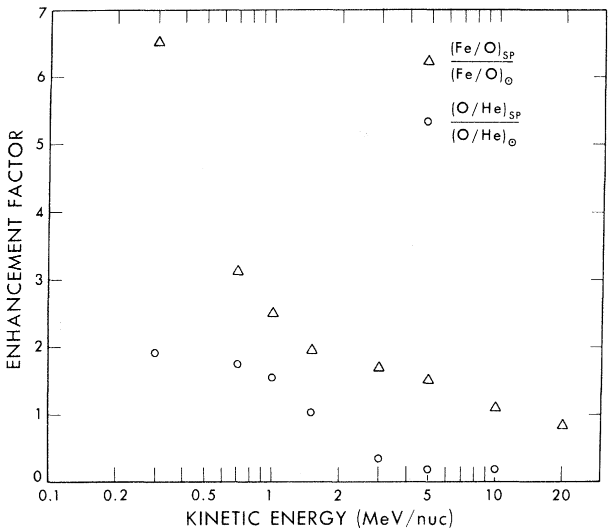

FIG. 2. Ratios of Fe/O and O/He as a function of energy. The ratios are normalized to solar abundances assumed to have the proportions He:O:Fe = 92:1:0.03. The absolute level of the ratios is uncertain by a multiplicative factor of ~ ±1.5.

nucleon, the top Lexan sheet was embedded in epoxy, ground at a shallow angle, then exposed to uv radiation and etched.

Figure 1 shows the energy spectra of the three abundant elements He, O, and Fe integrated over the flare. Unpublished He data of Lanzerotti and of van Hollebeke for the same flare are included for comparison. The agreement is excellent. The rapid change of composition with energy is plotted in Fig. 2. At energies above ~ 5 MeV per nucleon the He:O:Fe ratio is ~ 125:1:0.03, which is not significantly different from current estimates of the photospheric abundances.

These results compel us to reassess the notion[10] that chemical abundances of solar-flare particles mirror the composition of the solar atmosphere. It may be reasonably safe to assume that solar abundance ratios of elements with nearly the same Z can be inferred from solar-particle abundances at the highest energies for which data exist. Examples of interest to the astronomer would be the ratios Ne/Mg and Ar/Si, because spectroscopic data for Ne and Ar in the photosphere do not exist. However, until we have a satisfactory theory that accounts for heavy-element enhancements at low energies, we must be cautious about equating the entire abundance pattern of solar particles from He to Fe to the pattern in the sun. Possibly this equality holds for long-term averages at high energies.

We turn now to the question of the charge states of the solar-flare particles. Figure 3 shows the rigidity spectra of He, O, and Fe, computed from the data in two ways: (a) assuming the ions were completely stripped, using $R = m_p c^2 \beta (A/Z)/e$,

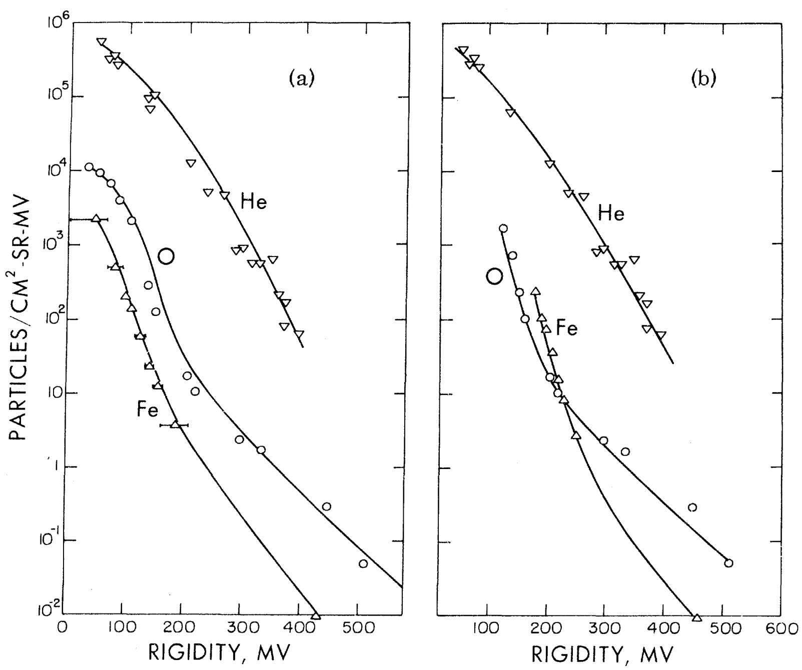

FIG. 3. Rigidity spectra for He, O, and Fe ions, computed (a) assuming fully stripped nuclei, and (b) assuming ions in charge equilibrium given by Eq. (1).

with βc the velocity and m_p the mass of a nucleon; and (b) assuming the ions had passed through enough matter to be in charge equilibrium, with Ze replaced by the effective charge Z^*e, using the semiempirical expression[11]

$$Z^* = Z[1 - 1.032 \exp(-137\beta/Z^{0.69})]. \qquad (1)$$

The shapes of the rigidity spectra computed in Fig. 3 depend strongly on the charge/mass ratios of the ions. The glass and Lexan detectors measure ionization rate and range, both of which are independent of the incident-ion's initial charge state, which will approach an equilibrium value given by (1) as soon as it has penetrated a few hundred angstroms of detector thickness. Though we cannot offer a convincing proof, it seems to us far more likely that the acceleration mechanism leads to rigidity spectra that are nearly parallel, as in Fig. 2(a), rather than to rigidity spectra that intersect and signify enormous heavy-ion enhancements at low rigidity, as in Fig. 2(b).

We therefore suggest that the ions were completely stripped of their electrons while being accelerated, at least in the final stage during which their rigidity spectra were being established. A suitable stripping mechanism would appear to be impact ionization by multi-keV electrons, whose presence in the flash phase of a flare is inferred from x-ray observations.

None of the existing models for preferential acceleration of heavy ions[1,12-15] can account for the strongly increasing abundance of heavy ions with decreasing energy, subject to the constraint that the ions were probably completely stripped while being accelerated. Perhaps we should consider differences in the behavior of light and heavy nuclei that do not depend on their charge/mass ratio. Two examples of such a difference are a Maxwellian distribution for which the most probable velocity scales as $A^{-1/2}$, and nuclear Coulomb scattering in a gas, for which the cross section has a complicated dependence on Z and A. The latter may be attractive in view of the recent evidence from He isotope studies[16] that flare particles may pass through several grams per square centimeter of gas while being accelerated.

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†Miller Institute Professor, 1972–1973.

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