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D. V. REAMES
C. E. FICHTEL

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Low Energy Cosmic Ray Composition and Energy Spectra Measured in June, 1965

D. V. Reames and C. E. Fichtel
NASA, Goddard Space Flight Center, Greenbelt, Maryland

ABSTRACT

Sounding rockets carrying nuclear emulsions to study the composition and energy spectra of the low energy cosmic rays were flown on June 17 and 23, 1965 from Fort Churchill, Canada. The results show that the intensity of the heavy nuclei ($Z \geq 3$) was about the same as that in July, 1964 and below that measured by other observers in May and early June 1965, before the Forbush decrease on June 15, 1965. The helium nuclei flux between 15 and 22 MeV/nucleon was found to be significantly lower on June 17, 1965 immediately after the Forbush decrease than on June 23, 1965. The charge spectrum indicates that in the region from 40 to 90 MeV/nucleon the ratio of light to medium nuclei fluxes is $0.19 \pm .07$, well below the value of 0.5 found at intermediate energies (200 to 400 MeV/nucleon) and that the carbon to oxygen ratio is about 1 rather than 1.6, as found at higher energies. A strong preference for even nuclei relative to odd is seen for charges 9 to 14 in the 60 to 180 MeV/nucleon range.

I INTRODUCTION

The composition and energy spectra of the heavy nuclei in the galactic cosmic radiation are of considerable interest because of the insight which they provide into the origin and interstellar history of the cosmic radiation. In order to have sufficient information to make meaningful comparisons with theoretical predictions and to indicate reasonable approaches for further theoretical studies, it is necessary to know the relative abundances and energy spectra of the various nuclear species over a wide range of energies.

A careful examination of the problems of energy loss, fragmentation and acceleration, both at the source and possibly in interstellar space, show that the lowest energy region is perhaps the most significant because it is there that differences in energy spectra and, hence, relative abundances would become most pronounced. The problem is complicated by the solar modulation of the cosmic radiation, but it is believed that the solar environment only effects the intensity and not the relative abundances of particles of the same charge to mass ratio (Z/M) and that effects on particles whose Z/M value varies only slightly can be estimated reasonably well.

Until recently, information on the lowest energy interval ($\lesssim$ 150 MeV/nucleon) was lacking because the earlier experiments on the composition had been conducted on balloons which remained below a few gm/cm^2 of the atmosphere, and, therefore, these experiments could not examine the lowest energy heavy nuclei.

Beginning in 1963, data[1] in this energy interval began to be collected, and subsequently several experiments flown on sounding rockets and satellites[2-4] have contributed to our knowledge of this region. In addition to the reasons already given, this information has the advantage of resulting from a direct measurement on the cosmic rays, uncontaminated by the interactions of these particles in the atmosphere. In this paper, the results of nuclear emulsion sounding rocket experiments flown in 1965 will be discussed and compared to previous results.

II THE EXPERIMENT

The results to be presented here come from the last of a series of experiments to study the relative abundances of the low energy galactic cosmic ray nuclei using nuclear emulsions flown on sounding rockets from Fort Churchill. The first exposures in the series were obtained in September, 1963 and July, 1964; the results of these flights have been reported previously[1,4]. The data to be discussed here was gathered during sounding rocket flights on June 17 and June 23, 1965.

The stacks of nuclear emulsions were placed two to a tray in three trays which could be extended at a 17.5° angle with respect to the skin of an Aerobee 150 rocket. The trays were kept inside the payload until the sounding rocket had left the atmosphere, at which time they were extended. As the trays were extended, the top emulsion segments which consisted of a sandwich of a 200 μ Ilford G-2 emulsion and a 200 μ Ilford G-5 emulsion were

displaced by 1cm from the remainder of the nuclear emulsion stacks so that subsequent matching of the tracks would allow the isolation of those particle tracks which entered during the exposure. The exposure lasted about 350 seconds, after which the trays were retracted, and the top sandwich section of each stack was restored to its initial position in preparation for re-entry into the atmosphere. Extension and retraction each took about 7 seconds. Except for the top sandwich, the nuclear emulsion detectors were 600 μ Ilford G-5 pellicles, 6.3 cm x 29 cm. The total amount of material above the top emulsion was .041 g/cm^2 (emuslion equivalent), and there was .026 g/cm^2 between the top sandwich and the rest of the stack.

After processing, two types of analysis were begun, one to detect particles of charge 3 or more and one to measure the low energy helium nuclei flux. In the former, the 200 μ G-5 plates in the top sandwich were area scanned for the tracks of all particle entering their surface within a dip angle $< 65^{\circ}$ and with an ionization greater than a specified amount. The minimum ionization accepted was set sufficiently low to insure that all tracks formed by particles with $Z = 3$ and an energy < 250 MeV/nucleon would be selected. In practice this meant many of the particles of charge 2 were also included in the preliminary selection. These tracks were then followed into the main stack and all tracks which failed to follow directly (i.e. were displaced by 1 cm with respect to the top pellicle) or failed to stop in the stack were rejected. Charges of the particles with $Z \geq 3$ were determined in a manner

essentially identical to that used in the earlier paper[4]. The solid angle calculation and the efficiency precautions were also the same as those reported previously[4] and will not be repeated here.

In the case of the helium nuclei analysis, scans at an appropriately lower ionization level were made and the separation of the helium nuclei from singly charged particles and heavy nuclei was made on the basis of the range of the particle in the emulsion stack and the grain density of the particle track in the 200 μ G-2 nuclear emulsion. The separation of doubly charged nuclei from singly and multiply charged nuclei was quite unambiguous, but the resolution was not satisfactory to separate clearly He^4 and He^3. In addition to the rescanning test for efficiency, the high helium nuclei detection efficiency could be verified by the recorded number of singly charged particles of appreciably lower grain density than that for the high energy limit of the helium nuclei.

The energy interval was determined by the minimum range accepted for charge determination on the low end and by the range restriction imposed by the finite size of the stack on the other. Since the range of a nucleus of given energy/nucleon is a decreasing function of Z^2/M, the energy interval was a function of charge and moved up in energy as Z increased. Thus the energy interval examined for the nuclei, of $Z \geq 3$ ranged from about 30 to 120 MeV/nucleon for light nuclei ($3 \leq Z \leq 5$) to 60 to 300 MeV/nucleon for the very heavy nuclei ($20 \leq Z \leq 28$).

III EXPERIMENTAL RESULTS

There are two somewhat related subjects of interest. These are the energy spectra of the various nuclear components and the relative abundances of the various charge species. The former are time dependent because of the solar modulation of the cosmic radiation, whereas the latter seem to be time independent for particles of the same charge to mass ratio, presumably because the solar modulation is a function of velocity and rigidity (and hence Z/M), but not of charge.

A. Energy Spectra

The energy spectra of the various charge groups obtained in the two 1965 rocket exposures are shown in Fig. 1. Since with one exception there was no statistically significant difference between the fluxes measured in the two flights the data in general have been combined. The one exception is the lowest energy helium nuclei point in the energy interval between 15 and 22.5 MeV/nucleon, where the points lie about three to four standard deviations apart. Also shown in Fig. 1 are the experimental results we obtained in 1964. Fig. 2 shows some representative data on helium and medium nuclei obtained by other groups at times when the differential fluxes expected to be similar only somewhat higher on the basis of the general level of cosmic ray activity. Generally there is seen to be reasonable agreement with the exception of fluctuations in the low energy helium nuclei differential flux measurements, and a general tendency for the data obtained during May and early June by Comstock et al.,[3] Fan et al.,[5] and Balasubrahmanyan et al.,[2] to

fall slightly higher than the data presented here. Data on the light nuclei and heavier nuclei obtained by Comstock et al.,[3] and Balasubrahmanyan et al.,[2] in the energy region which overlaps this also show similar agreement, but were not included in the Fig. 2 to avoid confusion.

There are several points which are immediately apparent. Firstly, there was essentially no significant change between the differential flux measurements in the four groups of nuclei with $Z \geq 3$ between July 1964 and June 1965 except that the latter generally fall below the former. This result is in agreement with the fact that the cosmic ray levels, as measured by the Deep River neutron monitor, and listed in Table I, were nearly identical. Secondly, there is generally a smooth continuation between the low energy data measured in these experiments and the higher energy data, with the medium ($6 \leq Z \leq 9$) nuclei seeming to show less variation with energy than the helium nuclei in the energy range from 30 to 150 MeV/nucleon. This feature has also been noted by Comstock et al.,[3] and Balasubrahmanyan et al.[7] Thirdly there seems to be a marked difference between the helium fluxes below 30 MeV/nucleon observed at different times. These differences seem to be roughly consistent with the changes in the general level of solar activity. For example, the data of Fan et al.,[5] Comstock et al.,[3] Balasubrahmanyan et al.,[2] obtained in the May 1965 period when the general cosmic ray levels were highest lie above those of Fan et al.,[6] and Comstock et al.,[3] obtained in November and December 1964 and the data of this work and Hagge et al.,[7] taken after the Forbush decrease in June 1965.

The medium nuclei of this work also fall below the May 1965 results of Comstock et al.,[3] and Balasubrahmanyan et al.,[2] which are actually much closer to the July 1964 results of Reames and Fichtel[4] Further, the helium flux in this lowest energy interval was lower on June 17, 1965, 2 days after the Forbush decrease, than on June 23, 1965 when a significant neutron monitor recovery had taken place. A more quantitive description of the general cosmic ray levels at these times can be seen in Table I, which gives the neutron monitor levels for the various times. Finally, the surprisingly high fluxes of heavy nuclei below 130 MeV/nucleon first observed in 1963[1] are now clearly established by the measurements of the several groups referred to here, and these fluxes must be explained by any theory of cosmic ray origin, interstellar travel, and solar modulation.

TABLE I

Date	Deep River Neutron Monitor[6] *
July 23, 1964	2085
July 25, 1964	2091
Typical May - early June, 1965	2120
June 17, 1965	2093
June 23, 1965	2114

* Scaled to old readings

B. Composition

A charge histogram of all particles ($Z \geq 2.5$) within the acceptance criteria of the 1965 exposure is shown in Fig. 3. The charge of each particle was determined by three independent delta-ray counts on its track using the technique described previously.[4] Tracks of light particles were further resolved by a count of their grain density in the K.2 pellicle vs. residual range.

Flux ratios of several charge groups are shown in Table II together with the energy interval from which they came. In an attempt to improve statistics we have combined the data of the 1964 and 1965 experiments. These results are also shown in the table.

The high value of the He/M ratio shown in Table II results mainly from the rather low value of the flux of medium nuclei obtained in 1965 in the low-energy region. It is not clear whether the flux of medium nuclei is really falling toward low energies or the lowest energy flux measurement is a statistical fluctuation.

One of the most significant features of the low energy data reported here is the value of $L/M = 0.19 \pm 0.07$ in the 40-90 MeV/nucleon region. This value is compared with other measurements (made at ≤ 8 g/cm^2 residual atmosphere) in Table III. As can be seen from the table, the value of the L/M ratio at low and at high energies is considerably smaller than the value $L/M \simeq .5$ near 400 MeV/nucleon. The energy dependence of the observed L/M ratio now seems to be well established and should be explained by any theory of cosmic-ray origin and propagation.

TABLE II Particle Flux Ratios Obtained in This Experiment

	1965	1964 + 1965	INTERVAL (MEV/NUCLEON)
He/M	32 ± 12		30 - 60
L/M	0.18 ± 0.10	0.19 ± 0.07	40 - 90
$(10 \leq Z \leq 14)/M$	0.34 ± 0.10	0.26 ± 0.06	60 - 150
$(15 \leq Z \leq 19)/M$	0.07 ± 0.04	0.06 ± 0.02	60 - 150
$(Z \geq 20)/M$	0.04 ± 0.03	0.07 ± 0.03	60 - 150
$(Z \geq 10)/M$	0.44 ± 0.11	0.39 ± 0.03	60 - 150
C/O		0.94 ± 0.21	40 - 150
N/O		$0.30 \pm 0.09^{(+0.15)}_{(-0.20)}$	40 - 150

TABLE III Energy Dependence of the L/M Ratio

Energy MeV/nucleon	L/M	Atmospheric Depth of Measurement (g/cm^2)	Source
40 - 90	0.19 ± 0.07	0	This Work
60 - 150	0.26 ± 0.04	0	Comstock et al.[3]
100	0.29 ± 0.07	0	Balasubrahmanyan et al.[2]
150 - 250	0.38 ± 0.13	2.7	Malmqvist[9]
200 - 575	0.45 ± 0.06	3.7	Anand et al.[10]
200 - 700	0.53 ± 0.11	4.7	Badhwar et al.[11]
200 - 700	0.51 ± 0.07	1.5-2.5	Koshiba et al.[12]
200 - 700	0.37 ± 0.05	8.0	Aizu et al.[13]
200 - 1000	0.43 ± 0.07	3.8	Foster & Debenedetti[14]
260 - 360	0.47 ± 0.04	2-6	
	0.42 ± 0.05	2-6	Webber[15] and Webber et al.[16]
350 - 450	0.50 ± 0.05	2-6	
	0.53 ± 0.04	2-6	
400 - 800	0.28 ± 0.08	5.0	Balasubrahmanyan & McDonald[17]
450 - 600	0.37 ± 0.04	2-6	
	0.47 ± 0.04	2-6	
600 - 800	0.32 ± 0.04	2-6	
	0.48 ± 0.05	2-6	Webber[15] and Webber et al.[16]
800 - 1200	0.34 ± 0.04	2-6	
	0.38 ± 0.03	2-6	
1000 - 2000	0.33 ± 0.03	2-6	
2000 - 5000	0.25 ± 0.04	2-6	

Continued Table III

Energy MeV/nucleon	L/M	Atmospheric Depth of Measurement (g/cm^2)	Source
> 575	0.22 ± 0.03	3.7	Anand et al.[10]
> 700	0.26 ± 0.02	2-3	Average of refs. 11,12,13, & 17
> 1500	0.25 ± 0.06	2.7	O'Dell et al.[18]
> 5000	0.29 ± 0.05	2-6	Webber et al.[16]
> 15000	0.25 ± 0.07*	6.7	Durgaprasad[19]

* Only Be and B were measured; a Li to (Li + Be + B) ratio of 1/3 was assumed.

In Fig. 4 we plot the abundance of the elements and element groups relative to oxygen. Data represented in this figure come from both the 1964 and 1965 experiments. The data on a given species are taken from the same energy/nucleon interval as the oxygen group to which they are compared. The intervals are as follows: $Z = 3, 4$ from 40 to 90 MeV/nucleon; $Z = 5$ from 40 to 120 MeV/nucleon; $Z = 6, 7$ from 40 to 150 MeV/nucleon; $Z > 8$ from 60 to 180 MeV/nucleon. This type of comparison is less dependent on the shapes of the spectra than is a ratio of simple averages of fluxes over the energy interval from which they were obtained. Error bars in Fig. 4 include errors in charge resolution as well as statistical errors. The results shown in Fig. 4 are in statistic agreement with those obtained by Comstock et al.[3]

The individual-nucleus composition in characterized by low abundances of nuclei of odd charge relative to those of even charge, as can be seen in Fig. 4. Our measurements of the abundances of all elements of odd $Z \geq 9$ are actually upper limits. As seen in Table II, we find $N/O = 0.30 \, ^{+0.15}_{-0.20}$ (where the error bars include errors in charge assignment) so that nitrogen comprises only about 15% of the flux of medium nuclei.

Of equal interest in the carbon to oxygen flux ratio which we find to be $.94 \pm .21$. The approximate equality of these two species has also been reported by Balasubrahmanyan el al.,[2] by Comstock et al.,[3] and by Malmqvist[9] at the same or slightly higher energies.

The difference between the recent, low-energy composition measurements on sounding rockets and satellites and previous higher-

energy measurements on balloons thus persists. As we have suggested previously[4], this difference could result partially or wholly from the effect of the residual atmosphere above the balloon measurements. In order to conclusively establish any real energy dependence in the relative composition of individual elements we must await further high-energy measurements above the atmosphere.

FIGURE CAPTIONS

Fig. 1 Differential energy spectra for the charge groups indicated below

	July 1964	June 17 1965	June 23 1965
He		asterisk	cross
Li, Be, B:	open circle	closed circle	
C, N, O :	open square	closed square	
$10 \leq Z \leq 28$:	open triangle	closed triangle	
$20 \leq Z \leq 28$:	open diamond	closed diamond	

Fig. 2 Differential energy spectra for helium and medium nuclei measured by several groups.

Nuclei Type	Measurement Date	Symbol	Ref.
Helium Nuclei:	Oct. - Nov., 1964	dashed line	5,6
Helium Nuclei:	Mar. 19 - June 12, 1965	open triangle	2
Helium Nuclei:	May - June, 1965	solid line	3,5
Helium Nuclei:	June 17, 1965	asterisk	This Work
Helium Nuclei:	June 23, 1965	cross	This Work
Helium Nuclei:	Sept., 1965	open circle	7
Medium Nuclei:	Mar. 19 - June 12, 1965	open diamond	2
Medium Nuclei:	May - June, 1965	open square	3
Medium Nuclei:	June 17 - 23, 1965	closed square	This Work

Fig. 3 Histogram of measured charge in the 1965 exposures.

Fig. 4 Relative number of nuclei of indicated charge, Z, with respect to oxygen in the energy/nucleon interval given below

Charge	Energy Interval
3,4	40 - 90 MeV/nucleon
5	40 - 120 MeV/nucleon
6,7	40 - 150 MeV/nucleon
Z>8	60 - 180 MeV/nucleon

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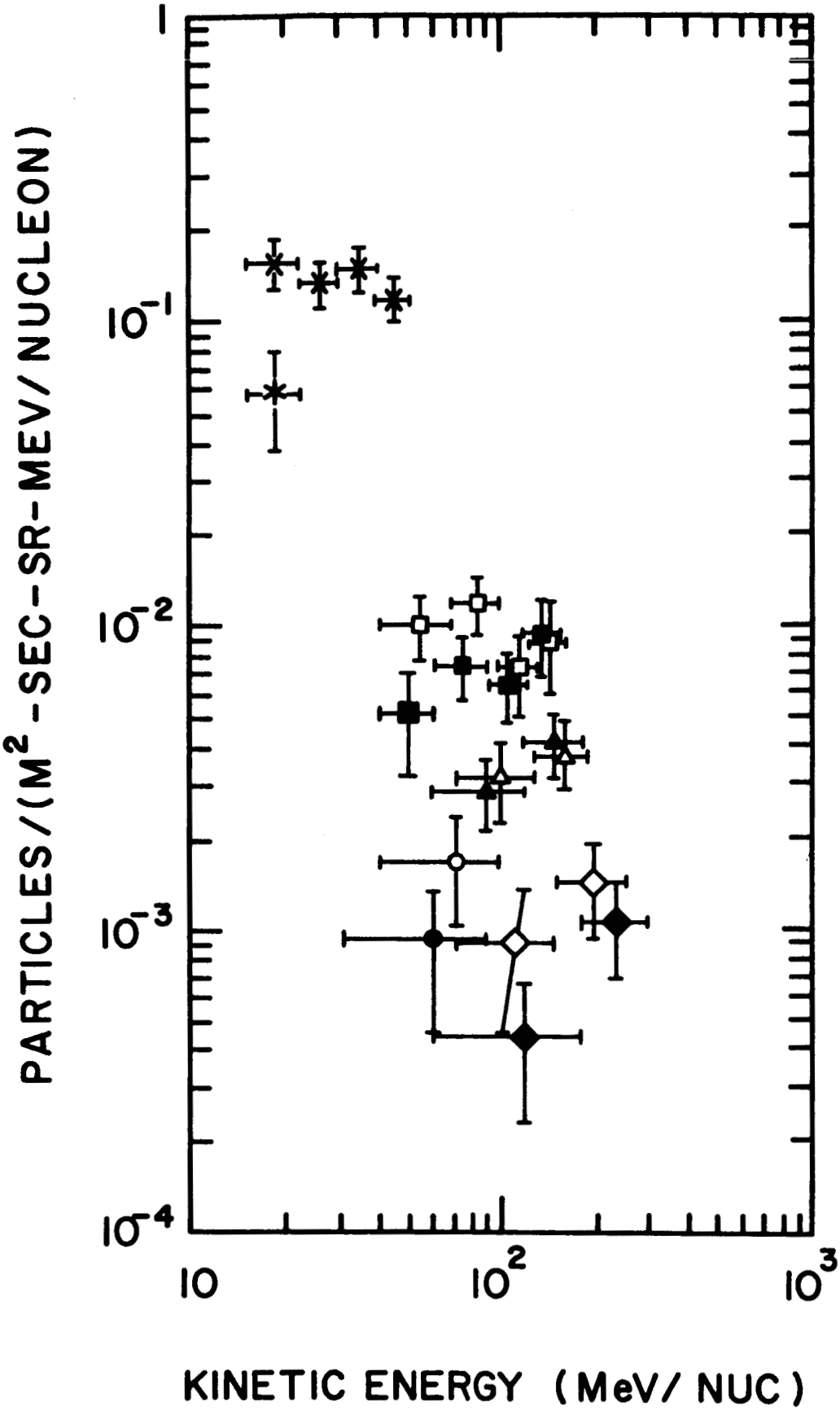
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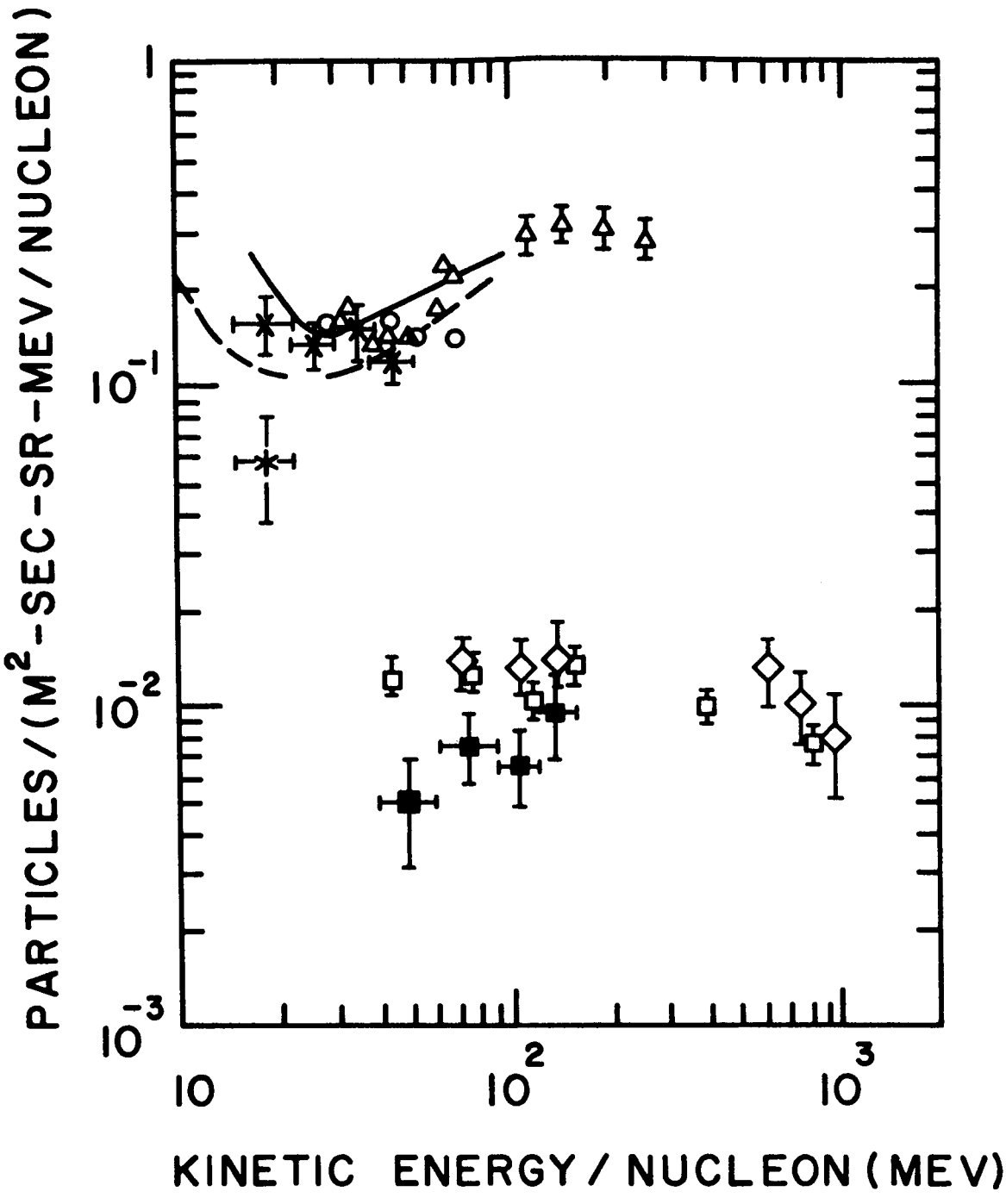
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10
10^2
10^3
KINETIC ENERGY (MeV/NUC)

Figure 1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10⁻¹
10⁻²
10⁻³
10
10²
10³
KINETIC ENERGY/NUCLEON (MEV)

Figure 2

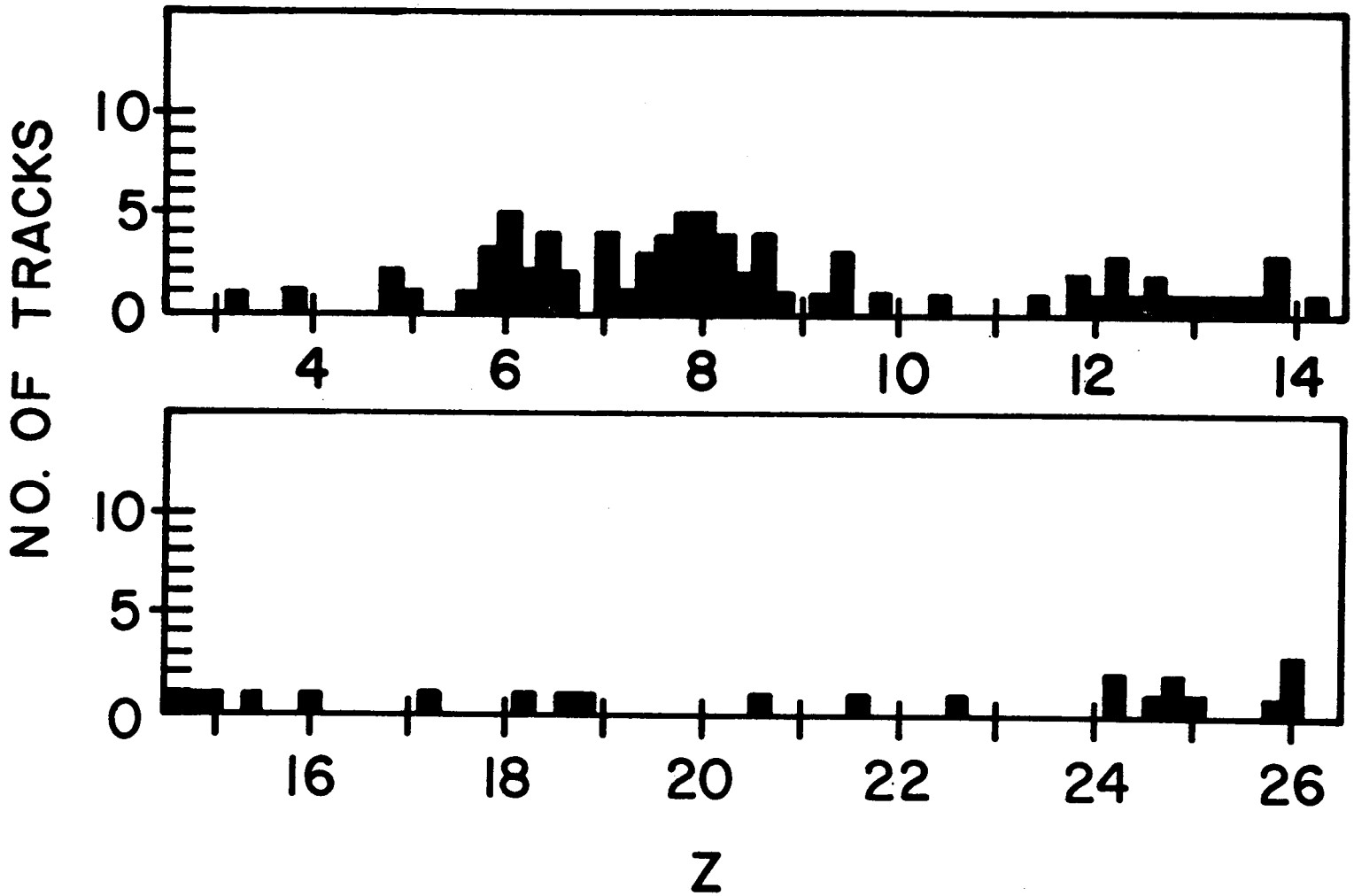

Figure 3

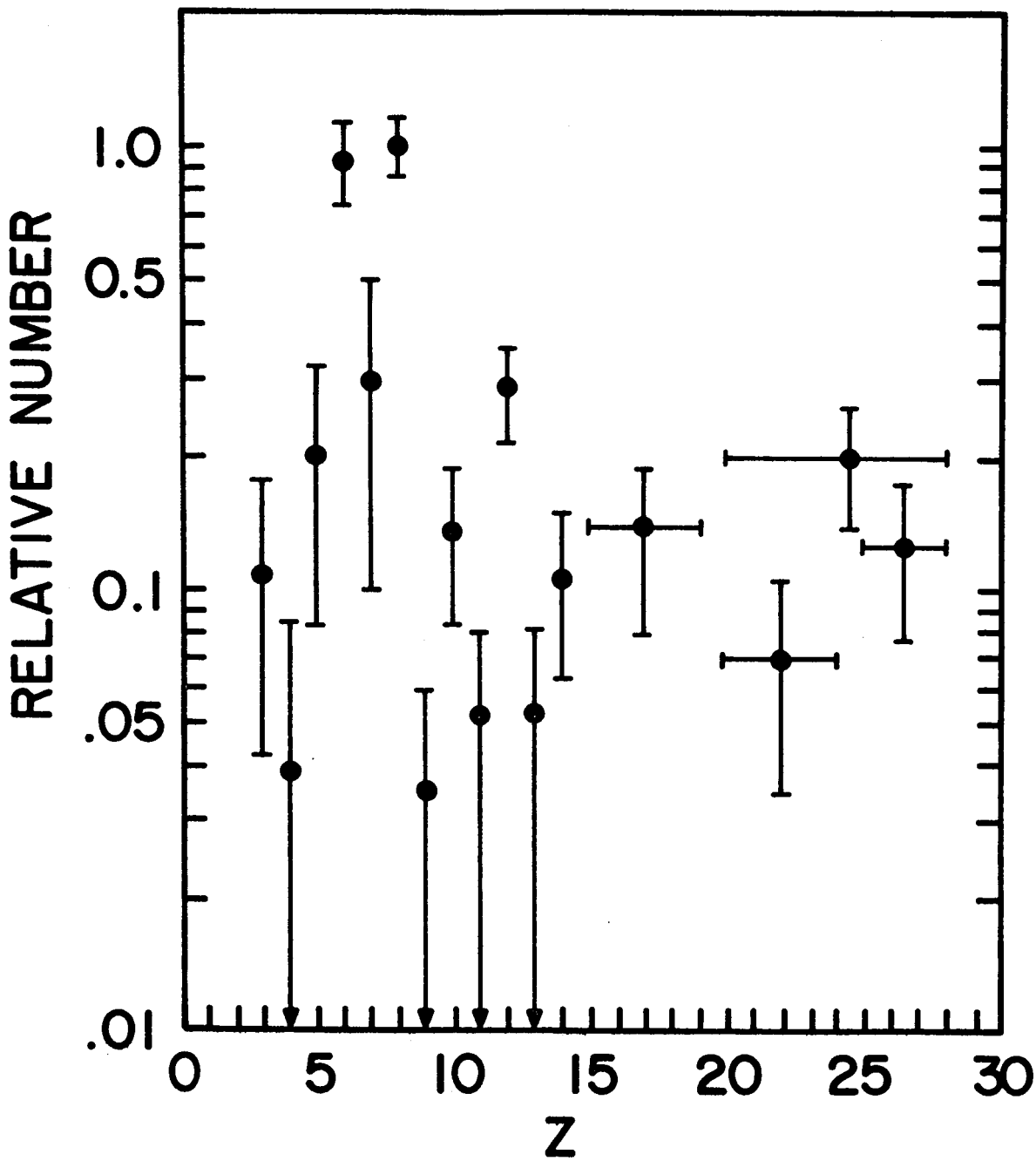

Figure 4