passing him between two events he wants to compare. This is proportional to V^2dt (the constant of proportionality being a universal one dependent only on the kind of atom and the particular transition chosen), in *agreement* with Eq. (9) for m-clocks. Thus, atomic standards and m-clocks measure the same "time," which is not Einstein's proper time.

The generalization to nuclei is fairly obvious. It is necessary to consider this in a little detail, however, because the best gravitational red-shift experiments use nuclear transitions.[9] Dicke's argument[11] on the constancy of α was based on the constancy of Coulomb corrections to nuclear binding energies established by the improved Eötvös experiment.[7] But the Coulomb corrections represent only a fraction of the binding energy; if the *nuclear* binding energy could vary with gravitational potential, the consequences for the Eötvös experiment would be catastrophic. Perhaps this is why Dicke passed over that point. Of course, there could conceivably be a peculiar cancellation of variations in the binding energies of nuclei due to variations in α and the nuclear (presumably mainly pion) coupling constant, but this seems far-fetched. It would have to cancel perfectly for a variety of nuclei, even though Coulomb corrections represent different fractions of the binding energy in the various nuclei used.[7]

Now that atomic and nuclear spectral frequencies have been shown to agree with the rate of m-clocks, one may study the gravitational red-shift problem. Gravitational red shifts may be distinguished from Doppler shifts due to relative motion only in static spaces. Therefore, the discussion will be confined to static spaces, and it may be assumed without loss of generality that preferred coordinates have been chosen such that g_{ij} is diagonal and time-independent. Then[12] the space is the direct product of the space sections $t=$ const with the time axis; in other words, all space sections are congruent and are orthogonal to the time axis. If we consider an atom at $x^\alpha(1)$ and another at $x^\alpha(2)$, the world lines of the photons from 1 to 2 are carried into each other by a translation of the time axis. Thus, to compute a spectral shift, one must compare the number of ticks of identical atomic clocks at locations 1 and 2 during equal intervals of coordinate time t. According to (7), with $d\sigma$ fixed at dL by Fock's hypothesis, m-clocks "tick" at intervals $d\tau$ proportional to g_{00}^{-1}, and so have rates (in terms of t) proportional to g_{00}. Presuming that atomic clocks behave similarly, one finds that a spectral line emitted at $x^\alpha(1)$ with frequency ω is observed at $x^\alpha(2)$ with frequency

$$\omega' = [g_{00}(1)/g_{00}(2)]\omega. \qquad (11)$$

This frequency ratio is the square of that found in Einstein's theory.[4,5] For the weak-field case, then, the spectral shift is twice that found in general relativity, showing that Fock's hypothesis contradicts experiment.[8,9]

The author is indebted to the National Aeronautics and Space Administration for support under grant No. NASA-NsG 233-62.

[12] *Gravitation, an Introduction to Current Research*, edited by L. Witten (John Wiley & Sons, Inc., New York, 1962), pp. 67–69.

PHYSICAL REVIEW VOLUME 162, NUMBER 5 25 OCTOBER 1967

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

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Sounding rockets carrying nuclear emulsions to study the composition and energy spectra of the low-energy cosmic rays were flown on 17 and 23 June 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 15 June 1965. The helium-nucleus flux between 15 and 22 MeV/nucleon was found to be significantly lower on 17 June 1965 immediately after the Forbush decrease than on 23 June 1965. The charge spectrum indicates that in the region from 40 to 90 MeV/nucleon the ratio of light- to medium-nucleus fluxes is 0.19 ± 0.07, 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

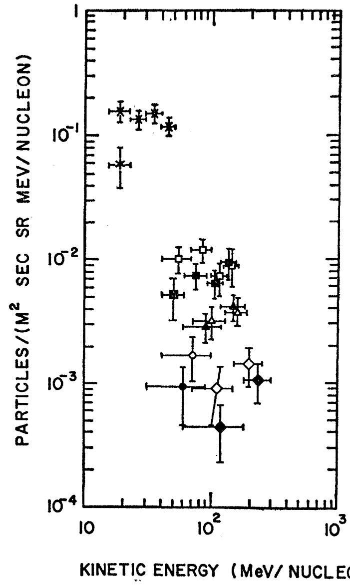

FIG. 1. Differential energy spectra for the charge groups indicated below.

	July 1964	17 June 1965	23 June 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	

theoretical studies, it is necessary to know the relative abundance 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 affects the intensity and not the relative abundance 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 g/cm² 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 comsic-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 were gathered during sounding rocket flights on 17 June and 23 June 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 1 cm from the remainder of the nuclear emulsion stacks, consisting of about 20 nuclear emulsions, 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 sec, after which the trays were retracted, and the top sandwich section of each stack was restored to its initial position in preparation for reentry into the atmosphere. Extension and retraction each took about 7 sec. Except for the top sandwich, the nuclear emulsion detectors were 600-μ Ilford G-5 pellicles, 6.3 cm$\times$29 cm. The total amount of material above the top emulsion was 0.041 g/cm² (emulsion equivalent), and there was 0.026 g/cm² 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 particles entering their surface within a dip angle $<65°$ 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

[1] C. E. Fichtel, D. E. Guss, and K. A. Neelakantan, Phys. Rev. **138**, B732 (1965).
[2] V. K. Balasubrahmanyan, D. E. Hagge, G. H. Ludwig, and F. B. McDonald, J. Geophys. Res. **71**, 1771 (1966).
[3] G. M. Comstock, C. Y. Fan, and J. A. Simpson, Astrophys. J. **146**, 51 (1966); and G. M. Comstock, Bull. Am. Phys. Soc. **12**, 582 (1967).
[4] D. V. Reames and C. E. Fichtel, Phys. Rev. **149**, 991 (1966).

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 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. Figure 2 shows some representative data on helium and medium nuclei obtained by other groups at times when the differential fluxes expected to be similar but 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.

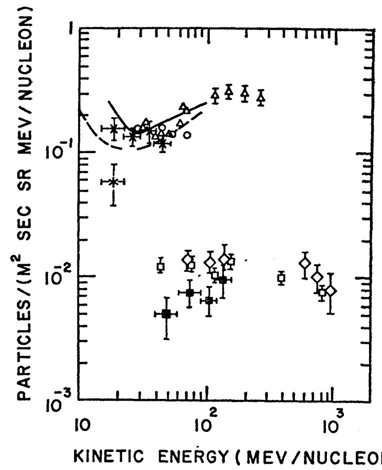

FIG. 2. Differential energy spectra for helium and medium nuclei measured by several groups.

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

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. 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

[5] C. Y. Fan, G. Gloeckler, K. C. Hsieh, and J. A. Simpson, Phys. Rev. Letters 16, 813 (1966).

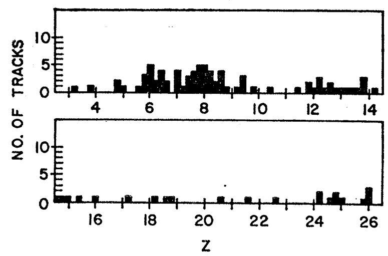

FIG. 3. Histogram of measured charge in the 1965 exposures.

et al.[6] 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] and 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.*[7] and Comstock *et al.*,[3] obtained in November and December 1964, and the data of this work and Hagge *et al.*,[6] 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 17 June 1965, 2 days after the Forbush decrease, than on 23 June 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.

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 δ-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 versus residual range.

TABLE I. Neutron monitor levels during measurements of interest.

Date	Deep River neutron monitor[a,b]
23 July 1964	2085
25 July 1964	2091
Typical May–early June 1965	2120
17 June 1965	2093
23 June 1965	2114

[a] Courtesy of Dr. H. Carmichael.
[b] Scaled to old readings.

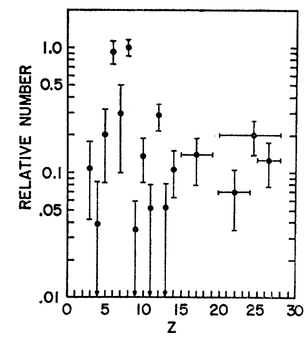

FIG. 4. Relative number of nuclei of indicated charge Z with respect to oxygen in the energy/nucleon interval given below.

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

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 $L/M=0.19\pm0.07$ 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 $L/M\simeq 0.5$ near 400 MeV/nucleon. The energy dependence of the observed L/M ratio now seems to be well established and

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		$0.30_{-0.20}^{+0.15}$	40–150

[6] V. K. Balasubrahmanyan, D. E. Hagge, and F. B. McDonald (private communication of work to be published).
[7] C. Y. Fan, G. Gloeckler, and J. A. Simpson, in *Proceedings of the Ninth International Conference on Cosmic Rays, London, 1965* (The Institute of Physics and The Physical Society, London, 1966).

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.*[a]
100	0.29±0.07	0	Balasubrahmanyan *et al.*[b]
150–250	0.38±0.13	2.7	Malmquist[c]
200–575	0.45±0.06	3.7	Anand *et al.*[d]
200–700	0.53±0.11	4.7	Badhwar *et al.*[e]
200–700	0.51±0.07	1.5–2.5	Koshiba *et al.*[f]
200–700	0.37±0.05	8.0	Aizu *et al.*[g]
200–1000	0.43±0.07	3.8	Foster and Debenedetti[h]
260–360	0.37±0.05	2–6	Webber and Ormes[i]
350–450	0.39±0.05	2–6	Webber and Ormes[i]
400–800	0.28±0.08	5.0	Balasubrahmanyan and McDonald[j]
450–600	0.32±0.04	2–6	Webber and Ormes[i]
600–800	0.27±0.04	2–6	Webber and Ormes[i]
800–1200	0.31±0.05	2–6	Webber and Ormes[i]
1200–2000	0.30±0.04	2–6	Webber and Ormes[i]
2000–5000	0.25±0.06	2–6	Webber and Ormes[i]
>575	0.28±0.03	3.7	Anand *et al.*[d]
>700	0.26±0.02	2–8	Average of footnotes e, f, g, and j
>1500	0.25±0.06	2.7	O'Dell *et al.*[k]
>5000	0.195±0.05	2–6	Webber and Ormes[i]
>15000	0.25±0.07[l]	6.7	Durgaprasad[m]

[a] See Ref. 3.
[b] See Ref. 2.
[c] See Ref. 8.
[d] K. C. Anand, S. Biswas, P. J. Lavakare, S. Ramadura, N. Sreenivasan, V. S. Bhatia, V. S. Chohan, and S. D. Pabbi, J. Geophys. Res. **71**, 4687 (1966).
[e] G. D. Badhwar, S. N. Devanathan, and M. F. Kaplon, J. Geophys. Res. **70**, 1005 (1965).
[f] M. Koshiba, E. Lohrmann, H. Aizu, and E. Tamai, Phys. Rev. **131**, 2692 (1963).
[g] H. Aizu, Y. Fujimoto, S. Hasegawa, M. Koshiba, I. Mito. J. Nishimura, and K. Yakoi, Progr. Theoret. Phys. (Kyoto), Suppl. **16**, 54 (1960).
[h] F. Foster and A. Debenedetti, Nuovo Cimento **28**, 1190 (1963).
[i] W. R. Webber and J. F. Ormes, University of Minnesota (unpublished).
[j] V. K. Balasubrahmanyan and F. B. McDonald, J. Geophys. Res. **69**, 3289 (1964).
[k] F. W. O'Dell, M. M. Shapiro, and B. Stiller, J. Phys. Soc. Japan, Suppl. AIII **17**, 23 (1962).
[l] Only Be and B were measured; a Li to (Li+Be+B) ratio of $\frac{1}{3}$ was assumed.
[m] N. Durgaprasad, Ph.D. thesis, University of Bombay, 1964 (unpublished).

should be explained by any theory of cosmic-ray origin and propagation.

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 is 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 $N/O=0.30_{-0.20}^{+0.15}$ (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 is the carbon-to-oxygen flux ratio which we find to be 0.94±0.21. The approximate equality of these two species has also been reported by Balasubrahmanyan *et al.*,[2] by Comstock *et al.*,[3] and by Malmqvist[8] 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.

[8] L. Malmqvist, Arkiv Fysik **34**, 33 (1967).