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NUCLEAR COMPOSITION AND ENERGY SPECTRA IN THE APRIL 12, 1969 SOLAR PARTICLE EVENT

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ABSTRACT

The charge composition for several of the multicharged nuclei and the energy spectra for hydrogen, helium, and medium ($6 \leq Z \leq 9$) nuclei were measured in the April 12, 1969 solar particle event. The energy/nucleon spectral shape of the medium nuclei was again the same as that of the helium nuclei, and the ratio of these two species was consistent with the present best average of 58 ± 5. By combining the results obtained here with previous work, improved estimates of the Ne/O and Mg/O values of $.16 \pm .03$ and $.056 \pm .014$ respectively were obtained. Si and S abundances relative to O were determined to be $.028 \pm .010$ and $.008 \pm .006$ respectively, and 85% confidence upper limits for A and Ca relative to O of .017 and .010 were obtained. Previously, these last four nuclei had only been listed as a group.

I. INTRODUCTION

The existence of heavy nuclei in solar cosmic rays has been known for about a decade, and they have now been seen by many observers in several different solar particle events (Fichtel and Guss, 1961; Yagoda, Filz, and Fukui, 1961; Biswas, Fichtel, and Guss, 1962; Ney and Stein, 1962; Pomerantz and Witten, 1962; Biswas, Fichtel, Guss, and Waddington 1963; Biswas, Fichtel, and Guss, 1966; Durgaprasad, Fichtel, Guss, and

Reames, 1968; Bertsch, Fichtel, and Reames, 1969; Beedle, Webber, and Van Allen, 1971; and Armstrong and Krimigis, 1971). However, because of the low abundances of nuclei with charges greater than two, only the most intense solar particle events have intensity levels sufficiently high to study details of the solar particle composition. Before the event to be reported here, there were only four events in which such measurements were made.

One outstanding feature of the solar cosmic ray composition which has been seen in an examination of the experimental results is the constancy of the relative abundances of particles with the same charge-to-mass ratio within experimental errors in all events where a comparison could be made at energies where the nuclei are fully ionized. Moreover, the observed abundances show a strong similarity to photospheric and coronal values measured by spectroscopic techniques.

Because of the interesting possibility that these particles may represent an unbiased sample of the sun, it seems worthwhile to summarize briefly here the existing experimental evidence related to this subject. The energy/nucleon spectral shape of the medium ($6 \leq Z \leq 9$) nuclei has been the same as that of helium within uncertainties each time they were measured above 10 MeV/nucleon in four different events (Biswas et al., 1962; Biswas et al., 1963; Biswas et al., 1966; and Durgaprasad et al., 1968) even though the proton spectra were generally quite different. In addition to having the same energy/nucleon spectra, the relative abundance of helium and medium nuclei in the same intervals has been found to be the same within uncertainties. Further, abundances of the heavy nuclei for those nuclei which could be measured in the same energy/nucleon intervals have been found to be the same each time a measurement was made, namely, eight times in four events, although the uncertainties in some cases are rather large. These results are presented in detail in the papers mentioned above.

As shall be discussed later, there are also reasonable theoretical arguments for believing that the solar particle acceleration and propagation mechanisms act similarly on particles with equal charge-to-mass ratios and that consequently the observed solar particle relative abundances should reflect solar abundances when comparisons are made between species having the same charge-to-mass values. Thus, a consistent picture seems to exist to suggest the possibility that solar cosmic rays provide a rather direct means for determining more detailed information about solar abundances than is otherwise available and thereby will assist in formulating models to describe the nucleogenesis and evolution of the Sun's constituents.

An opportunity to investigate further the composition of solar cosmic ray particles was afforded by the April 12, 1969 solar particle enhancement. This event was one of the most intense of the current solar cycle and differs from the major events in which measurements have been made previously in that no flare was observed on the visible disk that could be identified as the source. The most likely candidate is an importance 3 BSL or spray event that occurred at 1056 UT on April 10, 1969 just behind the east limb of the sun.[1] Judging from the

[1] Solar-Geophysical Data, IER-FB 298, pages 90-100 and 110, June 1969, U. S. Department of Commerce (Boulder, Colorado, 80302).

extent of the spot group when it rotated onto the disk, this event could have occurred as far as 20° behind the limb. A moderately large X-ray enhancement, marked by a long (~ 16 hours) decay time was recorded[1]. Also, type IV radio noise which is known to correlate strongly with particle acceleration was observed during this event[1].

In this report, the charge composition for several multicharged nuclei and the energy spectra for hydrogen, helium and medium nuclei ($6 \leq Z \leq 9$) measured on April 12, 1969 are presented.

II. EXPERIMENTAL TECHNIQUE

The data presented here were obtained from two nuclear emulsion stacks that were exposed to the solar particle radiation during a sounding rocket flight at 2319 UT on April 12, 1969. The payload and its Nike-Apache vehicle were kept on standby at the Fort Churchill Research Range in Manitoba, Canada prior to the event as part of a continuing SPICE (Solar Particle Intensity and Composition Experiment) program.

The flight occurred 60.4 hours after the flare believed to be responsible for the event and about three (3) hours before near-Earth satellites recorded maximum proton intensity. The Explorer 34 (IMP-F) satellite for example recorded an integral flux of $\sim 10^3$ protons/ ($cm^2 \cdot$ steradian $\cdot$ sec.) above 10 MeV at the time the emulsions were exposed (Bostrom et al., 1969), and the Churchill neutron monitor records reveal the onset of a 5% Forbush decrease commencing at about this time (Palmeira, 1971).

Each of two nuclear emulsion stacks consisted of 24 pellicles with lateral dimensions 2.5 in. x 2.8 in. A thin cover of stainless steel and mylar, having a total thickness equivalent to 72 microns of emulsion, separated the outermost pellicle from the particle radiation. This first pellicle was 200 microns thick. It was followed by three 300-micron and twenty 600-micron pellicles. Experience has shown that this arrangement of thicknesses is advantageous since the high density of solar proton tracks in the outer pellicles of the stack makes it difficult to analyze tracks in a 600-micron plate. The two stacks had different sensitivities: one was made from Ilford K.5 material sensitive to minimum ionizing events, and the other was made from Ilford K.2 emulsion sensitive to protons of energy less than 40 MeV.

During flight, the nosecone of the payload was opened while the payload was above about sixty kilometers yielding an exposure time of 245 sec. By means of spin stabilization, the emulsion plates were held in a vertical plane. The zenith angle of arrival of each particle in the stacks could therefore be determined during analysis. Those events that entered the stacks from directions below the horizon were excluded because of their unknown energy loss and possible interactions in the atmosphere.

An area scan of 9.6 cm^2 was made in the top plate of the K.5 emulsion stack to locate nuclei heavier than helium. Events with entrance angles from 10° to 60° with respect to the surface were accepted. In addition, a minimum projected length of 84 microns was demanded to ensure a sufficient track length for analysis. These criteria establish a geometric factor of 10.8 (cm^2 ster). For energies below 20 MeV/nucleon, the projected length cutoff decreased this value slightly depending on the particle's charge.

Identification of multiply-charged particles was accomplished by counting the number of secondary electron (δ-ray) tracks protruding 3.9μ from each primary track. The integral number of δ-rays obtained between the track ending and a residual range, R, was plotted as a function of R for each track. Such a plot is shown in Fig. 1 for a sample energetic particle obtained in this experiment. Curves for particles of different charge are displaced approximately diagonally by the logarithm of their charge as shown in the figure. The charge resolution seen in the figure was not considered adequate to determine abundances of the less abundant nuclei of odd charge.

Helium nuclei were resolved from protons in the less sensitive K.2 emulsion stack by measuring the grain density of each track near the point where the particle entered the emulsion plate. A plot of this grain density measurement versus the corresponding residual range of the track is shown in Fig. 2 for a sample of tracks in a particular emulsion plate in the stack. All helium fluxes obtained in this experiment, involved measurements of this type and the resolution of protons and helium nuclei shown in Fig. 2 is typical of that obtained in all cases. Because of the difficulty in tracing proton and helium events from one plate to the next, scans were made in several plates at different depths in the emulsion stack so as to sample different energy regions. The selection criteria in these scans included a minimum projected length of 88 microns, entrance angles of 10 to 45° from the surface plus the requirement that the event stop in the scan plate.

III. RESULTS AND DISCUSSION

The results which are of prime interest are those related to the relative abundances of the nuclei of different charges. However, for completeness and because of their importance in supporting the ideas to be developed, the energy spectral measurements will be discussed first. From the earliest work (Biswas et al., 1962) it was realized that it would be meaningful to talk of relative abundances only if it could be shown that the energy spectra of at least the two most abundant groups to be considered were the same, namely helium nuclei and (C, N, O) nuclei. The protons and helium nuclei which have different charge-to-mass ratios were known to have different energy/nucleon spectra in general and that the difference changed with time during an event. These two features were expected because the acceleration process most likely involves both particle velocity and rigidity and the propagation process certainly does; therefore, if the charge-to-mass ratio of two species are different, their energy spectra will be different, and the ratio of their abundances at any given velocity should not in general be expected to reflect that of the origin and indeed would be expected to vary with time in an event.

On the other hand particles with the same charge-to-mass (Z/M) ratio in the charge and energy interval to be discussed here are fully ionized, and would be expected to have negligible ionization energy losses. For these reasons and those cited in the previous paragraph, particles of the same Z/M will represent a sample of the sun if there is no bias in the acceleration process, since the propagation phase, including convection, diffusion, adiabatic deceleration, and possible Fermi acceleration will not affect the relative abundances. Two key tests then of whether or not the acceleration phase is unbiased are that the energy/nucleon spectra be the same and the composition of the solar cosmic rays agree with that of the solar spectroscopic abundances. Proceeding one step further, since the accuracy of some relative abundances in the solar cosmic rays can be determined more accurately than the spectroscopic abundances, a further test can be whether the relative abundances of the nuclei of the same Z/M are the same from one solar particle event to another. As indicated in the introduction, these features have indeed been observed within the limitations of the experimental errors for particles above 10 MeV/nucleon. Nonetheless, the limited data presently available make additional tests of value. Fig. 3 shows that again in this event the energy/nucleon spectra of the C, N and O nuclei were the same as that of the helium nuclei, although the proton spectrum was different, and Table I shows that the ratio of these two groups was the same in the event being discussed here as in the previous events, within uncertainties. It is perhaps worth mentioning again that the proton-to-helium ratio, which involves species of different Z/M, has been observed to vary by more than an order of magnitude (e.g. Fichtel and McDonald, 1967). The summary of previous results in Table I is restricted to those for which energy spectral measurements exist and those obtained at sufficiently high energy to insure that the nuclei are fully stripped of their electrons and therefore have the same Z/M.

Having shown that the key criteria are met and also having found no discrepancy with the previous work on the ratios of individual charges, the data obtained in the April 12, 1971 event were combined with previous work to obtain the best possible estimate of the relative abundances for which measurements could be made. These are given in Fig. 4 and Table II, using a base of 1.0 for oxygen. Also shown in Fig. 4 are the abundances predicted for the photosphere and corona from spectroscopic measurements. General agreement is seen to exist between the three, although there are some apparently different trends which will be discussed. There are no spectroscopic estimates of the photospheric abundances of He, Ne, and A known to us due to the lack of strong lines in the spectrum at the photospheric temperature. Also, Fe deserves special attention because its Z/M value is not exactly the same as the others and therefore a bias would be expected; we shall try to estimate the limits of this bias.

Beginning with Si, S, A, and Ca, estimates of Si and S abundances are given and 85% confidence upper limits are set for A and Ca. Previously (e.g. Durgaprasad et al., 1968) these four nuclei had only been listed as a group. Then, as now, we have assumed the relative abundances of the intervening odd charges are negligible. Notice that there is a decreasing abundance in the solar cosmic rays from Si to S to Ca consistent with the spectroscopic photospheric abundance estimates. It is also found that the "solar system" abundances such as those deduced by Cameron (1968) are generally consistent with the solar cosmic ray results. Further, theoretical calculations based on silicon burning (e.g. Bodansky, Clayton, and Fowler, 1968) for parameters representative of solar conditions generally agree, or can be made to agree, with abundances such as those reported by Cameron and also are seen to agree with the relative abundances for Si and S and the limits for A and Ca presented here.

If the composition of the solar cosmic ray nuclei of the same charge-to-mass ratio is accepted as representative of the sun, the abundances may be used to estimate the helium, neon, and argon abundances in the sun, as originally suggested by Biswas et al. (1962). The average neon-to-oxygen ratio is 0.16 $\pm$ .03, and the upper limit for the argon-to-oxygen ratio is .017. The latter is consistent with Cameron's estimate for the solar system of .010; for the former, Cameron (1967) uses our previous solar cosmic ray result so a comparison is not relevant in that case. Finally, the average helium-to-oxygen ratio is 103 $\pm$ 10, slightly lower than the value of 107 $\pm$ 12 reported in the last summary (Durgaprasad et al., 1968).

A more interesting ratio is that of protons to helium. Because of the different energy spectra for particles with different charge-to-mass ratios, there is no simple, reliable way to determine this ratio from solar cosmic rays alone. However, if the helium-to-medium ratio of 58 $\pm$ 5 is accepted as representative of the sun, and the proton-to-medium value from spectroscopic data (Lambert, 1967) is used, a proton-to-helium ratio of 16 $\pm$ 2 is obtained. The uncertainty in this number depends on the correctness of the assumption above and the uncertainty in the proton-to-medium ratio. It is worth noting that this number agrees with structure calculations. Continuing one step further, the distribution in mass between hydrogen, helium, and heavier nuclei becomes X:Y:Z:: .79 $\pm$ 03 : .20 $\pm$ .03 : .016 $\pm$ .004.

The one other nuclear species deserving particular mention is Fe, which is the only one shown in Fig. 4 whose charge-to-mass ratio differs from the others. Because of the low abundance of Fe and the steep energy spectrum*, the relative abundance of Fe has been measured only once (Bertsch et al., 1969), although consistent upper limits of about 0.02 have been measured in other events (Biswas et al., 1962; and Biswas et al., 1963), as well as this one. Bertsch et al. (1969) have considered the effect of the small difference in the charge-to-mass ratio of Fe^{56} and O^{16} and concluded that the solar cosmic ray propagation process affects this ratio by no more than 30% and probably less on the basis of the study of the proton and helium propagation. These same authors noted, however, that there is also probably a bias in the acceleration process at a given energy per nucleon, or velocity, due to the different charge-to-mass ratio.

A good theory which has been tested by experiment for the acceleration process does not exist. Biswas et al. (1963) pointed out that rigidity effects could, and probably do, enter into the acceleration process. The general effect is to suppress the flux of more energetic particles with the smaller charge-to-mass ratio because for a given velocity they will have a larger rigidity and escape more easily from the accelerating region.

Various estimates of the suppression factor range from essentially no effect to $\left(\frac{M_{Fe}\ Z_{\alpha}}{M_{\alpha}\ Z_{Fe}}\right)^{a}$, where a is the power of the integral rigidity spectra, which for this event was about three leading to a factor of about 1.25. If this factor is combined with 1.3, from the upper limit estimated for propagation effects, it appears unlikely that the

*Because the rate of energy loss of a charged particle increases rapidly with charge, Z, the given minimum particle range needed for detection and identification corresponds to increasingly large energy/nucleon values as Z increases.

Fe/O ratio is suppressed by more than a factor of two. The upper end of the uncertainty estimate for the Fe abundance deduced from the solar particle abundances has accordingly been raised by a factor of two in Fig. 4 for comparison with the spectroscopic estimates for the photospheric and coronal abundances. However, the solar Fe abundance deduced from solar energeticle particle measurements should necessarily be considered to be less certain than the others.

It will be very desirable to measure the relative abundance of Fe in other events to understand better the suppression effect, and we hope to do so. However, it should be noted that upper limits set in the events of November 12, 1960, November 15, 1960, and April 11, 1969, seem to speak against the Fe/O value exceeding the upper value shown in Fig. 4.

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FIGURE CAPTIONS

Fig. 1 Integral delta ray counts made between a particle track endpoint and a given residual range as a function of residual range. Each line represents an event from a sample of tracks with energy $\geq$ 20 MeV/nucleon. The charge scale is logarithmic along a diagonal (see text). Normalization is made at the oxygen group.

Fig. 2 Grain density measurements as a function of residual range for protons and helium nuclei. These results are from one of several Ilford K.2 type of emulsion plates studied. Each point represents one event. Notice that the separation between proton and helium counts decreases as range decreases owing to saturation effects at the track core.

Fig. 3 Differential energy spectra for protons, helium and medium group nuclei ($6 \leq Z \leq 9$). Proton fluxes shown here are divided by 10 for ease of representation. Proton fluxes Determined from ionization and range measurements on individual events are shown by triangles whereas fluxes determined by taking the difference of integral particle counts at different depths in the stack are labeled by diamonds. Helium nuclei are represented by squares. Medium nuclei are multiplied by 58, the best estimate of the helium-to-medium ratio, and are shown by circles. Solid circles are used for energy regions where charges could be assigned to individual members of the medium group. Open circles refer to medium nuclei which are resolved from helium but are not individually identified.

Fig. 4 Solar abundances relative to oxygen determined from solar cosmic ray measurements and from spectroscopic measurements of the solar corona and photosphere. The uncertainties in the results from solar cosmic ray abundances represent experimental uncertainties in abundance ratios relative to oxygen. For both spectroscopic studies, the error bar symbol is used to denote a range of values quoted by different authors. The horizontal bars on the iron point denote a group of charges for both cosmic ray and spectroscopic data. For the general coronal abundances, see Dupree and Goldberg (1967) and Pottash (1964a and 1964b). For the iron abundance in the corona see Jordan (1966), Nikolsky (1969), Pottash (1967), and Wilding and Sandlin (1968). General photospheric abundances are from Goldberg, Muller, and Aller (1960); and Lambert and Warner (1968). For the iron abundance in the photosphere see Garz and Koch (1969), Garz et al. (1969), Goldberg, Kopp, and Dupree (1964), Grevèsse and Swings (1969), Rogerson (1969), and Warner (1968). The uncertainties in the iron abundance from cosmic ray data has been adjusted to take into account propagation and acceleration effects, as described in the text.

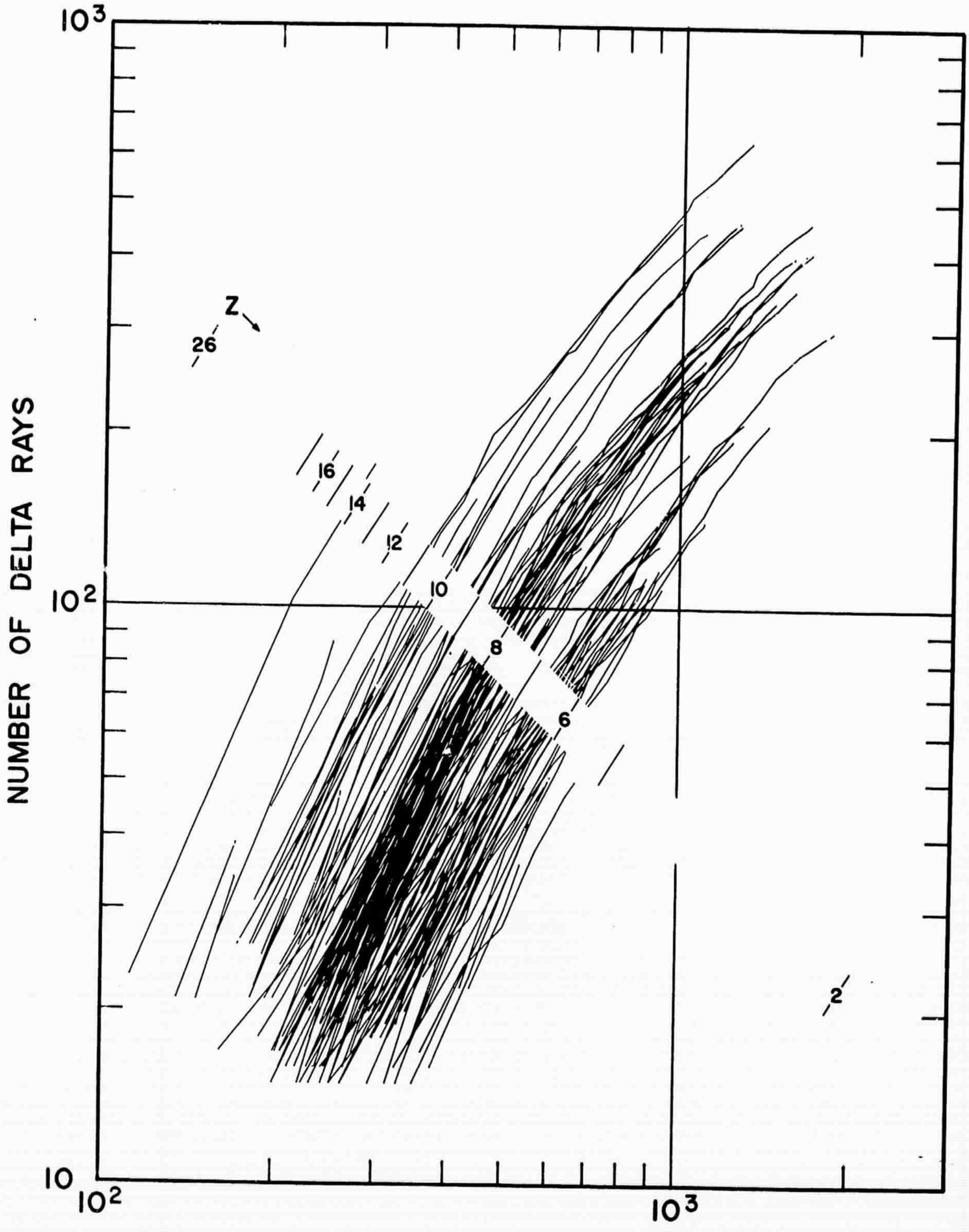
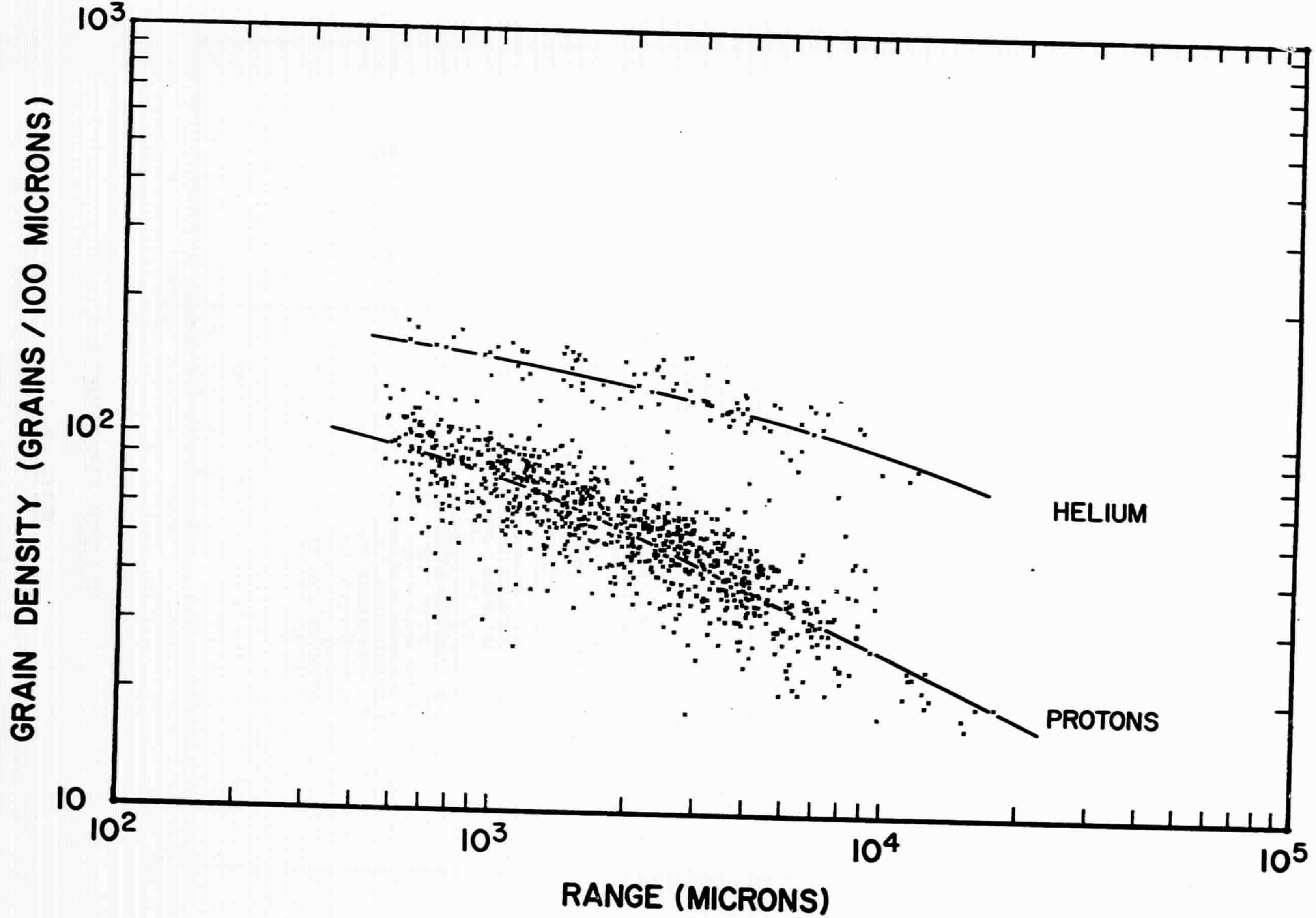
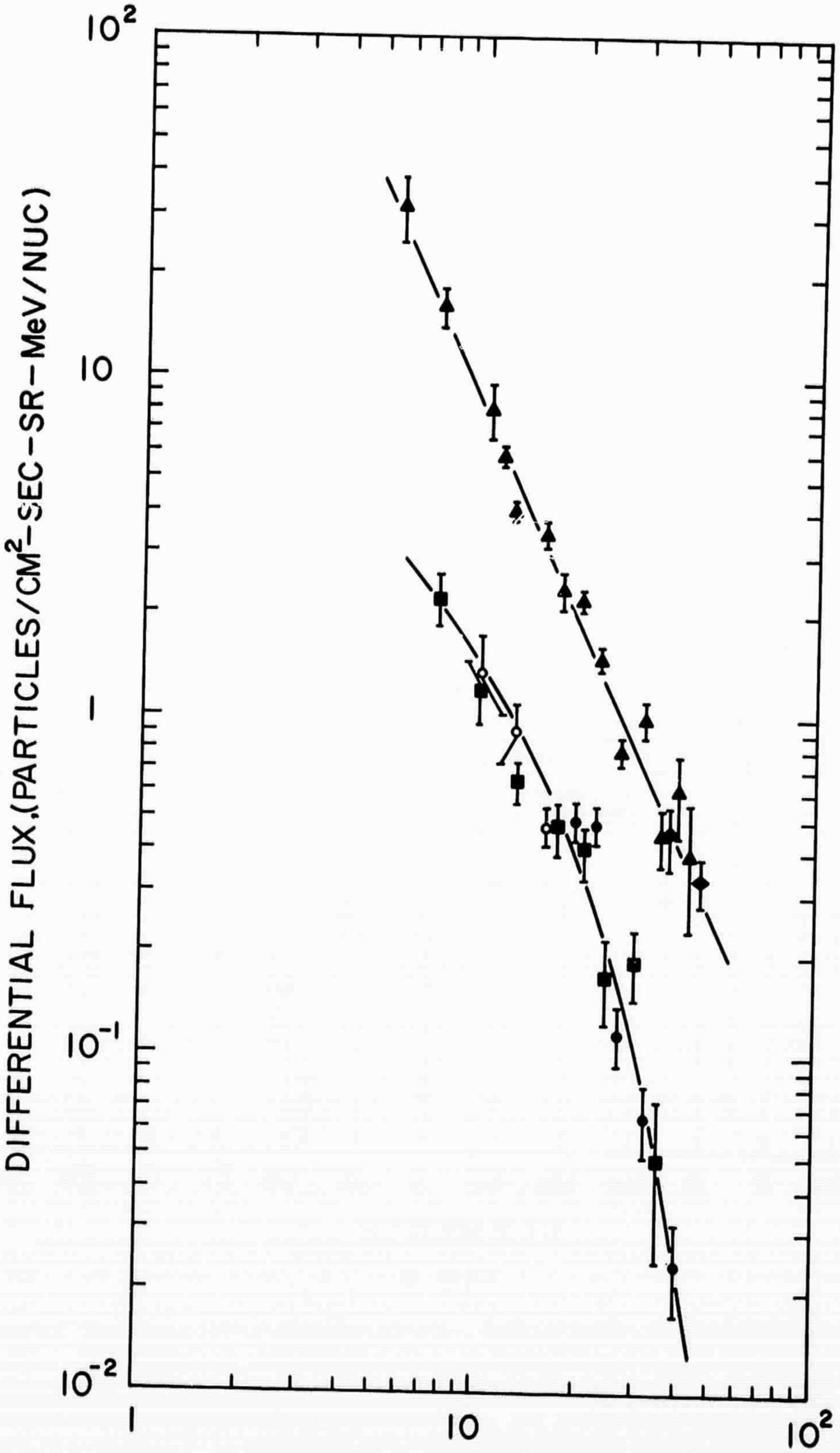


FIG. 1



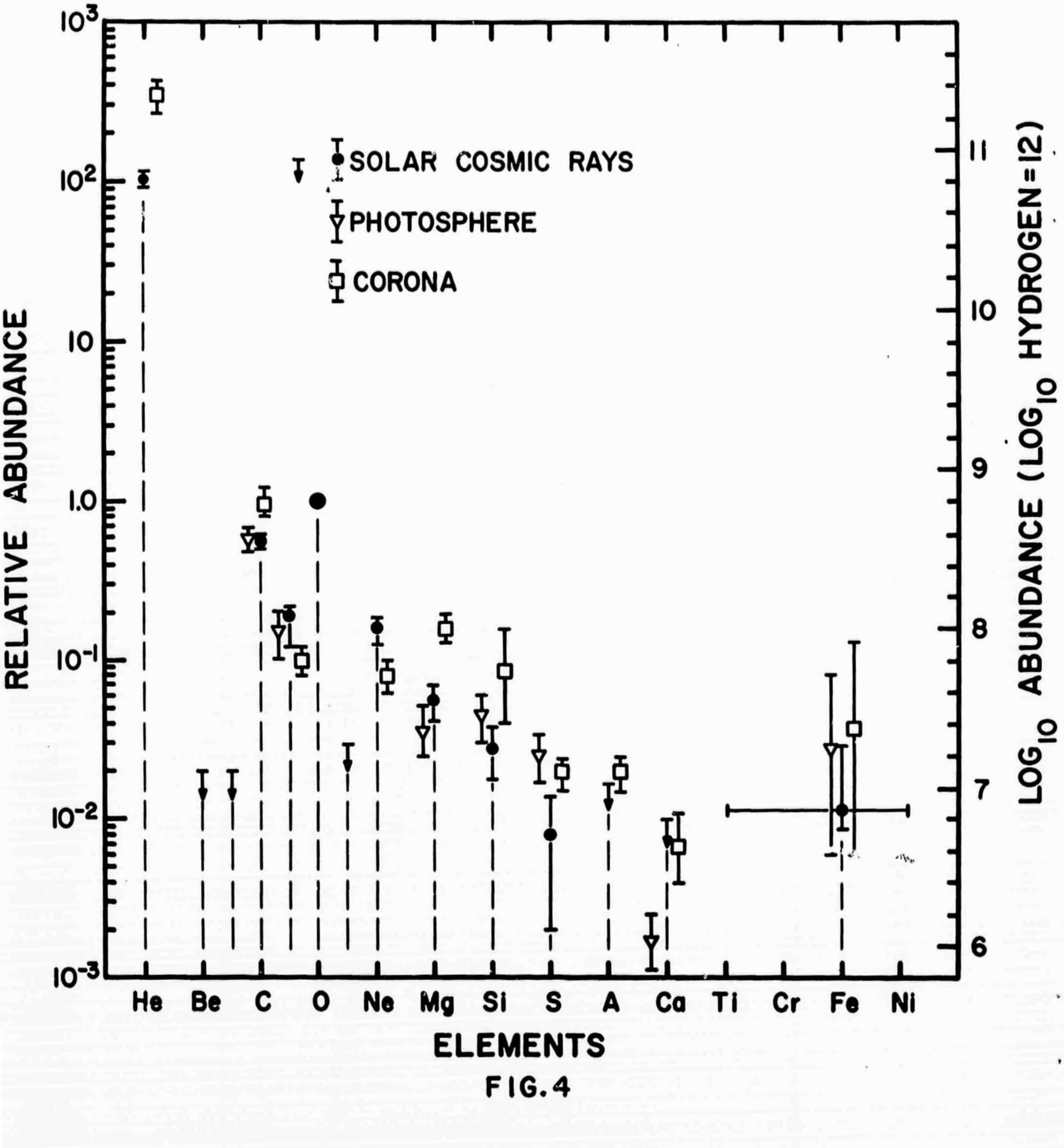
GRAIN DENSITY (GRAINS / 100 MICRONS)
10^3
10^2
10
10^2
10^3
10^4
10^5
HELIUM
PROTONS
RANGE (MICRONS)

FIG. 2



10^2
10
1
10^{-1}
10^{-2}
DIFFERENTIAL FLUX, (PARTICLES/CM^2-SEC-SR-MeV/NUC)
1
10
10^2
KINETIC ENERGY (MeV/NUC)

FIG. 3



SOLAR COSMIC RAYS
PHOTOSPHERE
CORONA
RELATIVE ABUNDANCE
LOG10 ABUNDANCE (LOG10 HYDROGEN = 12)
ELEMENTS
He
Be
C
O
Ne
Mg
Si
S
A
Ca
Ti
Cr
Fe
Ni

FIG. 4

TABLE I
HELIUM-TO-MEDIUM NUCLEI RATIO

TIME OF MEASUREMENTS	ENERGY INTERVAL MeV/NUCLEON	He/M	REFERENCE
1408 UT, SEPT. 3, 1960	42.5–95	68 ± 21	FICHTEL & GUSS, 1961
1840 UT, NOV. 12, 1960	42.5–95	63 ± 14	BISWAS, FICHTEL & GUSS, 1962
1603 UT, NOV. 13, 1960	42.5–95	72 ± 16	BISWAS, FICHTEL & GUSS, 1962
1951 UT, NOV. 16, 1960	42.5–95	61 ± 13	BISWAS, FICHTEL, GUSS & WADDINGTON, 1963
0600 UT, NOV. 17, 1960	42.5–95	38 ± 10	BISWAS, FICHTEL, GUSS & WADDINGTON, 1963
0339 UT, NOV. 18, 1960	42.5–95	53 ± 14	BISWAS, FICHTEL, GUSS & WADDINGTON, 1963
1305–1918 UT, JULY 18, 1961	120–204	79 ± 16	BISWAS, FICHTEL & GUSS, 1966
1443 UT, SEPT. 2, 1966	12–35	48 ± 8	DURGAPRASAD, FICHTEL, GUSS & REAMES, 1968
2233 UT, SEPT. 2, 1966	14–35	53 ± 14	DURGAPRASAD, FICHTEL, GUSS & REAMES, 1968
2319 UT, APRIL 12, 1969	18–34	55 ± 8	PRESENT WORK
WEIGHTED AVERAGE OF ABOVE READINGS		58 ± 5	
1225–2345 UT, JULY 12, 1959	150–200	$\geq 100 \pm 35$	BISWAS, 1961
1030–1230 UT, NOV. 15, 1960	175–280	$\sim 100^{+100}_{-50}$	NEY & STEIN, 1962

TABLE II

ELEMENT	SOLAR COSMIC RAY RELATIVE ABUNDANCE
^{2}He	103 ± 10
^{4}Be	$< .02$
^{5}B	$< .02$
^{6}C	$.56 \pm .06$
^{7}N	$.19 \pm {}^{.03}_{.07}$
^{8}O	1.0 (NORMALIZATION REFERENCE)
^{9}F	$< .03$
^{10}Ne	$.016 \pm .03$
^{12}Mg	$.056 \pm .014$
^{14}Si	$.028 \pm .010$
^{16}S	$.008 \pm .006$
^{18}A	$< .017$
^{20}Ca	$< .010$
$^{22}Ti - {}^{28}Ni$	$.011 \pm .003$