Performing once again the substitution $\xi/\lambda_1=x$ and separating the divergent part from the integral, we obtain

$$\operatorname*{Re}_{\lambda\to 0,\ \arg\lambda=0} v(\lambda)=\frac{1}{2q\beta^2}\operatorname*{Re}_{\lambda\to 0,\ \arg\lambda=0}\left\{\lambda_1\int_0^1\left(\frac{1-x}{1+x}\right)^{\mu}dx - i\alpha\int_0^1\frac{dx}{x}\left[\left(\frac{1-x}{1+x}\right)^{\mu}-1\right]-i\alpha\ln\left(\frac{\lambda_1}{\lambda}\right)\right\}.$$

Inserting $x=\tanh(t/2)$ and separating the real part, we get

$$\operatorname*{Re}_{\lambda\to 0,\ \arg\lambda=0} v(\lambda)=\frac{1}{2q\beta^2}\left\{-\frac{\pi\alpha}{4}+\alpha\int_0^\infty e^{-st}\frac{\sin st}{\sinh t}dt+\frac{1}{2}\left(\frac{\beta}{2}\right)^{\frac{1}{2}}\int_0^\infty e^{-st}\frac{\cos st+\sin st}{\sinh(t/2)}dt\right\}.$$

Thus,

$$\int_0^\infty \operatorname{Re}\varphi_2 dz=\int_0^\infty \operatorname{Re} f dz=\frac{1}{6\alpha\beta q}\phi(s), \tag{6A}$$

where

$$\phi=3s\int_0^\infty e^{-st}\frac{\cos st+\sin st}{\cosh^2(t/2)}dt+24s^2\int_0^\infty e^{-st}\frac{\sin st}{\sinh t}dt-6\pi s^2$$
$$=12s^2\int_0^\infty \coth(t/2)e^{-st}\sin st dt-6\pi s^2. \tag{7A}$$

The functions $\phi(s)$ and $G(s)$ can be expressed through the logarithmic derivatives of the Γ function.[8]

$$\begin{aligned}\phi(s)&=12s^2\{-\operatorname{Im}[\Psi(s-is)+\Psi(s+1-is)]-\tfrac{1}{2}\pi\}\\&=6s-6\pi s^2+24s^3\sum_{k=1}^{\infty}\frac{1}{(k+s)^2+s^2},\\G(s)&=48s^2[\tfrac{1}{4}\pi+\operatorname{Im}\Psi(s+\tfrac{1}{2}-is)]\\&=12\pi s^2-48s^3\sum_{k=0}^{\infty}\frac{1}{(k+s+\frac{1}{2})^2+s^2}.\end{aligned} \tag{8A}$$

These formulas are useful for the tabulations of $\phi(s)$ and $G(s)$.

[8] Relations (8A) were obtained by S. A. Heifetz.

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Time Variation of Primary Heavy Nuclei in Cosmic Radiation*

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The time variation of heavy nuclei in the primary cosmic radiation was investigated by using the method of a moving-plate mechanism which was flown to an altitude of 100 000 feet by a Skyhook balloon. The results obtained clearly indicate a time variation of primary heavy nuclei $Z\gtrsim 10$. The variation is characterized by its maximum at around 9:00 A.M., having an amplitude of $34\pm 7\%$ at the maximum. Comparisons are made with other experimental data on the same subject and also with the neutron intensity variation on the same day at Climax, Colorado. Possible consequences of this rather large fluctuation of the primary heavy nuclei are discussed.

I. INTRODUCTION

THE primary cosmic radiation has long been studied as to the intensity, the energy spectrum, the chemical or isotopical composition.[1] The investigation of the intensity variation with time, among others, is of importance in order to understand the problem of where and how the primary cosmic radiation is accelerated or modulated. Some information on this subject has been obtained from the observations at sea level or at mountain altitudes using counters, ionization-chambers, and neutron detectors. For example, from these observations we know approximately the type of intensity variations that exist in the cosmic radiation, the energy dependence of the intensity variation of a certain type, etc.[1]

These investigations, however, are based on the observations of secondary effects which were generated in the atmosphere by the interactions of the primary radiation; thus implying, among others: (1) that it is, in general, impossible to detect the intensity fluctuations of very low-energy primary particles which do not give rise to observable effects in detectors deep in the atmosphere, and (2) that at the present time the variations of heavy nuclei which constitute only a small fraction of the primary cosmic radiation cannot

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[1] Summaries on these subjects are given, for example, in J. G. Wilson, *Progress in Cosmic-Ray Physics* (North-Holland Publishing Company, Amsterdam, 1952); W. Heisenberg, *Kosmische Strahlung* (Springer-Verlag, Berlin, 1953).

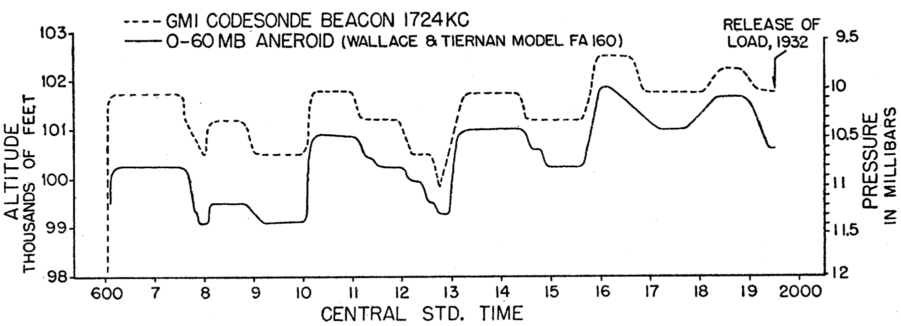

Fig. 1. Atmospheric pressure change during the flight at high altitude.

be studied in a clear-cut way since the attenuation mean free paths of these particles are much shorter than those of protons which constitute the main body of the primary cosmic radiation.

Obviously, observations at high altitudes by means of ballons or rockets have been the answer to overcome the first difficulty and have given additional information[2] on the energy dependence of various types of intensity fluctuations. The high altitude observations also render a possibility for observing the primary heavy nuclei before they are destroyed by collisions with air nuclei. The investigations of the intensity fluctuation of primary heavy nuclei was initiated in particular in 1950 by Lord and Schein,[3] and by Freier, Ney, Naugle, and Anderson[4] who used balloon-borne photographic emulsions for detecting heavy nuclei. Additional experiments followed since then; some with photographic emulsions,[5–7] some with a cloud chamber triggered by proportional counters,[8] some with scintillation counters,[9] and some with ionization-chambers.[10,11] The results of these investigations, however, do not yield a very consistent picture. It must be borne in mind in this connection that: (1) the observations at sea level and at mountain altitude of the diurnal variation of the neutron intensity[12] indicates that both the amplitude and phase change from day to day; (2) for charged particles coming from the direction of the sun, there seem to exist a few impact zones outside which the arrival of these particles to the earth, depending on the local time, is theoretically not allowed.[13] Since the observation of the primary cosmic radiation by means of balloon flights is, in general, limited in time within a fraction of a day, the above considerations may explain the lack of consistency between the experimental data. It is, therefore, important to show by a clear-cut and definite experiment, whether there does exist a variation of heavy primaries and, if that is so, when the maximum of the variation does occur and what the amplitude of it is.

II. EXPERIMENTAL PROCEDURES

The method used in this work is the one proposed by Lord and Schein[3] and subsequently developed by the University of Chicago group. It is called the method of moving plates. A similar technique was used by Freier and others.[4–6] The details of the method used in this laboratory were described by Yngve.[7] A moving plate mechanism which contained two 4 in.×4 in. G-5 600μ thick emulsions similar to that used by Yngve was flown in a Skyhook balloon which was launched from Minnesota at 4:30 A.M. on June 24, 1955, and the apparatus containing the emulsion was dropped by parachute at 7:32 P.M. on the same day. The trajectory was very nearly a straight line connecting the launching and recovery point. The altitude variation at the top of the atmosphere for this flight is given in Fig. 1.

The atmospheric pressure during the flight was measured by three independent barometers, one of which recorded for the first four hours (not shown in figure) and the other two for the entire flight period. These independent measurements of the atmospheric pressure agreed with each other for all three barometers within a few tenths of a millibar on a relative scale throughout the whole flight. For the purpose of correcting the percentage intensity variation of primary heavy nuclei for the change of the atmospheric pressure, the absolute magnitude of the pressure is actually not needed as long as we assume the exponential dependence on air depth for the attenuation of heavy nuclei. However, the pressure fluctuations during the flight are the ones to be measured with utmost precaution. As seen from Fig. 1, the measurement of the atmospheric pressure variation during the flight can be considered to be correct within an error of less than a few tenths of a millibar. If we take an attenuation mean free path

[2] W. P. Jesse, Phys. Rev. **58**, 281 (1940); R. A. Millikan and H. V. Neher, Phys. Rev. **56**, 491 (1939); Lord, Elston, and Schein, Phys. Rev. **80**, 970 (1950).

[3] J. J. Lord and M. Schein, Phys. Rev. **78**, 484 (1950).

[4] Freier, Ney, Naugle, and Anderson, Phys. Rev. **79**, 206 (1950).

[5] Freier, Anderson Naugle, and Ney, Phys. Rev. **84**, 322 (1951).

[6] Anderson, Freier, and Naugle, Phys. Rev. **91**, 431 (1953).

[7] V. H. Yngve, Phys. Rev. **92**, 428 (1953).

[8] T. H. Stix, Phys. Rev. **95**, 782 (1954).

[9] E. P. Ney and D. M. Thon, Phys. Rev. **81**, 1069 (1951).

[10] G. W. McClure and M. A. Pomerantz, Phys. Rev. **84**, 1252 (1951).

[11] Work of the cosmic-ray group at the State University of Iowa (private communication from Dr. Van Allen).

[12] R. P. Kane, Phys. Rev. **98**, 130 (1955).

[13] A. Schluter, Naturforschung **6a**, 613 (1951). For a review of the work on this subject, see A. Schluter in *Kosmische Strahlung*, edited by Heisenberg (Springer-Verlag, Berlin, 1953), Chap. 1. See also J. Firor, Phys. Rev. **94**, 1017 (1954).

of 25 g/cm², which is considered to be a good approximation for nuclei of $Z \gtrsim 10$, even an error of one millibar which is more than twice the error in the barograph in the measurement of the atmospheric pressure change, will lead to a spurious percentage variation of only about 4%.

After the processing, the two plates of the moving plate mechanism were aligned and put together face to face as they were at the time of exposure. One of them was scanned for heavy nuclei using a 10× objective. The criterion for the acceptance of tracks was set to locate nuclei which are definitely heavier than oxygen nuclei. Since the tracks of shorter length give, in general, more accurate results of the measurement of their arrival time, we have to include many tracks of large dip angle with respect to the emulsion surface. Therefore, the δ-ray counting on individual tracks will not render a criterion much better than the comparison by inspection with some tracks of identified charges. The tracks of relativistic oxygen nuclei were located in the preliminary scanning by one of the authors (M.K.) and identified by their breakup into α particles. The tracks were accepted when they were, by inspection, very definitely heavier than these oxygen tracks. Hence, the actual Z spectrum of the accepted tracks sharply dropped at atomic number Z equal to or smaller than 8. However, a 10–15% contribution from the group of C, N, O nuclei cannot be excluded. The contamination of slow α particles is negligible. It is then concluded that the accepted tracks were predominantly due to nuclei of $Z \gtrsim 10$. We do not claim that all the nuclei of $Z \gtrsim 10$ in the scanned area were collected by this method or that the contamination of medium nuclei was very small. A contamination of $Z<10$, however, does not introduce any error in the intensity fluctuation experiment as long as the tracks are randomly chosen irrespective of of their relative displacement between the two moving plates, i.e., irrespective of their arriving time. When a track was found to be acceptable in the scanned plate, it was traced to the partner plate which was aligned on top of the former. The criterion here to assure the correct tracing was the visual density of the track and the two angles, the dip angle and the projected angle. Because of a low population of these heavy nuclei in the plate, the tracing was a very easy task. Since the two plates were moving with respect to each other at the time of exposure, the displacement of a track going from one plate to the other gives the arrival time of this track. The displacement in the direction of the plate motion was measured on each individual track. The correction for the dip angle and for the air gap between the plates has been done in a way similar to that described by Yngve.[7] A total of 1796 tracks were analyzed in this way.

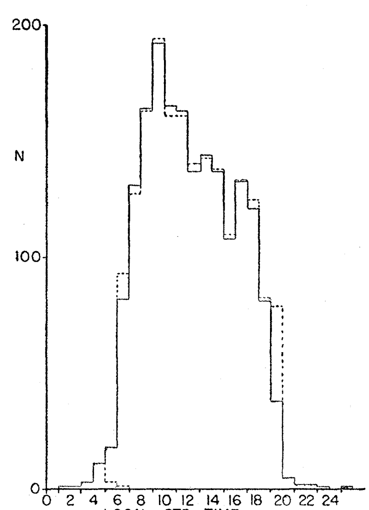

FIG. 2. Number of heavy nuclei as a function of their arrival time. The solid line and the dotted line represent the data without and with the corrections due to altitude change and latitude change, respectively.

In order to convert the displacement scale into the time scale, we made use of the following factual situation: first, utmost precaution was taken to ascertain that the two plates were moving with a constant velocity, and second, that due to the very short attenuation mean free path of heavy nuclei, they are observable only close to the top of the atmosphere. Hence the sharp rise and the sharp decrease in the number distribution of heavy nuclei on the displacement scale were identified as the rising and the descending time of the balloon (see Fig. 2). Then the actual procedure was as follows: A distribution of the number of tracks was obtained in each 100-micron cell of displacement. The two ends of the number distribution were examined more carefully by using two sets of overlapping intervals, each of these 200 microns long and both derived from the original 100-micron interval. The number distribution in these two sets of displacement intervals gave a cross-check for the determination of the effective arriving and leaving time to and from the upper atmosphere. The two end points thus found were 462 ± 12 and 4162 ± 21 microns of displacement corresponding to 6 A.M. and 7:30 P.M. Central Standard Time as recorded in the flight data. The uniform velocity of the moving plate mechanism was hence found to be 275 ± 6 microns per hour. The tracks were now regrouped according to the new set of displacement cells which started from 462 microns and had constituent cells of a width of 275 microns each. The final results are presented in Fig. 2, where the number of tracks is plotted against the time of arrival.

III. RESULTS AND DISCUSSION

In order to obtain the actual time variation of heavy nuclei, we have to make two corrections, i.e., for the altitude variation and for the latitude drift during the flight. The altitude correction in this experiment is very small because of the leveled flight at high altitude, as can be seen from Fig. 1. The correction was, in effect, found not to exceed 3% in any time interval throughout the flight at high altitude. The attenuation mean free path of heavy nuclei, as mentioned previously, was taken to be 25 grams/cm². This value may be somewhat too small (which makes the correction smaller), the change of this value within a reasonable range does not give any noticeable effect on the final results of the time variation of heavy nuclei since the absolute magnitude of the correction itself is very small. In addition to this altitude correction, we have to make another correction for the latitude changes (north-south drift) during the flight. This drift gives a spurious time variation during the flight due to the influence of the earth's magnetic field on the trajectories of incoming heavy nuclei. The latitude correction was made by using the data on the trajectory of the flight and using a momentum spectrum of the form[14] $1/P$ for the integral spectrum of heavy primaries. The total change in intensity due to this effect was found to be less than 8%, from the launching point to the end point of the flight. This correction would actually become still smaller if the exposure at Minneapolis took place above the knee of the latitude curve, as was reported by Ney.[15] Applying the corrections for altitude and latitude on the results shown by a solid line in Fig. 2, the dotted line was obtained. Twice as large time intervals were used for a final plot, in order to increase the statistics within each interval.

The results are shown in Fig. 3. In this figure the percentage variation of the intensity of heavy nuclei is plotted against local time. The points represent the variation from the average intensity over the period from 6:00 A.M. to 7:30 P.M. The vertical lines indicated in each interval are the statistical errors and accordingly were taken to be the square root of the total number of tracks in the interval. The results shown in Fig. 3 clearly indicate a large increase, 30±7%, of the heavy nuclei intensity at a time between 8:00 A.M. and 10:00 A.M. If we derive the ratio of the afternoon intensity to that in the morning, we get a value of 0.87±0.05. This value is in agreement with the value 0.86±0.16 which Stix[8] derived from his experiment at 41° N with a balloon borne cloud-chamber. The experiments of Ney and Thon with scintillation counters detecting predominantly α particles and $Z<10$ nuclei,[9] and Anderson, Freier, and Naugle[6] with nuclear emulsions, on the other hand, gave 1.44±0.18 and 1.0±0.2 for this ratio, respectively. However, it is important to point out that both of these experiments did not cover the period around 9:00 A.M. where the maximum was observed in this experiment. Therefore, their results do not directly contradict the existence of an increase at around 9:00 A.M. as observed here. The results of a similar experiment by Yngve[7] seemed to show, in general, an over-all increase around noon. However, his results cannot be compared in detail with the ones presented here, since the altitude correction he had to make could have caused a considerable shift of the position of the maximum. The other experiments[3–5,10] gave their results in terms of the ratio of night flux to day flux. Lord and Schein,[3] and Freier, Ney, Naugle, and Anderson[4] reported that the night flux was considerably smaller than the daytime flux. In the present experiment we do not have the data on the night flux. These results, however, are not in contradiction with ours if we assume we had only a small variation, if any, of the intensity during the night-time. Such an assumption is not unreasonable if the particles which give rise to the increase of the intensity arrive from the general direction of the sun, since calculations[13] showed that the main impact zone at the location of the exposure (Minneapolis) occurs around 9:00 A.M. for particles coming from the general direction of the sun. On the other hand, Freier, Anderson, Naugle, and Ney[5] in their experiment with nuclear emulsions reported approximately equal fluxes for day and night time. Most, $\frac{2}{3}$, of their results on the daytime flux were, however, obtained from balloon flights which did not cover the 9:00 A.M. time period. As far as the experiment of McClure and Pomerantz is concerned,[10] a direct comparison cannot be made since at the present time it is difficult to separate nuclei of $Z \gtrsim 10$ with ionization chambers.[16]

In conclusion, it is of great interest to know whether the observed intensity maximum at around 9:00 A.M.

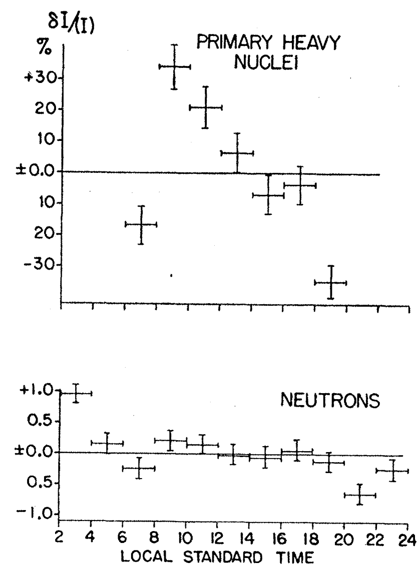

FIG. 3. Percentage variation of heavy nuclei flux with the loca time. In the lower figure the neutron data at Climax, Colorado are plotted on the same day. The vertical lines in both the figures are the statistical standard errors.

[14] For primary protons the shape of the integral spectrum is well represented by $1/P$ (P. H. Barrett *et al.* Revs. Modern Phys. **24**, 133 (1952). The spectrum of heavy nuclei is not much 'different in general from that of protons. See reference 1.

[15] E. P. Ney (private communication).

[16] G. W. McClure and M. A. Pomerantz, Phys. Rev. **79**, 911 (1950).

is of a permanent nature or whether the explanation in terms of a varying amplitude and varying phase should be applied in order to make all the experiments appear to be consistent with each other. Only additional experiments can yield a final decision between these two alternative interpretations.

As to the problem of the intensity variation of heavy nuclei observed on this particular day of June 24, 1955, there may be raised the question that the observed fluctuation might have been due to some rare disturbances in the cosmic radiation on this particular day so that this result does not represent the general behavior of the heavy component on a so-called undisturbed day. For this purpose one may compare the results of this experiment with those obtained by neutron detectors on the same day. Simpson's neutron detector at Climax, Colorado, was chosen for this purpose because of its location at a higher altitude (11 200 feet) and at a latitude and longitude not much different from that of this experiment. The neutron data are also shown in Fig. 3 and were plotted in a way comparable to those of the heavy nuclei. The errors indicated in the neutron data are statistical errors.[17] The small over-all change in neutron intensity indicates that this day, June 24, 1956, was a so-called "quiet" day with no marked disturbances present. However, a possible slight decrease in the intensity of the neutron component running somewhat parallel to that of the heavy nuclei is indicated in the figure. Therefore, we can conclude that the large variation in the intensity of the heavy nuclei component, $Z\gtrsim 10$ in the primary cosmic radiation occurred on a day which was relatively undisturbed as far as the neutron component at Climax is concerned.

Some remarks may be made as to the cause of this intensity fluctuation. First we assume an electric modulation mechanism which gives an amplitude for the variation approximately inversely proportional to the total energy of the particles.[18] Accordingly, one estimates that a 30% variation at 55° N of the heavy nuclei component $Z\gtrsim 10$ would correspond to a 9% variation in the neutron component at Climax, Colorado. This is in direct contradiction with the observation shown in Fig. 3, which shows no variation larger than 1%. However, as an alternative we can consider a varying energy cutoff of the primary particles, possibly due to varying magnetic fields. In this case in general, it is not impossible to obtain a fluctuation as large as that observed at 55° N while the neutron component at Climax remains unaffected. This is due to the fact that the geomagnetic latitude of Minneaplois is very close to the knee of the intensity-latitude curve. (Lately some indication was obtained that Minneapolis is already beyond the knee for α particles.[15]) The third possibility for the cause of the observed effect may be the direct emission of heavy nuclei from the sun. The position of the observed maximum in the present experiment would not seem inconsistent with this assumption. However, in order to explain the constancy of neutron detector data within 1% as shown in Fig. 3, one would have to restrict this process to heavy nuclei only, of energy less than about 2 Bev per nucleon.[19]

The final answer to the problem of the nature of the intensity variation of heavy nuclei obviously requires further studies. It is our intention to carry out additional experiments similar to the one described in the present paper.

ACKNOWLEDGMENTS

We wish to thank Mr. David Haskin for his assistance in preparing the moving plate mechanism and for processing the plates. The authors are also grateful to Miss H. Probst for her aid in scanning the plates.

[17] 7000 counts/min given by J. A. Simpson *et al.* [Phys. Rev. **90**, 934 (1953)] for the typical counting rate of this detector. We wish to thank Professor Simpson for furnishing us the neutron data.

[18] See, for example, W. H. Fonger, Phys. Rev. **91**, 351 (1953).

[19] α particles should be excluded from the process since otherwise neutron monitors would show a considerable variation, except if the α component undergoing the variation has energies less than 0.8 Bev corresponding to the cutoff energy for the neutron detector.