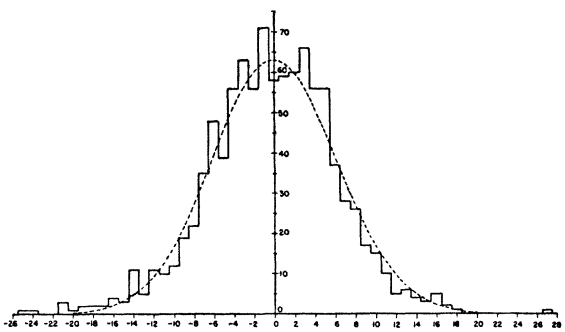

FIG. 1. Distribution curve of second differences (in units of 0.93μ) for 978 intervals of 100μ each. The dotted curve is the corresponding Gaussian distribution with the same mean as for the observed data out to second differences of 20 units.

are always larger than the true mean angles because (1) the observer records the coordinates of the track with an uncertainty Δy, (2) the emulsion may have distortions, and (3) the microscope stage motion may be more or less erratic. There is no evidence for systematic distortions (Fig. 1).

The observer uncertainties and the short-distance microscope irregularities can be treated in the following way. The coordinate y is assumed to be measured with an average uncertainty $\langle\Delta y\rangle_{\text{Av}}$. Then one can show that the measured second difference $\langle D_m(X)\rangle_{\text{Av}}$ for an interval X is related to the true value $\langle D_T(X)\rangle_{\text{Av}}$ by

$$\langle D_m(X)\rangle_{\text{Av}}^2=\langle D_T(X)\rangle_{\text{Av}}^2+6\langle\Delta y\rangle_{\text{Av}}^2.$$

One can show further that

$$\langle D_T(X)\rangle_{\text{Av}}=\langle\alpha_T(100)\rangle_{\text{Av}}X^{\frac{3}{2}}/(100)^{\frac{1}{2}}$$

so that a $\langle D_m(X)\rangle_{\text{Av}}^2$ *vs.* X^3 plot gives $\langle\alpha_T(100)\rangle_{\text{Av}}$ and $\langle\Delta y\rangle_{\text{Av}}$. Figure 2 is such a plot, giving $\langle\alpha_T(100)\rangle_{\text{Av}}=0.17°\pm0.020$ per 100μ. $\langle\Delta y\rangle_{\text{Av}}$ is about 0.1μ.

I have arbitrarily attributed all deflections greater than four times the mean to single scattering and therefore eliminated them from consideration here.

The simplest multiple scattering theory with which to compare these data is that of Williams,[2] as modified by Rossi and Greisen.[3] For a relativistic particle the mean projected angle between successive chords of length t (measured in radiation lengths) is given by $\langle\alpha\rangle_{\text{Av}}=(2t/3\pi)^{\frac{1}{2}}(21/E)=9.70t^{\frac{1}{2}}/E$ radians per radiation length for a particle of kinetic energy E (measured in Mev). The radiation length is $29{,}200\mu$.[4] Using microns and degrees, we have $\langle\alpha\rangle_{\text{Av}}=3.25X^{\frac{1}{2}}/E°/X\mu$. For 115-Mev electrons this gives $\langle\alpha\rangle_{\text{Av}}=0.28°/100\mu$, which is appreciably greater than the measured value of $0.17°\pm0.02°/100\mu$. The major part of the disagreement probably lies in the maximum angle above which all scatterings are disregarded. As pointed out by Bethe[5] the finite size of the nucleus, which sets an upper limit to the scattering angle in Williams' theory, may not set the limit in such a measurement as this. In fact the angle corresponding to the nuclear radius in this case is 15° or 20° whereas angles greater than about one degree are disregarded.

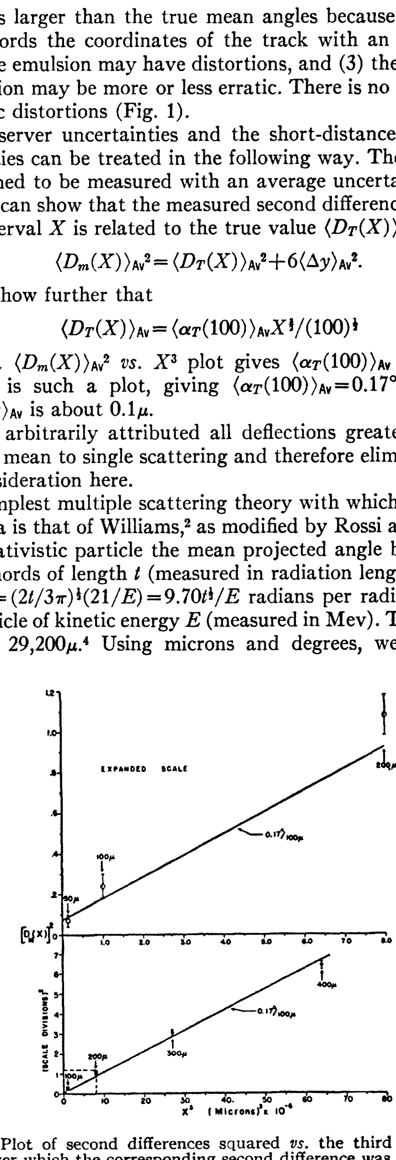

FIG. 2. Plot of second differences squared *vs.* the third power of the interval over which the corresponding second difference was observed. The upper curve is the same portion of the lower curve enclosed by dotted lines but plotted on an expanded scale. The slope of the straight line indicates a mean angle between chords of $0.17°/100\mu$.

A more satisfactory comparison can be made with the theory of Snyder and Scott.[6] The mean free path λ and the unit angle η_0 of this theory can be calculated for the emulsion to be $\lambda=1.6\times10^{-5}$ cm and $\eta_0=6.2\times10^{-3}$ degree. The mean angle $\langle\alpha\rangle_{\text{Av}}$ (considering only angles less than four times the mean) between chords can be computed to give $\langle\alpha\rangle_{\text{Av}}=0.20°/100\mu$, which is to be compared with the measured value of $0.17°\pm0.02°$.

I am indebted to Mrs. Margaret Keck for most of the observations on which these measurements are based and to Mr. J. E. Treat for some of the observations.

* This work was supported in part by the ONR.

[1] See Camerini, Fowler, Lock, and Muirhead, Phil. Mag. **41**, 413 (1950).
[2] E. J. Williams, Proc. Roy. Soc. **169**, 531 (1939); Phys. Rev. **58**, 292 (1940).
[3] B. Rossi and K. Greisen, Rev. Mod. Phys. **13**, 240 (1941).
[4] Reference 1 quotes a radiation length of $23{,}000\mu$, which I cannot account for unless it is based on some other definition of radiation length.
[5] H. A. Bethe, Phys. Rev. **70**, 821 (1946).
[6] H. Snyder and W. Scott, Phys. Rev. **76**, 220 (1949).

Diurnal Variation of Primary Cosmic-Ray Heavy Nuclei*

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SINCE the large decrease observed[1–3] in the flux of heavy nuclei at night is of interest in any theory concerning the origin of cosmic rays, additional measurements of greater accuracy and at higher elevations are reported in this paper.

Ilford G-5 photographic plates with emulsions located vertically were arranged in two separate stacks. The plates were placed in a large balloon gondola and covered with a considerable amount of thermal insulating material, since night temperatures in the stratosphere can be as low as −60°C. Several containers of water were placed below the plates so that the heat liberated in the formation of ice kept the temperature of the plates above 0°C.

A General Mills-type balloon was employed to expose the plates in the stratosphere and was launched at 6:00 P.M. on May 22, 1950, from Minneapolis. The balloon attained an altitude higher than 90,000 ft. at 7:50 P.M. CST, and from this time until 5:40 A.M. the balloon was kept between 90,000 and 94,000 ft. by a ballast release mechanism. The first of the two groups of plates was dropped by parachute at 5:45 A.M. After this the balloon rose slightly and remained almost exactly at 95,000 ft. until 12:05 P.M. when the second group of plates was dropped. The altitude was determined from pressure measurements made with a special new type of temperature-compensated barometer. The absolute accuracy of the instrument was ±1 mb over a temperature range of 60°C.

To determine the time of exposure in the stratosphere accurate corrections[2] were applied for the time of ascent and descent of plates as well as the very slight variations of altitude from the average ceiling elevation of 93,500 ft.

All of the plates were developed by the familiar temperature variation method. Each plate was scanned carefully for heavy nuclei tracks at low magnification. Each track was then re-examined with an oil immersion objective and the numbers of delta-rays longer than 1.1μ were enumerated along each track. The tracks were grouped according to their numbers of delta-rays

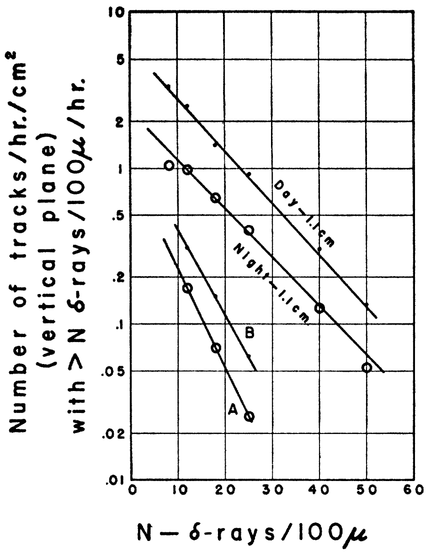

FIG. 1. Number of tracks/cm²/hr. having more than n delta-rays per 100μ. Note that the cm² is in the vertical plane.

per hundred microns. In order to show that temperature variations during the balloon flight could not affect the delta-ray intensities, measurements of the temperature sensitivity of the photographic plates were made which showed that all grain densities of tracks changed less than five percent in the interval of −15 to +28°C. At a temperature of −50°C the grain density of tracks of ionization energy loss 15 times the minimum value was reduced by 30 percent from the value at 20°C, while the tracks of minimum ionization were reduced by less than 10 percent in the same temperature interval. Thus the relatively small temperature change (20°C) occurring during the entire balloon flight could have no effect on the delta-ray intensity. This is substantiated further by the fact that the delta-ray intensity of primary nuclei of $Z\cong 26$ (iron nuclei) is the same on both the day and night portions of this balloon flight.

The flux of heavy nuclei having more than n delta-rays per hundred microns as a function of n is given in Fig. 1. In the interval from $n=10$ to $n=55$ the atomic number changes from $Z\cong 10$ to $Z\cong 26$. The upper two curves give the results of the measurements described in this paper. The ratio of the flux of heavy nuclei during the day to that at night is 2.55±0.26, and within experimental error is the same for all atomic numbers from $Z\cong 10$ to $Z\cong 26$. As given previously[2] the two curves marked A and B (Fig. 1) give, respectively, the corresponding intensities during the night and during the day at an elevation of approximately 70,000 ft. The steeper slope of the curves, A and B, at 70,000 feet is the result of the increase of the absorption cross section of heavy nuclei with Z (atomic number).

The effect to be expected at sea level due to this observed diurnal variation of heavy nuclei can be estimated. Such an estimate is based on the known altitude variation of the rate of production of relativistic particles by nuclear interactions produced by the primary heavy nuclei, which will be published shortly. If approximately one-half of the relativistic particles produced are assumed to be mesons of high energy, then a change of the order of 0.1 percent would be produced in the total meson component at sea level by the observed diurnal variation of heavy nuclei. This is in agreement with the magnitude (0.3 percent) of the well-established diurnal variation of the total intensity of cosmic rays at sea level.[4,5] This diurnal variation of heavy nuclei would also account for the observed absence of any change with altitude in the time variation of the total cosmic-ray intensity.[6,7]

Measurements will need to be made at geomagnetic latitudes of less than about 40° in order to determine whether or not only low energy heavy nuclei are responsible for the observed diurnal effect. The evidence given above suggests strongly that the origin of the heavy nuclei is closely related to the sun.

Further experiments are now in progress in which two emulsions in contact are moved at a uniform rate with respect to each other, so that the time at which each heavy nucleus passes through the plates can be determined. This will make it possible to carry out a much more detailed study of the diurnal variation. In addition, the measurements are now being extended to include particles with $Z=6$ to $Z=10$.

The efforts of Mr. C. B. Moore of the General Mills Company in making possible such an excellent balloon flight and in arranging for highly accurate altitude determinations is gratefully acknowledged. We would also like to thank Mr. J. Litwin for his assistance in the measurements.

* Assisted by the joint program of the ONR and AEC.
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[2] J. J. Lord and Marcel Schein, Phys. Rev. **78**, 484 (1950).
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A Direct Determination of the Magnetic Moment of the Proton in Nuclear Magnetons*

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September 5, 1950

THE method of Alvarez and Bloch[1] for reducing the measurement of a magnetic moment in units of the nuclear magneton μ_n to that of a frequency ratio has been applied to the magnetic moment μ_P of the proton. If ν_N and ν_R are the frequencies of nuclear resonance and orbital rotation, respectively, of a proton, both measured in the same homogeneous magnetic field H, one has

$$\nu_N = 2H\mu_P/h, \quad (1)$$

$$\nu_R = eH/2\pi Mc \quad (2)$$

(h = Planck's constant, e = elementary charge, c = velocity of light, M = mass of proton), and therefore

$$\mu_P/\mu_N = \mu_P/(eh/4\pi Mc) = \nu_N/\nu_R. \quad (3)$$

By means of relation (3) we have determined μ_P/μ_n with a relative accuracy better than 1/10,000; since nuclear induction makes it easily possible within a few parts in 100,000, both to measure ν_N and to ascertain the homogeneity of the magnetic field, the problem consisted essentially in an accurate determination of ν_R. This has been achieved by the arrangement schematically indicated in Fig. 1. A proton beam of 20,000 ev, originating from the arc source A passes through a tube T of 4 ft. length with three differential pumping stages before entering into the gap of the electromagnet M and the dee cavity of a very small decelerating cyclotron; the diameter of the dees is 8.5 cm and their width is 1.7 cm. Up to the injection region R, the path is held approximately straight by nine compensating electrodes C and the last injection

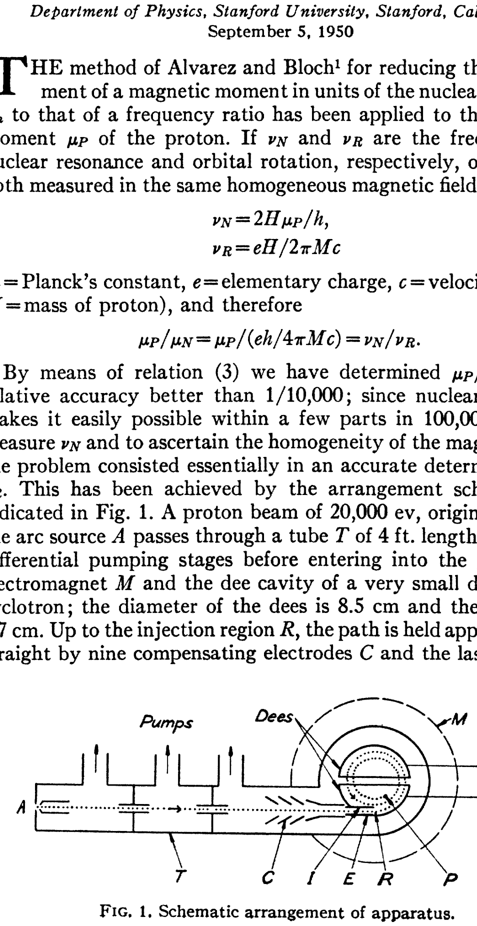

FIG. 1. Schematic arrangement of apparatus.