THE

PHYSICAL REVIEW

A Journal of Experimental and Theoretical Physics Established by E. L. Nichols in 1893

VOL. 59, No. 10 MAY 15, 1941 SECOND SERIES

Recurrence Phenomena in Cosmic-Ray Intensity*

JAMES W. BROXON
University of Colorado, Boulder, Colorado
(Received March 19, 1941)

The adaptation of Chree's method of analyzing geomagnetic data, as carried out by Monk and Compton for their Mexican cosmic-ray data, has been applied to cosmic-ray intensity measurements at Boulder, Colorado. Secondary pulses in the cosmic-ray intensity are apparent in the difference curves. These occur at approximately 28-day intervals both before and after the primary pulse, in good agreement with the findings of Monk and Compton, but the Boulder pulses are somewhat smaller and more irregular. Within the four (previous and subsequent) pulse intervals investigated, magnitudes of the secondary pulses do not appear to depend upon the interval from the primary pulse.

FOLLOWING a preliminary application of Chree's[1] method of analysis by Gill,[2] Monk and Compton[3] made an extended investigation of cosmic-ray data from a Carnegie Institution Model C meter at Teoloyucan, Mexico. For the period of investigation, February, 1937, through December, 1938, they found intensity variations of considerable regularity at about 28-day intervals from the primary pulse. The secondary pulses, of about 0.3-percent amplitude, did not display the decrease in amplitude with increase of pulse number which characterized Chree's magnetic character pulses.

Having available cosmic-ray data obtained at Boulder by means of locally designed and constructed equipment, it was thought desirable to investigate whether these displayed similar recurrences of intensity fluctuations. The observations were made by Dr. V. A. Long and Mr. R. M. Whaley[4] for the purpose of investigating bursts, diurnal and seasonal variations in intensity, and various geophysical influences. Because they will give a more detailed discussion of the apparatus when their findings are prepared for publication, only a brief description is included here.

The writer's[5] 13.8-liter chamber with air at about 160 atmospheres was used. The 3.7-inch diameter sphere used in an earlier investigation[6] was incorporated as a symmetrical central electrode. Equipped with a 5-inch lead shield, the chamber was located in a room in the basement of the same building where the earlier visual observations were made. Guard tubes were made small. In the sealed compensation condenser (of the usual resistance-capacitance bridge arrangement for application of the collecting field) was

* Presented at the 1940 annual meeting of the American Physical Society in Philadelphia.
[1] C. Chree, Phil. Trans. Roy. Soc. **A212**, 75 (1913); **A213**, 245 (1914); C. Chree and J. M. Stagg, Phil. Trans. Roy. Soc. **A227**, 21 (1928).
[2] P. S. Gill, Phys. Rev. **55**, 429 (1939).
[3] A. T. Monk and A. H. Compton, Rev. Mod. Phys. **11**, 173 (1939).
[4] V. A. Long and R. M. Whaley, Phys. Rev. **59**, 470A (1941).
[5] J. W. Broxon, Phys. Rev. **37**, 1320 (1931).
[6] J. W. Broxon, Phys. Rev. **42**, 321 (1932).

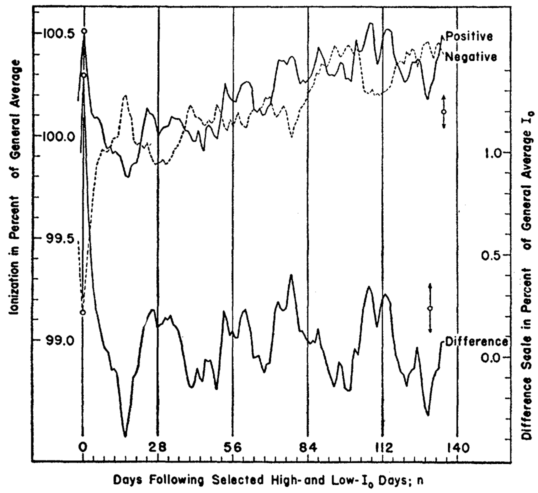

FIG. 1. Primary and subsequent pulses in cosmic-ray intensity at Boulder, Colorado. The arrows show the largest of the probable errors of the means of the 63 to 75 values for each of a dozen n-days selected at random.

placed a capsule of radium salt which produced a compensation current slightly in excess of the average cosmic-ray current. The indicator was a quadrant electrometer automatically earthed for 2 minutes at intervals of 1 hour. Deflections were recorded on a 20″×8″ photographic paper on a drum revolving once in 25 hours. Sensitivity was checked daily. The room temperature was regulated, and all the equipment except the photographic apparatus was contained in an insulating box. The temperature of the air in the box varied about 1°C during the 18 months of observation.

Data for the period from May 25, 1938, through December 1, 1939, were used. Deflections for the individual hours, corrected for bursts, were supplied by Dr. Long and Mr. Whaley. These were arranged according to Greenwich days, daily averages found, and barometric coefficients determined for every month. Because these showed no regular seasonal variation, an average barometric coefficient was used in reducing to the average barometric pressure of 24.75 in. Hg. Corrections for the slight decay of the Ra were hardly necessary, but were applied. Application of the instrument constants indicated an average cosmic-ray ionization current of 38.16 ions per cc per sec.

Unfortunately, complete records were not obtained for all days. On this account, 14 days of the period were regarded as blank because records for less than 8 hours per day were available. However, 67 imperfect daily records were retained. Of these, 5 had records for 8 but less than 12 hr., 16 had records for 12 but less than 18 hr., 27 had records for 18 but less than 23 hr., and 19 had records for 23 hr. In view of the method of analysis, it is significant that the 14 recordless days among the 556 were distributed in such a manner that not more than 4 occurred in any single calendar month.

The procedure of Monk and Compton was followed closely. The five days with greatest cosmic-ray intensity in each month from June, 1938, through November, 1939, were selected as the zero-days for the positive-pulse curves. The five with least intensity in each month served as zero-days for the negative-pulse curves. For any particular zero-day, the subsequent days were assigned positive numbers and the previous days, negative numbers, in the order of their occurrence after or before the corresponding zero-day.

Tables of cosmic-ray ionizations were then formed with a column for each of the zero-days during the first 15 months and for each corresponding day with positive number to $n=135$. Similar tables were formed for the zero-days of the last 15 months and the corresponding days with negative numbers to $n=-135$. Full columns had 75 items; none had less than 63.

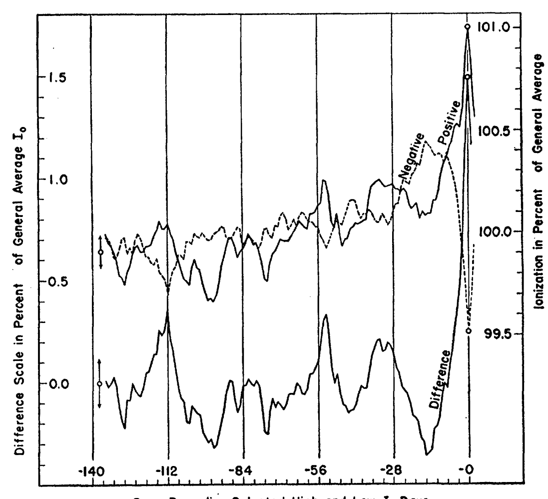

FIG. 2. Primary and previous pulses in cosmic-ray intensity at Boulder, Colorado.

The averages of the values in the several columns were plotted as ordinates with the corresponding day numbers as abscissae to obtain the upper pairs of curves of Fig. 1 and Fig. 2. The full-line "positive" curve in each case has as its zero-days the five per month of greatest ionization. The broken-line "negative" curves have days of least ionization as zero-days. In Fig. 1 are the subsequent-pulse curves corresponding to positive day numbers, while Fig. 2 contains the previous-pulse curves corresponding to negative day numbers. The lowest curve in each diagram, labeled "difference," has ordinates obtained by subtracting from the ordinate of the "positive" curve for a particular day number, the ordinate of the "negative" curve for the same day number.

The "primary pulse" variations corresponding to zero-days for the entire 18 months (not shown in the diagrams) were about 0.7 percent of the average for the period. The corresponding primary pulse magnitude was about one percent for the Mexican data. The secondary pulses shown in both the positive and negative curves for both positive and negative day numbers are quite irregular, and the season-like variation is considerable. The unidirectional trend is canceled out in the difference curves, however, and rather distinct though quite irregular pulses are apparent. These appear to be centered fairly well at the 28-day intervals designated by the vertical lines. It should be borne in mind that the deviations or "pulses" represented in the difference curves must be regarded as of double the magnitude of the "pulses" in the original curves. On this basis the "amplitude" or magnitude of the pulse deviations in the original curves must be regarded as rather less than 0.2 percent of the mean. Neither subsequent nor previous pulses show any regular tendency to decrease with distance from the primary pulse. In this respect they confirm the observations of Monk and Compton who have found recently[7] that the pulses in the intensity at Teoloyucan persist for ten 27- or 28-day intervals without decrease in amplitude. (Professor Compton informed the writer that when extended to ten intervals the persistence of the pulse amplitude was shown clearly, although the earlier extension to eight pulses had indicated a decrease of amplitude.)

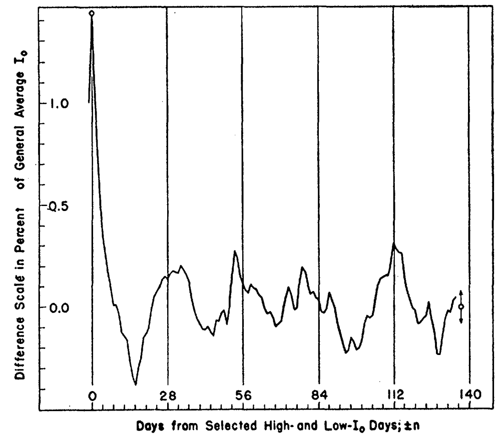

FIG. 3. Combination of difference pulses of Fig. 1 and Fig. 2. Ordinates are averages of differences for the same day number, regardless of sign.

In Fig. 3 is shown the combination difference curve. The ordinates of this curve represent the average of the ordinates for positive and negative day numbers of the same magnitude. Irregularities are not removed in this curve as in the corresponding curve by Monk and Compton. Although quite as irregular as in the individual difference curves, the pulses in this combination curve are of about the same magnitude and frequency as in the difference curves of Fig. 1 and Fig. 2. Perhaps it is quite as significant that they are not less regular or less definite.

The smaller magnitude and the greater irregularity of the pulses shown here in comparison with those found by Monk and Compton may be due in part to the differences in geographical location and in part to the fact that a shorter period was considered in the present instance, but they may also be due in part to differences in meteorological and other conditions. In both cases corrections were made for barometric changes, but none were applied for temperature or other effects. The Boulder data display a pronounced long time outdoor temperature effect, and a somewhat smaller short time temperature effect, as well as a magnetic effect. While the temperature at Teoloyucan is very uniform (and the temperature coefficient is small according to Gill[2]) the *monthly average temperature* at Boulder

[7] A. H. Compton and A. T. Monk, Phys. Rev. **59**, 112 (1941).

varied about 50°F. It should also be mentioned that no "absolute" calibration of the apparatus by comparison with one whose residual ionization has been measured under an enormous shield has ever been made. However, the cumulative observations made with the apparatus and the magnitudes of the several "coefficients" obtained from the data it yields, have satisfied the writer that the radioactive contamination of the chamber must be very small.

While Monk and Compton consider the pulses likely due to a solar influence, they consider that the persistence of the pulse amplitude of the cosmic-ray fluctuations and the decrease in Chree's magnetic pulses with distance from the primary pulse indicate the two varieties of disturbance are of different origin. However, the similarities of the frequencies of the pulses obtained by the same method of analysis combined with Graziadei's[8] association of his approximately 0.4-percent cosmic-ray intensity fluctuations of 27.2-day periodicity with solar disturbances, indicate the desirability of further examination of this point.

[8] H. T. Graziadei, Akad. Wiss. Wien. [IIa] **145**, 495 (1936).

MAY 15, 1941 PHYSICAL REVIEW VOLUME 59

Scattering in the Pair Theory of Nuclear Forces

J. W. WEINBERG
Department of Physics, University of California, Berkeley, California

(Received March 12, 1941)

The scattering of particles of spin $\frac{1}{2}$ and mesotronic mass m by heavy nuclear constituents is investigated with the pair theory of Critchfield and Teller, in which a nucleus appears as an extended source of mesotrons. A rigorous formula, (19), is found for the cross section, by obtaining explicitly the normal coordinates of the perturbed mesotron field. When the "constants" are adjusted to give a model of nuclear forces with approximately the right range and saturation properties, $\sigma \simeq 32\pi(mc^2/E)^4(\hbar/mc)^2$. Although, in other models, σ may decrease more rapidly with the energy E, it is always about 10^{-24} cm^2 at low energies, as contrasted with the cross section of about 10^{-28} cm^2 observed for cosmic-ray mesotrons. These results are discussed in relation to other accounts of the pair field theory.

CRITCHFIELD, Teller, Wigner and Lamb[1–4] have developed a field theory which explains, in a qualitative way, the saturation and spin dependence of nuclear forces. The field, when unperturbed by nuclei, is assumed to be a Fermi gas of charged particles with the mass of the mesotron and described by the Dirac equation. A proton or neutron interacts with this field by emission and absorption of neutral pairs of "mesotrons," and such processes can occur not only at the point which specifies the position of the nucleus, but over a finite region, spherically symmetrical about that point, and of, roughly, the nuclear radius.

Past discussions have been concerned with bound states of the pair field and with nuclear forces; but here we shall find how mesotrons are scattered by nuclei. It is of some interest to compare our conclusions with the remarkably small experimental cross section for the scattering of cosmic-ray mesotrons by nuclei: for mesotron energies of $\lesssim$350 Mev, Wilson[5] has obtained an upper limit of 10^{-28} cm^2 for the cross section. Our results seem to be about a hundred times larger.[6]

[1] C. L. Critchfield and E. Teller, Phys. Rev. **51**, 289 (1937).
[2] Wigner, Critchfield and Teller, Phys. Rev. **56**, 530 (1939).
[3] C. L. Critchfield, Phys. Rev. **56**, 540 (1939).
[4] C. L. Critchfield and W. E. Lamb, Jr., Phys. Rev. **58**, 46 (1940).

[5] J. G. Wilson, Proc. Roy. Soc. **174**, 73 (1940).
[6] R. E. Marshak and V. F. Weisskopf [Phys. Rev. **59**, 130 (1941)], have found agreement with experiment with a similar pair-field theory, which, however, pictures the nucleus as a point source. The divergent nuclear interaction characteristic of such a model is fitted to experiment by