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GREENBELT, MARYLAND

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ABSTRACT

Heavy nuclei ($Z \geq 3$) were detected in the September 2, 1966 solar particle event. This brings to five the number of events in which these particles have been detected. The proton energy spectrum was measured down to energies as low as 3 MeV and up to energies as high as 100 MeV, with measurements on the helium and heavier nuclei covering a more restricted range. The relative abundances of helium, light, medium, and heavy nuclei obtained in this experiment in the energy range from about 14 to 35 MV nucleon agree with those measured in previous solar particle events at higher energies and hence with those of the solar photosphere. This result strengthens the concept of a

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**The untimely death of Dr. Guss, who made a major contribution to the success of this program, prevented his participation in the final analysis.

multi-charged nuclear composition which is a characteristic of solar particle events. The proton spectrum agrees with an exponential rigidity spectrum above 250 MV, but shows sharp deviations below 250 MV early in the event. An examination of the relative abundances of protons and medium nuclei shows that the propagation of solar particles in this event cannot be described by a simple diffusion model with a diffusion coefficient proportional to β or βR.

INTRODUCTION

The sun is now known to be a frequent emitter of energetic solar protons and alpha particles. Although nuclei with charges greater than two are rare, they have also been observed every time the intensity of an event was sufficiently great to expect to be able to detect them on the basis of their abundance in other events. Before the measurement to be reported here on the September 2, 1966 solar particle event, heavy nuclei (nuclear charge ≥ 3) had been seen four times, in the events of September 3, 1960 (Fichtel and Guss, 1961), November 12, 1960 (Biswas, Fichtel and Guss, 1962; Ney and Stein, 1962; Yagoda, Filz, Fukui, 1961; Pomerantz and Witten, 1962), November 15, 1960 (Ney and Stein, 1962; Yagoda, Filz and Fukui, 1961; Pomerantz and Witten, 1962; Biswas, Fichtel, Guss and Waddington, 1963) and July 18, 1961 (Biswas, Fichtel and Guss, 1966). Upper limits have been set in other events (Biswas, 1961) and also there have been reported increases in the flux of heavy nuclei apparently unassociated with major flares (Kurnosova, Razorenov and Fradkin, 1962). An interesting result of the early measurements was that the multi-charged nuclei with the same charge to mass ratio appeared to have the same composition each time that it could be determined. Further, the composition seemed to reflect that of the sun's photosphere in so far as measurements could be made. The helium and heavier nuclei, having a charge to mass ratio which is half that of the proton, can also be used to study solar particle propagation in the interplanetary medium by comparing their abundance to that of the protons as a function of time.

In an attempt to expand our knowledge of the charge composition of the nucleonic component of the solar cosmic radiation and make further studies on the solar particle propagation characteristics, SPICE (Solar Particle Intensity and Composition Experiment) was undertaken. The program is similar to the one undertaken in 1960 which led to the measurements of the relative abundances of the solar particle events in 1960 (Fichtel and Guss, 1961; Biswas, Fichtel and Guss, 1962; Biswas, Fichtel, Guss and Waddington, 1963). Scientific sounding rockets were placed on stand-by at Fort Churchill in July, 1966 to be shot into a solar particle event, when one of sufficient intensity occurred. The first such event occurred on September 2, 1966.

This event was associated with a flare that began about 0538 U.T. on September 2, 1966, reached a maximum about 0600 U.T. and ended at about 930 U.T. It was reported as a 2B by Manilla and a 3B by Anacapri (Italy). The flare occurred at N23 W55 on the sun, and therefore was at a position on the sun which was quite favorable for efficient propagation of particles from the sun to the earth along the roughly spiral interplanetary magnetic field lines. Three sounding rockets were fired into the event at the times given in Table I, which also gives the approximate time from the maximum of the flare.

Table I

Flight	Time at Peak Altitude	Time from Flare Maximum
1	1443 U.T. Sept. 2, 1966	8.7 hours
2	2233 U.T. Sept. 2, 1966	16.5 hours
3	1733 U.T. Sept. 3, 1966	35.5 hours

This paper is aimed at a description of the results obtained in this event and a discussion of their relation to the study of the solar particle phenomena mentioned above. This treatment will be preceeded by a brief description of the SPICE payload and the data analysis techniques.

EXPERIMENTAL PROCEDURE

The nuclear emulsion stacks flown in this experiment were located beneath the nose cone in the payload section of the

Nike-Apache sounding rocket. The nose cone was extended to expose the stacks after the vehicle left the atmosphere and was retracted prior to reentry. The duration of this exposure was approximately 250 sec; the extend and retract operation each took about 5 sec.

Two of the emulsion stacks were mounted on the sides of the vehicle with the emulsion face outward so that particles entered normal to the emulsion surface. These stacks consisted of a single 200 μ pellicle and a lower section of twenty 600 μ pellicles, each of which was 6.4 cm x 7.1 cm in area. As the nose cone extended and retracted the lower section was displaced beneath the upper pellicle so that particles entering during the exposure could be unambiguously isolated.

A third large stack of forty 7.1 cm x 13.8 cm x 600 μ pellicles was located farther down the rocket axis with the normal to the emulsion surfaces along the direction of flight. The long dimension of the stack was approximately equal to the vehicle diameter so that particles could be observed entering the pellicle edges at either end of the stack. This stack was used to observe the high-energy portion of the particle spectra.

Ilford G5 emulsion was used throughout. Twenty pellicles in the lower stack were underprocessed, however, to improve the grain-density descrimination between singly-and doubly-charged particles.

The amount of material that intervened between the particle and the emulsion surface was 0.26 gm/cm^2 (emulsion equivalent); this thickness determined the minimum detectable energy which was 3 MeV for protons.

Proton spectra were obtained by making range measurements at low energies ($\lesssim$12 MeV) and from integral flux counts at various depths in the stacks at higher energies. Helium nuclei were resolved from protons by measurements of grain density vs residual range. Heavier particles were resolved by counts of δ-rays vs range using a technique which has been described previously (Reames and Fichtel, 1966). Owing to the very steep spectra in this event the residual range of the heavy particles were too short to allow clear resolution of individual charges above Z=6.

RESULTS AND INTERPRETATION

The experimental results can be best understood by first presenting the energy spectrum of the various components during the three flights. A study of the energy spectrum is necessary background for the discussion of the composition and provides the basis for the considerations of solar particle propagation. Therefore, this section will be divided into three parts which will consider energy spectra, composition, and propagation.

(a) Energy Spectra: In order to see the proton intensity level clearly and at the same time to observe the general variation of the energy spectra during the event, the three integral spectra for protons are shown in Fig. 1. The intensity at low energies is large, with the flux between 3 and 15 MeV being in excess of 10^3 protons /(cm^2 sr. sec.) for all three flights, but above 100 MeV it is quite small, of the order of 10 protons /(cm^2. sr. sec.) or less. The helium and medium nuclei also have steep energy/nucleon spectra as shown in Fig. 2. The helium and medium nuclei spectra are even much steeper than the proton spectrum, as shown in Fig. 3. The integral medium nuclei spectrum in the two other exposures are similar to the first one in their being significantly steeper than the proton spectrum. They are all then steeper than the previous solar flare particle events for which composition data exists, namely Sept. 3, 1960; Nov. 12, 1960; Nov. 15, 1960; and July 18, 1961.

Returning specifically to the proton spectral data, there are several features worth noting. The spectra reflect the now well established tendency for the particles of lowest energy to rise to their maximum and subside most slowly. This feature can best be shown by looking at the differential spectra. Since it is also desirable to discuss the rigidity spectra, the differential-rigidity spectra rather than the differential-energy spectra will be used. Fig. 4 shows that the highest rigidity particles ($\gtrsim$ 250 MV) decrease with increasing time from the flare. At intermediate rigidities (about 150 to 200 MV), the intensity was still increasing during the period from the first to second flight, but shows a decline from the second to the third flight. Below 120 MV, there is a progressive increase in particle intensity with time from the flare, with the exposure about 36 hours after the flare showing the maximum intensity.

It is also clear from the data shown in Fig. 4 that, although the spectra could be well represented by the form

$$J = A(t) \exp[-R/R_0(t)] \qquad (1)$$

for rigidities above 250 MV in the first two exposures and by this form over most of the measured range in the third flight, there are marked deviations from this expression at low rigidities in the first and second flights. These results then clearly demonstrate that although solar proton spectra may often be represented by the form of equation (1), and it is extremely useful in working with solar particle data, as originally suggested by Freier and Webber (1963), this form does not apply early in events at low rigidities. Deviations from exponential rigidity spectra have also been observed in several other events previously (Bryant, Cline, Desai and McDonald, 1963, 1965).

Fig. 4 shows that over the small region of overlap the shape of the rigidity spectra of the hydrogen and heavier nuclei are similar. Application of the form of equation (1) to the observed data and using the least squares fit method gives the values for R_o shown in Table II. There appears to be a variation of R_o with time which is different for protons

Table II

Flight	R_o of Protons	R_o of Helium Nuclei	R_o of Medium Nuclei
1	$66.7^{+4.8}_{-4.2}$	$69.0^{+2.9}_{-2.7}$	$64.1^{+3.3}_{-3.0}$
2	$50.3^{+5.7}_{-4.7}$		$62.9^{+3.6}_{-3.2}$
3	$38.8^{+6.7}_{-5.0}$		$56.2^{+6.6}_{-5.5}$

and medium nuclei, leading ultimately in the third flight to values which differ by three standard deviations. It has already been shown (Biswas and Fichtel, 1965) that the values of R_o for protons and heavier nuclei are not always exactly the same, although they are usually similar (Freier and Webber, 1963; Biswas and Fichtel, 1965).

The tendency of spectra toward the form of Eq. (1) especially late in events led Freier and Webber (1963) to suggest that the source spectra might be of this form. The electromagnetic spectrum (radio and visible) from at least one solar particle event has been shown by Stein and Ney (1963) to be in agreement with synchrotron radiation from electrons with an energy spectra of the form of Eq. (1) with R_0 values similar to those observed for the solar nuclei. It is possible to conceive of solar particle acceleration mechanisms which will give this type of spectrum and of a propagating mechanism which at least late in solar particle events would roughly preserve it. A review of the problems of acceleration and propagations is given elsewhere (Fichtel and McDonald, 1967).

Returning to Fig. 2, notice that when the differential spectra for medium nuclei are multiplied by 60, the average ratio of medium to helium nuclei in previous events (Biswas and Fichtel, 1965), the spectra agree with the helium nuclei spectral points within the errors. The reason for the limited data on helium nuclei is the high proton to helium ratio which makes the task of scanning for helium nuclei tracks in the nuclear emulsion, following the tracks to the end, and identifying them a long, tedious one. However, the fact that the normalizing factor for multiplying the medium nuclei spectra was selected from previous work makes the agreement quite significant, especially in view of the large variation from event to event of so many of the parameters associated with solar particle events.

(b) Nuclear Composition: One of the principal aims of the experimental series was to determine whether the composition of the multicharged nuclei is really the same in each event. The

September 2, 1966 event was one whose intensity was very great at low energies, but decreased quickly with increasing energy as mentioned before; therefore, it was possible to obtain considerable information at low energies/nucleon, but not at high energies where the ranges of the particles are sufficiently great to allow good charge identifications. The experimental approach described earlier permitted the detection and identification of medium nuclei down to about 7 MeV/nucleon, rather than about 35 MeV/nucleon as in the earlier experiments (Fichtel and Guss, 1961; Biswas, Fichtel and Guss, 1962; Biswas, Fichtel, Guss and Waddington, 1963; Biswas and Fichtel, 1965). However, individual charge identification was not possible at these low energies and at higher energies there were very few particles and exact charge identification is difficult even then due to the high background. Thus, although detailed charge measurements were not possible, the relative abundances of important charge groups, namely He, light nuclei, medium nuclei, and heavier nuclei, can be given.

Beginning with the helium to medium nuclei ratio, it was already shown that the energy spectra were similar and that the intensities appeared to be the same when the medium nuclei spectra were multiplied by the average ratio of helium to medium nuclei obtained in previous work. To make these statements more quantitative, the helium to medium nuclei ratios were found to be 48 $\pm$ 8 in the energy interval from 12 to 35 MeV/nucleon in the first flight and 53 $\pm$ 14 in the energy interval from 14 to 35 MeV/nucleon in the second. A summary of these and earlier measurements is given in Table III. The error quoted for the average value of all the measurements assumes that this represents measurements of the same number.

Table III Helium-to-Medium-Nuclei Ratio

Time of Measurements	Energy Interval MeV/nucl. (ΔE)	$\frac{He}{M}(\Delta E)$	Reference
1408 UT, Sept. 3, 1960	42.5-95	68 ± 21	Fichtel and Guss, 1961.
1840 UT, Nov. 12, 1960	42.5-95	63 ± 14	Biswas, Fichtel, and Guss, 1962.
1603 UT, Nov. 13, 1960	42.5-95	72 ± 16	Biswas, Fichtel, and Guss, 1962.
1951 UT, Nov. 16, 1960	42.5-95	61 ± 13	Biswas, Fichtel, Guss and Waddington, 1963.
0600 UT, Nov. 17, 1960	42.5-95	38 ± 10	Biswas, Fichtel, Guss and Waddington, 1963.
0339 UT, Nov. 18, 1960	42.5-95	53 ± 14	Biswas, Fichtel, Guss and Waddington, 1963.
1305-1918 UT, July 18, 1961	120-204	79 ± 16	Biswas, Fichtel, and Guss, 1966.
1443 UT, Sept. 2, 1966	12-35	48 ± 8	present work
2233 UT, Sept. 2, 1966	14-35	53 ± 14	present work
weighted average of above readings		(59 ± 5)	
1225-2345 UT, July 12, 1959	150-200	$\gtrsim 100 \pm 35$	Biswas, 1961
1030-1230 UT, Nov. 15, 1960	175-280	$\approx 100\ {}^{+100}_{-50}$	Ney and Stein, 1962.

There was no positive evidence for any light nuclei. A three-sigma upper limit for the ratio of nuclei of charges four and five to the medium nuclei is .04 which is in agreement with the previous more severe limit of .02 set in the November 1960 events. There is also no positive evidence for the presence of lithium nuclei, but in that case no number will be quoted for the upper limit since the exact efficiency for detecting these nuclei is difficult to determine. Since lithium is formed in the same general way as beryllium and boron if the latter is not present the former is not likely to be either. The absence of light nuclei at these very low energies is not surprising because they are absent in the source, and it is not likely that the solar cosmic rays have gone through much material before reaching the earth. Even if they have, the total probability for producing light nuclei below about 30 MeV/nucleon is fairly small. The reasons for believing that the energetic solar particles have passed through very little material include the absence of light nuclei at higher energies in other events (Biswas, Fichtel and Guss, 1962; Biswas, Fichtel, Guss and Waddington, 1963; Biswas and Fichtel, 1965), and the failure to observe any indication of a significant decrease in the slope of the energy spectrum of solar protons down to energies as low as 3 MeV- which is not clearly an early event propagation effect.

Because of the very steep energy spectrum very few nuclei with charges of ten or more could be clearly identified. Nonethe less, a neon to medium nuclei ratio above 38 MeV/Nucleon of $.12 \pm .04$ was determined where the quoted error reflects the charge identification problem as well as the statistical limitations. This agrees with the average value for previous events of $.08 \pm .02$ (Biswas and Fichtel, 1965). Some nuclei of clearly higher charges were observed particularly in the low scans as expected on the basis of the abundance of these elements in previous events, but charge identification difficulties, and hence the inability to make energy measurements and a flux determination in a given energy interval, make it impossible to quote a quantitative relative abundance for those nuclei.

Thus, although the detailed conclusions that can be reached on charge composition are limited, the fact that at least the gross feature of the composition of the multicharged nuclei are the same as previous measurements gives added confidence that it is meaningful to speak of a composition of multicharged nuclei in solar particle events. This feature is particularly remarkable in view of the large variations in so many of the other properties of solar particle events including size, energy spectra, relative abundances of electrons, protons, and helium nuclei, and time variations.

Recent spectroscopic results with improved accuracy have shown that the agreement between the spectroscopic measurements and the solar cosmic ray measurements of the composition of multicharged nuclei is still excellent even within the narrower limits set by the more recent results. Table IV summarizes these results.

Table IV

Element	Solar Cosmic Rays (1)	Solar Photosphere
^{2}He	107 ± 12	
^{3}Li		$<10^{-5}$ (2)
^{4}Be - ^{5}B	<0.02	$<10^{-5}$ (2)
^{6}C	$0.59 \pm .07$	0.60 ± 0.10 (3)
^{7}N	$0.19 {}^{+.04}_{-.07}$	$0.15 \pm .05$ (3)
^{8}O	1.0	1.0 (3)
^{9}F	<0.03	0.001 (2)
^{10}Ne	$0.13 \pm .02$	0.11 (4)
^{12}Mg	$.042 \pm .011$	0.051 ± 0.015 (5)
^{14}Si - ^{21}Sc	$.090 \pm .020$	$0.097 \pm 0.0.3$ (6)
^{22}Ti - ^{28}Ni	<0.02	0.006 (2)

1. Biswas, Fichtel and Guss, 1962; Biswas, Fichtel, Guss and Waddington, 1963; Biswas and Fichtel, 1965.
2. Goldberg, Muller and Aller, 1960; Aller, 1961.
3. Lambert, 1968.
4. Lambert, 1967.
5. Lambert and Warner, 1968a.
6. Lambert and Warner, 1968b.

(c) Propagation: The study of the time variation of the relative abundances of two nuclear species whose charge to mass ratios differ by a factor of two gives one a means of looking at the characteristics of solar particle propagation in terms of its possible velocity or rigidity dependence. These measurements are particularly pertinent in determining whether the diffusion coefficient in the solar wind diffusion model (Parker, 1956; Parker, 1963; Krimigis, 1965; Axford, 1965; Reid, 1964; Fibish and Abraham, 1965; Roelof, 1966) of solar particle propagation can be expressed with a simple velocity and rigidity dependence or if a more complex picture must be used. In general, the diffusion coefficient is the product of the particle velocity and some function of the particle rigidity which depends on the nature of the magnetic fields. In principle, this dependence on rigidity could be simply a constant, that is, propagation would be independent of particle rigidity. Evidence for this purely velocity dependent propagation mode has been seen in some events, e.g., November 12, 1960 (Biswas, Fichtel and Guss, 1962) and September 28, 1961 (Bryant, Cline, Desai and McDonald, 1965). Evidence in other events speaks against this simple mode. One of the best examples of an event which does not have this characteristic is the one under discussion here. Fig. 5 shows that the proton to medium nuclei ratio in a given energy/nucleon, and hence velocity, interval varies greatly with time. Clearly, if the propagation were a purely velocity dependent one, this ratio would be independent of time in the event.

Another dependence which has been suggested recently is a mean free path which is proportional to rigidity and hence a diffusion coefficient which is proportional to βR (Gloeckler and Jokippi, 1966). This possibility is also excluded by the results of this event as shown in Fig. 6. It is seen that the ratio of the flux of protons to that of medium nuclei in the same βR interval varies by a factor of 3 from the first to the last flight. Thus, neither of the two simplest possibilities for the diffusion coefficient which have been proposed are correct in this event.

SUMMARY

The study of the particle characteristics of the energetic hydrogen, helium, light, medium, and heavy nuclei in the Sept. 2, 1966 solar particle event confirmed many aspects which appear to be characteristic of these phenomena. There are, however, two features which deserve particular attention; these are the evidence in support of a characteristic composition of multicharged nuclei which is independent of the solar particle event and the complete lack of agreement between the results and those predicted either by a diffusion coefficient proportional to β or βR.

As mentioned before, the measurement of a helium to medium nuclei ratio which agrees with those measured in the four previous events of the last solar cycle in a different energy/nucleon interval gives strong support to the concept that the relative abundances of the multicharged nuclei are always the same. In this event, this was substantiated further by the measured neon to medium nuclei ratio, the absence of light nuclei, and the agreement between the shapes of the helium and medium nuclei spectra. As we have noted in previous articles (e.g., Biswas and Fichtel, 1965), this is a factor which any accelerating mechanism must explain, and further, this feature provides the tantalizing possibility of making very good measurements of the composition of the region of the sun from which these particles come. It was shown that the composition of the energetic multicharged solar nuclei within the errors of present measurements agrees with measurements made for the sun's photosphere, and hence, as indicated previously (Biswas, Fichtel, Guss and Waddington, 1963; Biswas and Fichtel, 1965) give a means of estimating the sun's helium abundance. Using the recent solar spectroscopic data quoted by Lambert (1967b) for the relative abundances of carbon, nitrogen, oxygen, and hydrogen in the photosphere and the helium to medium nuclei ratio obtained here, a hydrogen to helium ratio of 16 $\pm$ 2 is obtained.

The results of the measurements reported here showed clearly that this event could not be described by a simple diffusion model with the diffusion coefficient proportional to β or βR. This result adds to a growing body of evidence which indicates that a more complex picture of solar particle propagation is needed - probably one which includes anisotropic diffusion with the possibility of a complex rigidity dependence for the diffusion tensor, the possibility of time dependence of the interplanetary medium, and probably the dependence of the diffusion coefficient on position.

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Fig. 1: Integral spectra for protons measured during the three sounding rocket flights. The experimental points indicated by triangles, squares, and circles are for the first, second, and third flights respectively. See Table I for the flight times.

Fig. 2: Integral medium and helium nuclei spectra measured during the three sounding rocket flights. Open symbols refer to medium nuclei data multiplied by 60 and closed symbols to helium nuclei data. The experimental points indicated by circles, diamonds, and squares refer to the first, second, and third flights respectively. There is only one helium date point available in the third flight which is above 20 MeV/Nucleon, and it is not shown. See Table I for flight times.

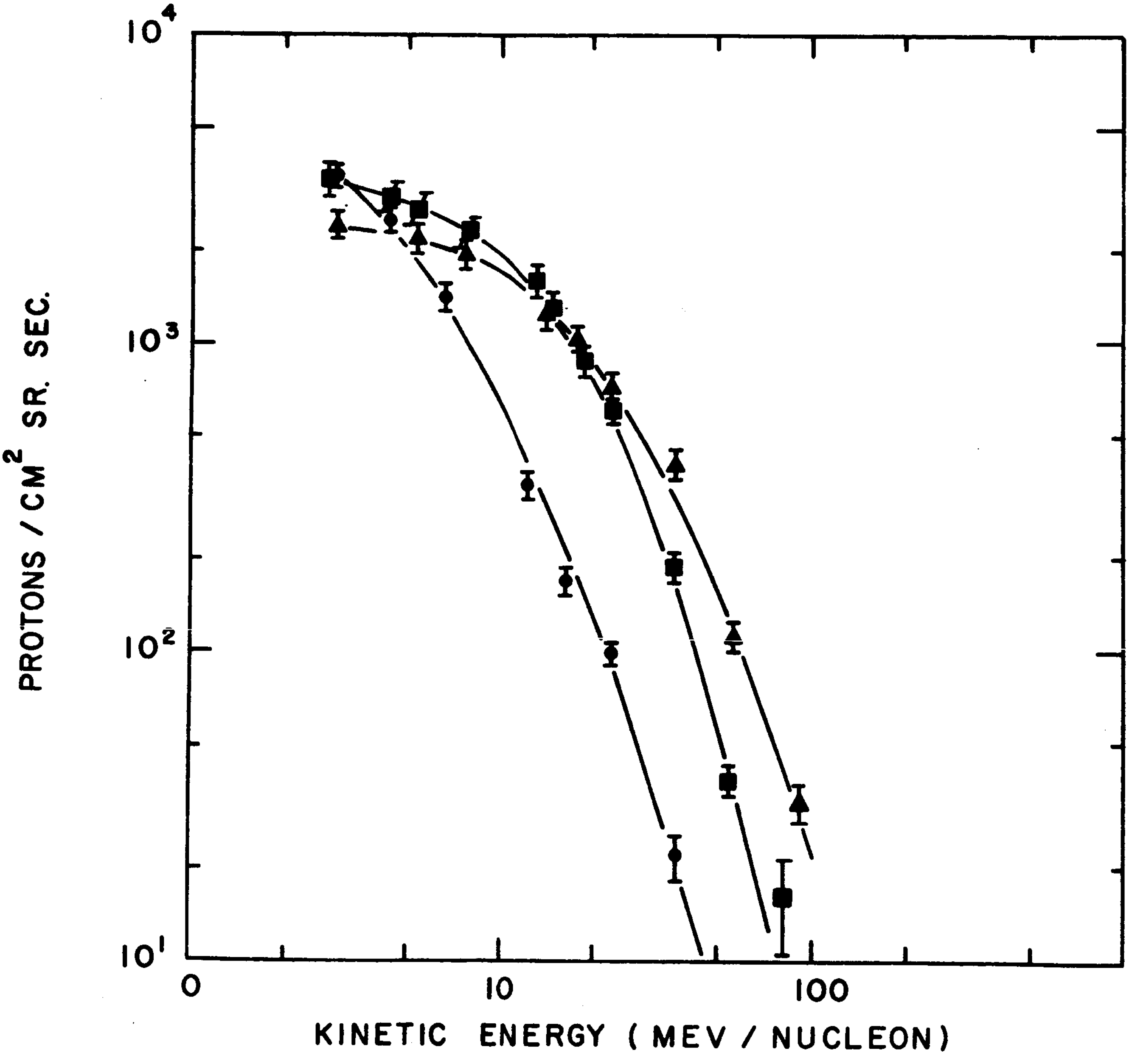
Fig. 3: Integral energy/nucleon spectra measured at 1443 U.T., Sept. 2, 1966 for protons (triangles), helium nuclei (circles), and medium nuclei (crosses).

Fig. 4: Differential rigidity spectra for protons during the three sounding rocket flights. The experimental points indicated by circles, crosses, and squares are for the first, second, and third flights respectively. See Table I for the flight time.

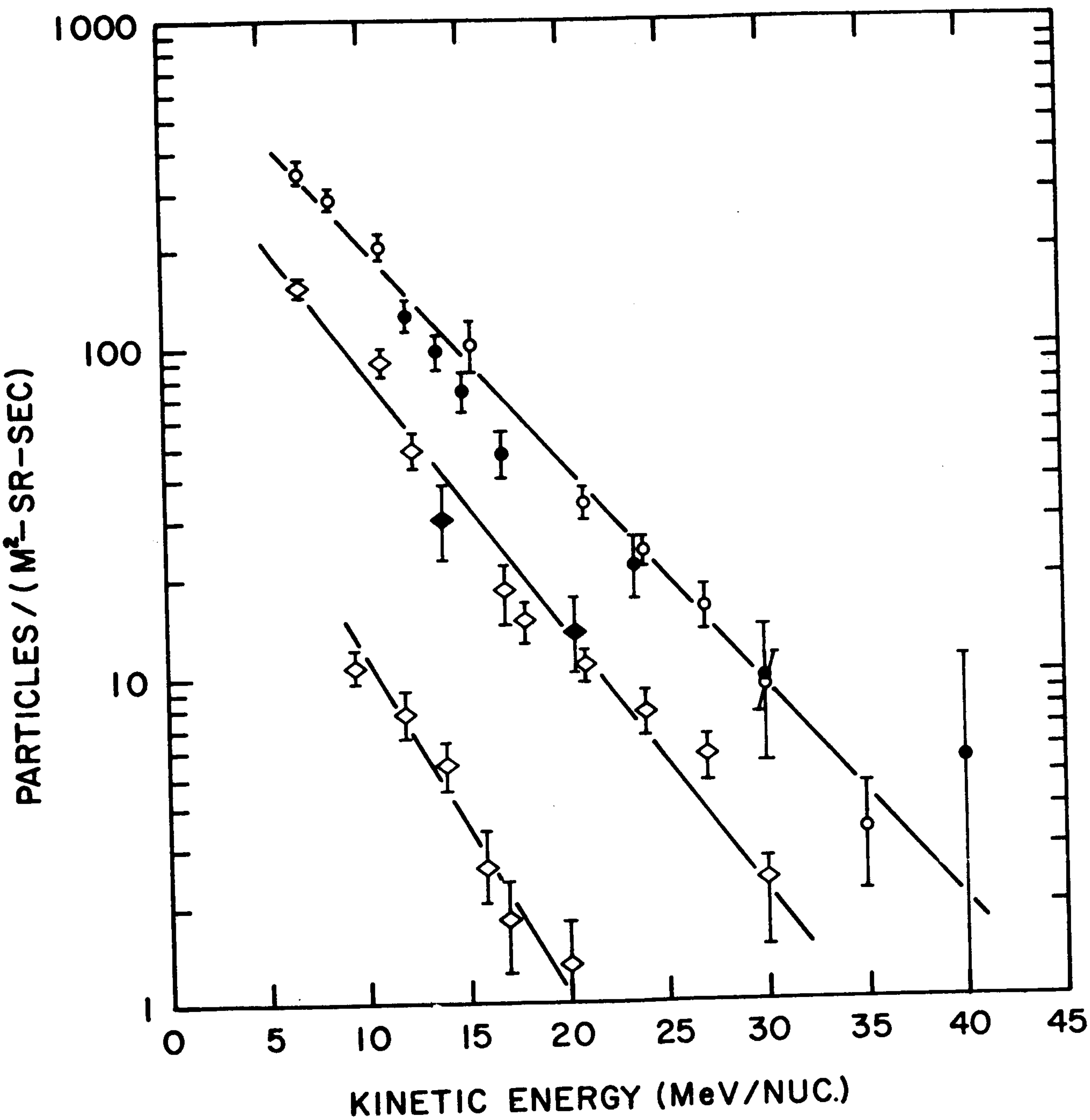
Fig. 5: Proton to medium nuclei ratio for the three flights for the two different energy/nucleon intervals, which are

specified in the figures, plotted as a function of time from the flare.

Fig. 6: Proton to medium nuclei ratio for the three flights for the βR (velocity in units of the velocity of light times particle rigidity) interval shown in the figure plotted as a function of time from the flare.



PROTONS / CM^2 SR. SEC.
10^4
10^3
10^2
10^1
0
10
100
KINETIC ENERGY (MEV / NUCLEON)



PARTICLES / (M²-SR-SEC)
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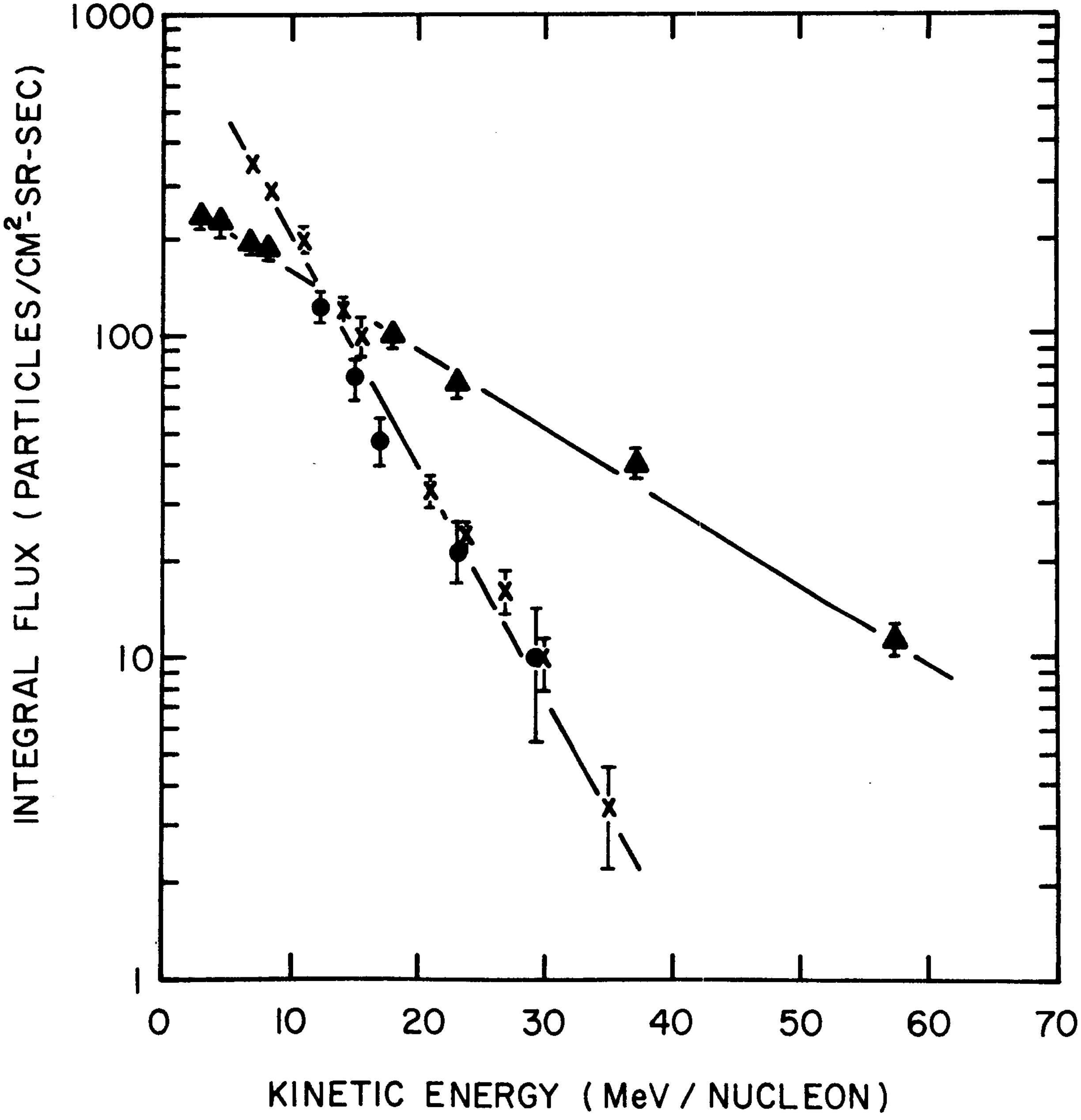
100
10
1
0
5
10
15
20
25
30
35
40
45
KINETIC ENERGY (MeV/NUC.)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100
10
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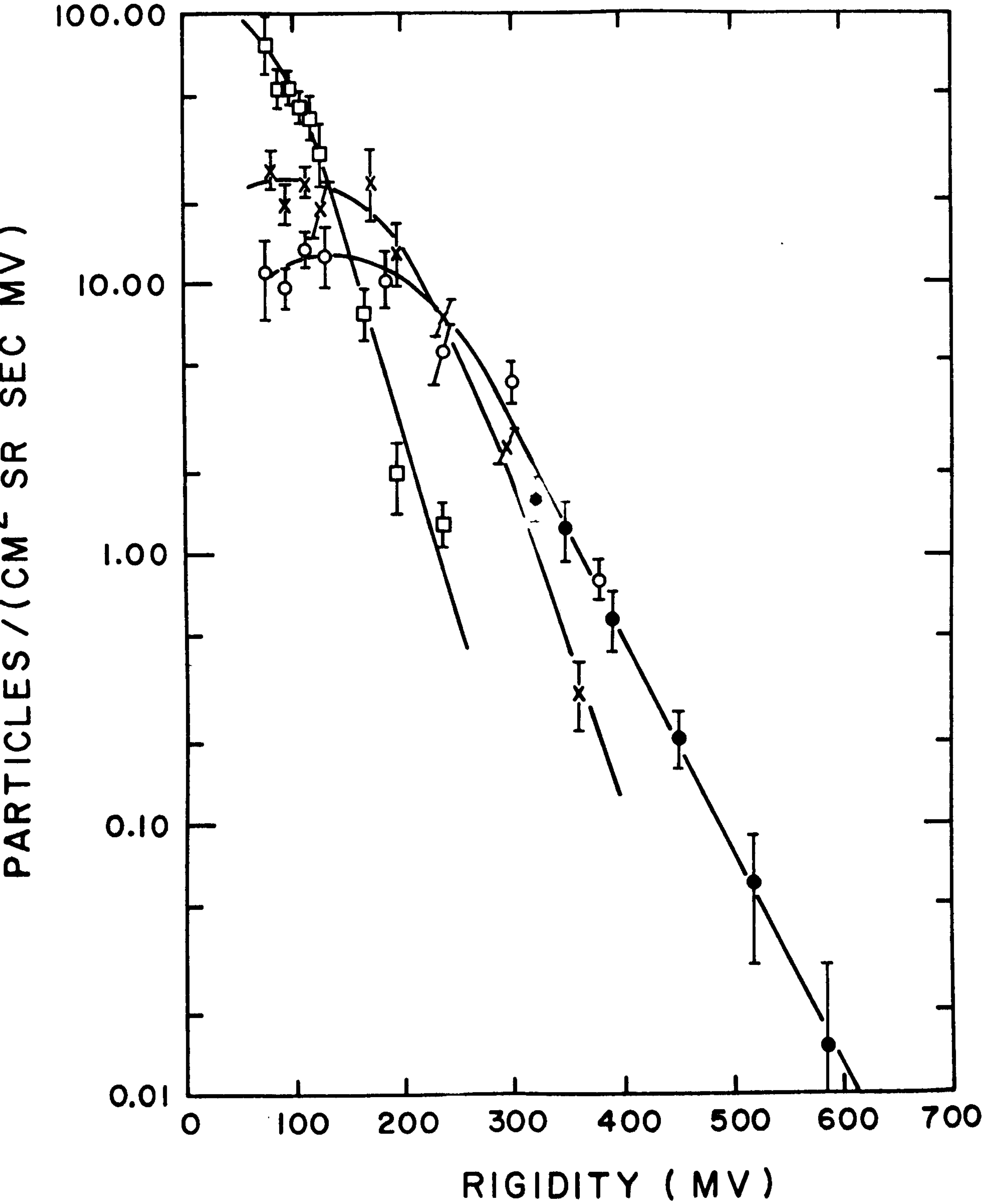
0
10
20
30
40
50
60
70
KINETIC ENERGY (MeV / NUCLEON)



100.00
10.00
1.00
0.10
0.01
PARTICLES / (CM2 SR SEC MV)
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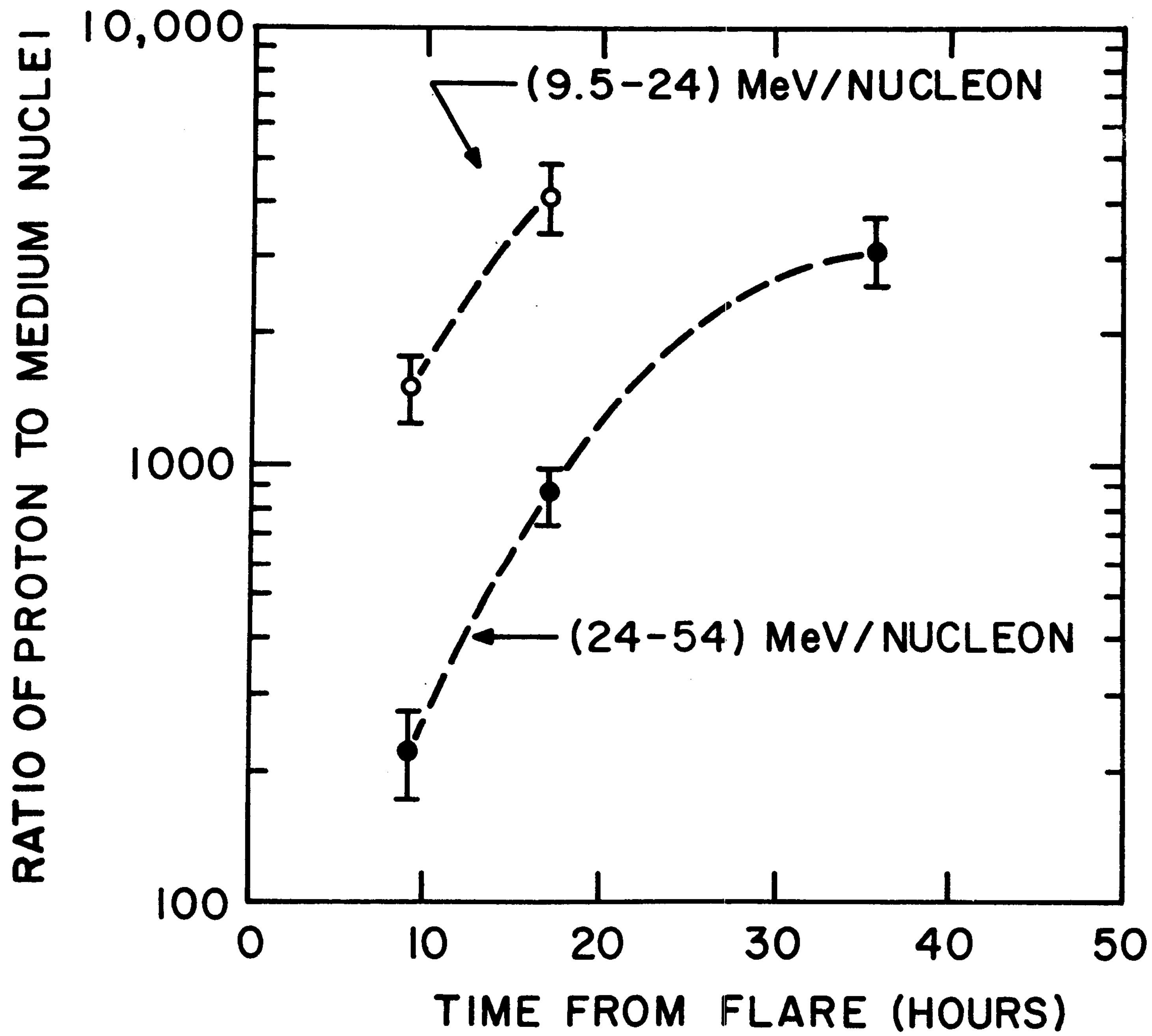
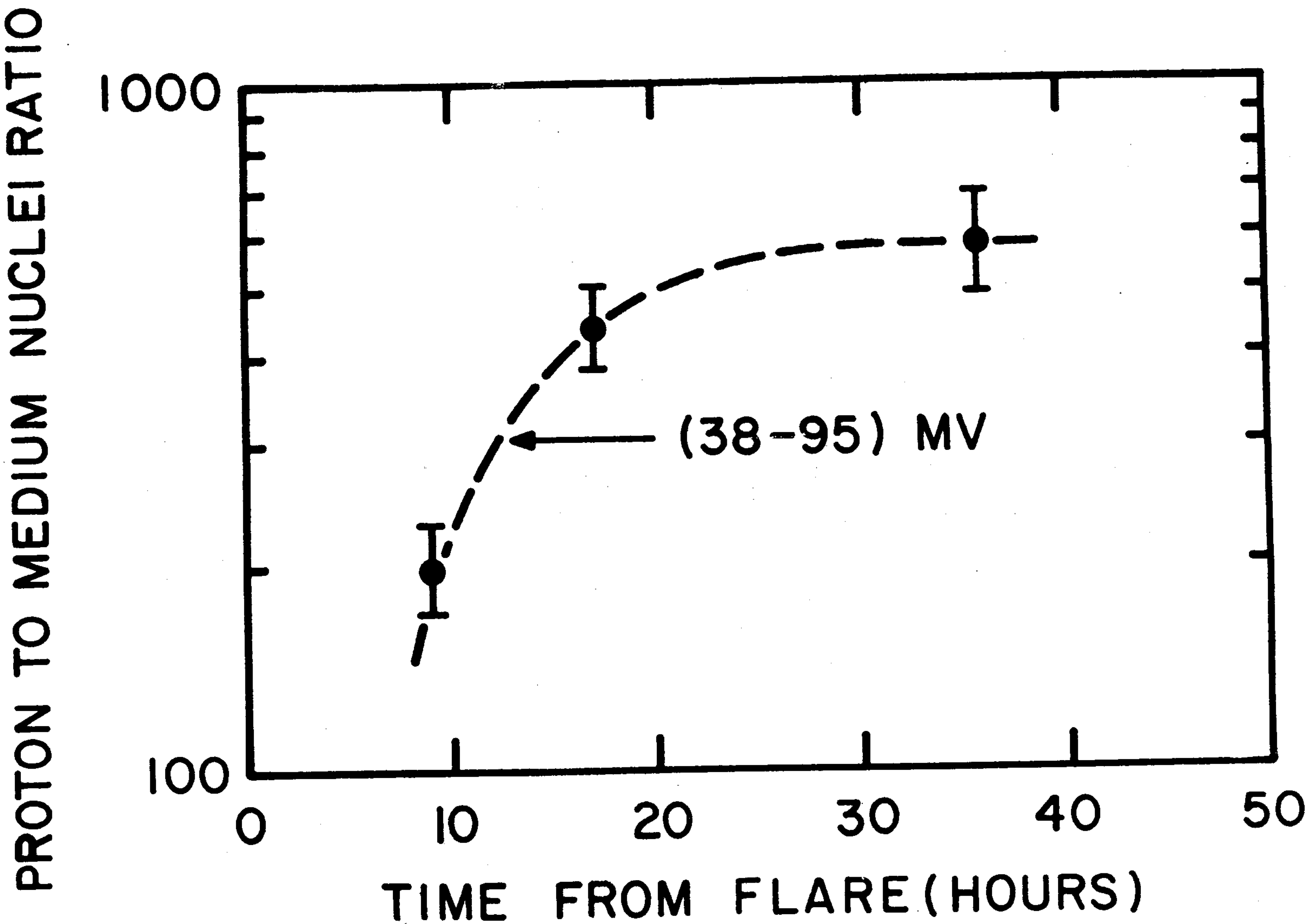
100
200
300
400
500
600
700
RIGIDITY (MV)


RATIO OF PROTON TO MEDIUM NUCLEI
10,000
1000
100
(9.5-24) MeV/NUCLEON
(24-54) MeV/NUCLEON
0
10
20
30
40
50
TIME FROM FLARE (HOURS)


PROTON TO MEDIUM NUCLEI RATIO
1000
100
0
10
20
30
40
50
TIME FROM FLARE (HOURS)
(38-95) MV