Composition of the September 2, 1966 solar particle event[1]

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Three Nike-Apache sounding rockets were launched from Fort Churchill, Manitoba, Canada to study the composition and the characteristics of the September 2, 1966 solar flare event. These launches occurred approximately 9, 16, and 36 hours following the event. Nuclear emulsions were used to study all the components, namely, the singly, doubly, and multiply charged nuclei emitted in the solar event and propagated within the solar system. The helium nuclei were separated from protons by using grain density and range measurements and from multiply charged nuclei by δ-ray density and range measurements. The multiply charged nuclei were identified as to charge from δ-ray density and range measurements. The energies of these nuclei were determined mainly from their residual range in the emulsion. The energy spectra measured in the event are much steeper than those reported for events in which the composition studies were made previously. The measured ratio of helium to medium (C, N, O,F) nuclei for energies above 12.7 MeV/nucleon in the first flight is 54 ± 8 to 1. This value is in agreement with the previous measurements, which strongly supports the ideas held that the acceleration mechanism does not appreciably alter the spectroscopically observed abundance of the solar photosphere.

INTRODUCTION

Detailed observations on the charge composition of the solar particles emitted in solar flares were made during the years 1960 and 1961, a period close to the solar maximum, with nuclear emulsion detectors flown in balloons and rockets (see Biswas and Fichtel (1965) for a summary of experimental information). These studies have indicated that (1) the heavy nuclei may be present in every solar particle event, but in most events there were just too few to be detected; (2) the relative abundances of the heavy nuclei ($Z \geqslant 3$) of the same charge-to-mass ratio ($Z/A \sim 0.5$) are independent of the event, whereas the ratio of protons to helium nuclei varied appreciably in the same energy interval from event to event and with energy in an event; and (3) the abundances of multiply charged nuclei thus deduced are similar to that of the sun's photosphere. This last feature is clearly sufficiently interesting, in terms of both solar composition and particle acceleration in astrophysical situations, that it is well worth determining whether the results suggested in these early experiments based on a few events will be consistent with measurements made in other solar events near solar minimum and in the next solar cycle. Further, it will be useful to make detailed measurements on the charge composition, whenever possible. With this in mind, a standby sounding rocket program was begun at Fort Churchill, Canada in 1966. The present paper describes the results obtained during September 1966 from the solar-flare-emitted particles recorded in the nuclear emulsion detectors.

EXPERIMENTAL DETAILS

Three packs of Ilford G5 emulsion detectors were used in each payload section of the rocket; two packs were mounted on the sides and are herein referred to as "side packs"; the third pack was mounted at the bottom and is referred to as the "bottom pack". Each of the side packs consisted of one 200-μ-thick and twenty 600-μ-thick emulsions of size 14.5 cm $\times$ 12.5 cm. The 200-μ-thick emulsion was mechanically positioned at the time of the exposure. The bottom pack consisted of 40 pellicles of 600-μ-thick emulsions, of size 27 cm $\times$ 14 cm. All the side packs and 20 of the 40 emulsions in the bottom pack were normally developed; the remaining 20 emulsions were underdeveloped.

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Three such payloads were fired in three Nike-Apache sounding rockets at times of 14:40 h U.T. and 22:30 h U.T. on September 2, 1966 and at 17:30 h U.T. on September 3, 1966, approximately 9, 17, and 36 hours following the class 3 flare observed at 05:38 h U.T. on September 2, 1966. These three flights will be herein referred to as first, second, and third flights respectively. The nose cone of the rocket was opened, in each of these flights, to such an extent that the emulsion detectors were exposed directly to the incident particles. Nuclei that have an equivalent range of 0.26 g/cm^2 of emulsion could be thus recorded in the detectors; this corresponds to a minimum detectable energy of about 3 MeV for protons.

Energetic protons and helium and heavy nuclei were recorded in the side and bottom packs. The charge and energy spectra were obtained for all the components in the three flights. The general experimental procedures are somewhat similar to those adopted by Biswas *et al.* (1962); hence we shall describe them only briefly here.

1. *Protons.* The energy spectrum of protons was obtained in the energy region 3–10 MeV from the main scan of the side pack under 100 × 20 magnification; the protons could be separated visually from the heavy nuclei. The energy of protons was obtained from a measurement of particle range using the range–energy relation given by Barkas (1963). The proton energy spectrum was extended to the higher energy of ~70 MeV by making the integral counts of tracks on scans made at distances of 500 μ, 1 mm, 2 mm, 5 mm, and 2 cm away from the side edges of the bottom stack. The integral energy spectrum of protons in the energy region 3–70 MeV was then obtained by combining the differential spectrum data with these measurements.

2. *Helium nuclei.* The energy spectrum of helium nuclei was obtained in the region 7–50 MeV/nucleon from scans made under 53 × 20 magnification at distances of 600 μ and 2 mm from the edge of the bottom stack. The helium nuclei were separated from protons by range vs. grain density measurements, and their energies were estimated from their residual ranges.

3. *Heavy nuclei.* The scan was made for heavy nuclei under 22 × 20 magnification for tracks of length greater than 224 μ and entering the stack from the upper hemisphere. These were then followed through the stack until they were brought to rest. The charge identification was made from the observed variation of δ-ray density with range. The calibration curves were obtained from well-identified stopping nuclei recorded in stacks flown in an Aerobee rocket, and having the same ionization characteristics as the present stack. Because of the limitation of the experimental technique and the very short range of tracks involved, it is not possible to resolve the charges of the neighboring nuclei unambiguously, and we have used in our analysis only charge groups He, medium (C, N, O, F), and heavy ($Z \geqslant 10$) nuclei. The results of the medium and helium nuclei are quoted here in further analysis. The energies of the medium nuclei were obtained from the measured charge and range of the nucleus.

EXPERIMENTAL RESULTS

(a) Energy Spectrum

The differential and integral energy spectra of protons have been measured in all the three flights in the energy range 3–70 MeV. Similar measurements were made for helium nuclei in the first flight in the energy region 7–50 MeV/nucleon. The differential spectra of the nuclei are shown in Fig. 1. From these figures, a general observation can be made that the energy spectra become steeper with time, there being relatively more low-energy particles compared with higher-energy ones later in the event. These energy spectra are normally represented as power laws in total energy per nucleon or in rigidity, and in some events it was observed that a simple representation like $dJ/dR = ke^{-R/R_0}$ (Freier and Webber 1963) would fit the experimental data well; where dJ/dR is the differential intensity of protons, R is the particle rigidity, and k and R_0 are constants. For the first flight the data are available for protons and helium nuclei, and their rigidity spectra are shown in Fig. 2. It can be seen that down to 200 MV, the rigidity spectra are similar.

The integral spectra of medium nuclei were measured in all three flights. It was found that these spectra are similar to that of the helium nuclei, where measurements are available, and

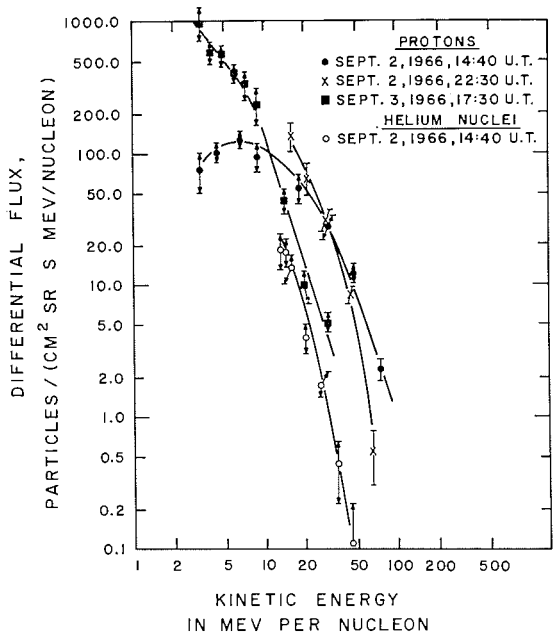

FIG. 1. Differential energy spectra of protons measured in three flights and of helium nuclei in the first flight.

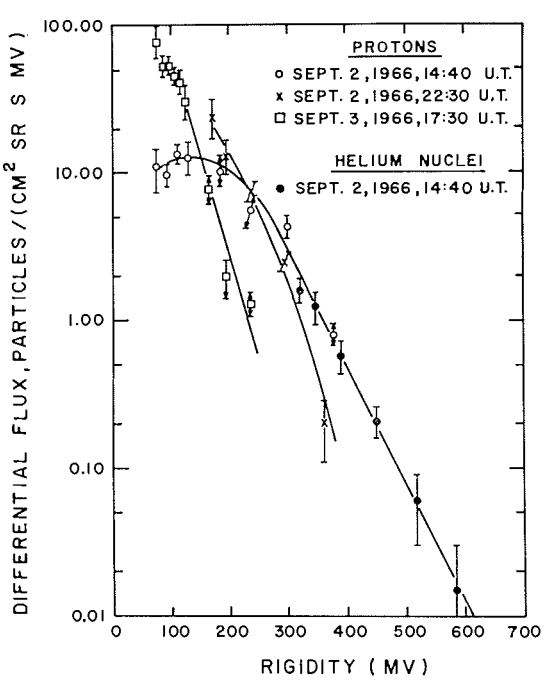

FIG. 2. Differential rigidity spectra of protons measured in the three flights and of helium nuclei in the first flight.

fall on the same curve when multiplied by a factor of 60. Since all of the medium nuclei that occur in detectable amounts have the same charge-to-mass ratio as ^{4}He, the rigidity spectra of these nuclear species are also the same in shape, assuming, of course, then that these nuclei have been completely stripped of their electrons.

(b) Ratios

1. *Ratio of protons to helium nuclei.* Of particular interest in the study of propagation characteristics is the ratio of protons to helium nuclei as a function of time in the event, for these particles have the same energy for different values of rigidity. Although the proton and helium nuclei spectra seem similar when expressed in rigidity (at least up to about 200 MV), the proton to helium nuclei ratio in the same rigidity interval varied from 1 to 50 in different events and by as much as 5 late in an event (Freier and Webber 1963; Biswas and Fichtel 1965), indicating that the variation is at least a propagation effect, although large variations within an event are probably not common. A summary of proton to helium nuclei ratios observed in these events is given

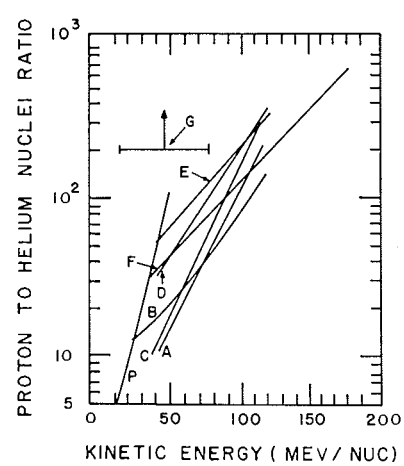

FIG. 3. Ratio of protons to helium nuclei as a function of kinetic energy per nucleon at different times in several events. The events in which the measurements were made are: A and B—November 12, 1960 (Biswas *et al.* 1962); C, D, and E—November 15, 1960 (Biswas *et al.* 1963); F—September 3, 1960 (Biswas and Fichtel 1964); G—March 16, 1964 and February 5, 1965 (McDonald *et al.* 1965); P—present work.

in Fig. 3, together with the value measured in the present experiment in the first flight.

2. *Ratio of helium nuclei to medium nuclei.* The ratio of helium to medium nuclei in the same energy per nucleon interval and hence in similar rigidity intervals was found to be constant in the events observed earlier and had a mean value of 60 ± 7 to 1 in the interval of energies 42.5–95.0 MeV/nucleon. The measured value deduced in the present experiment for this ratio for energies above 12.7 MeV/nucleon in the first flight is 54 ± 8 to 1. This value is thus in agreement with the previous measurements and strongly supports the idea held that the acceleration mechanism of solar cosmic rays does not appreciably alter the observed abundance of the solar photosphere.

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