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Changes in the Low-Energy Particle Cutoff and Primary Spectrum of Cosmic Radiation*

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The low-rigidity cutoff for particles in the primary cosmic-ray spectrum has decreased within the period 1948 through 1951. This decrease corresponds to a 3° change (northward) in the "knee" position of the geomagnetic latitude curve for the nucleonic component. The phenomenon is accompanied by both a change in the primary spectrum for particle rigidities less than approximately 4 Bv and by an increase in total primary intensity. The spectral change is such that if the differential primary intensity, j, at low rigidities in 1948 was $j=C(p/z)^{-2}$; then the new spectrum for 1951 through 1954 is approximately $j\approx C'(p/z)^{-2.7}$. The total change of intensity arising from the changes in spectrum and low-rigidity cutoff is more than 13%.

The measurements were obtained in 1948 and 1951, and have been confirmed and extended in November, 1954 using nucleonic component detectors. The vertical charged particle intensity was also measured and displays changes equivalent to those reported for the nucleonic component.

Three regions of space are considered for the location of the mechanism producing the low energy cutoff; namely, the vicinity of the earth, the region of the solar system, and regions of the galaxy outside our solar system. Although the general solar dipole moment is at least an order of magnitude too small to account for the observations, it is concluded that the mechanism is operative within the solar system and is not a terrestrial phenomenon.

I. INTRODUCTION

MEASUREMENTS to determine the energy distribution of primary cosmic-ray particles have for many years revealed an apparent absence of particles with magnetic rigidities less than approximately 1 Bv. This so-called low-rigidity (or low-energy) cutoff of the primary particle spectrum is of great interest since insight into this property of the spectrum may assist in further understanding the origin of the cosmic-ray particles. We do not know whether this cutoff is a general property of the spectrum at its source or is a characteristic introduced as a result of the special position of the observer, i.e., at the earth. For example, although the cutoff may be a fundamental characteristic of the entire cosmic radiation, it might, on the other hand, be produced by a mechanism within the dimensions of the solar system, or only within the vicinity of the earth.

Early attempts to explain this effect have been based upon the assumption that the sun possesses a large and permanent magnetic dipole moment which could prevent low-rigidity particles from reaching the region of the earth's orbit.[1] But solar observations accumulated over the past decade have demonstrated that the solar magnetic moment is far too small to account for the observed cut-off effect.[2] Consequently, the origin of the cut-off mechanism is unknown and, at present, it appears that only experiments may lead to a further clarification of the problem.

In 1948 and 1951, the nucleonic component intensity as a function of geomagnetic latitude was measured showing that there was probably a change in the value of the low-rigidity cutoff within this approximately three-year period. If such a change with time could be established, it may assist in deciding whether the cut-off is a purely local or remote mechanism. Consequently, we have undertaken additional measurements in 1954 to confirm whether or not this change with time exists.

We shall show in this paper that, indeed, we find a change not only in the low-rigidity cutoff but also a change in the primary spectrum, and we shall discuss the bearing of these results upon the cut-off mechanism.

II. EXPERIMENT

The theory for the motion of charged particles in the earth's magnetic field shows that for each geomagnetic latitude there exists a corresponding minimum rigidity which an incoming cosmic-ray particle from a given direction must exceed in order to reach the earth. Hence, measurements of cosmic-ray intensity as a function of geomagnetic latitude will yield information about the shape of the primary spectrum and the low-rigidity cutoff.

There are two possible approaches to the problem of measuring cosmic-ray intensity as a function of latitude. First, measurements could be undertaken at extreme high altitudes by means of balloons or rockets at a series of discrete latitudes, in order to determine the lowest energy particles which are present in the primary cosmic-ray spectrum. The second possibility is to measure the intensity of secondary particles at high altitudes within the atmosphere by means of aircraft. In the second case, it is possible to cover a relatively wide range of geomagnetic latitudes continuously and within a short time. There was an over-riding reason why the investigation reported here was made in an aircraft, using a nucleonic component detector; namely,

* Assisted in part by the Office of Scientific Research and the Geophysics Research Directorate, Air Force Cambridge Research Center, Air Research and Development Command, U. S. Air Force.

[1] L. Janossy, Z. Physik **104**, 430 (1937).

[2] See, for example, H. von Kluber, Monthly Notices Roy. Astron. Soc. **114**, No. 2, 242 (1954); G. Thiessen, Nature **169**, 147 (1952); H. W. Babcock and H. D. Babcock, Astrophys. J. **121**, 349 (1955).

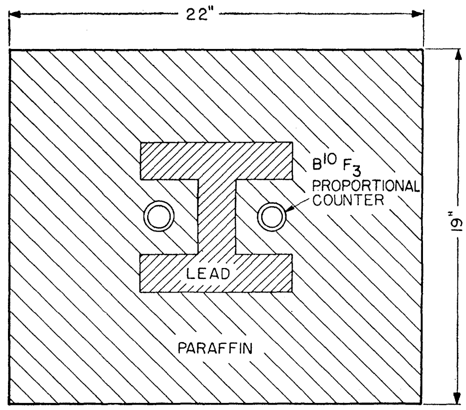

FIG. 1. Cross section of the detector geometry for measuring nucleonic component intensity. This geometry for the local production of neutrons yields $>1.2\times10^4$ counts per minute at 30 000 feet pressure altitude and at $\lambda>58°$ N.

the first evidence for a change in the low rigidity cut-off was originally obtained by this method in 1948 and 1951 while pursuing other studies of intensity changes with time.[3,4] Therefore, we undertook our new measurements in such a way as to directly compare them with earlier data. In restricting ourselves to measurements within the atmosphere, we used a nucleonic component detector which is the most sensitive detector for low energy primaries.

A suitable detector has been described earlier in the literature.[5] The arrangement used for the 1954 flights is shown in Fig. 1. The intensity of the nucleonic component is measured by the number of neutrons locally produced by nuclear disintegrations in the lead. In order to prove that there were no instrumental fluctuations, each of the two counters was connected to a separate electronic system and its counting rate was recorded individually. The ratio of the counting rates of the two systems remains constant. This detection system was installed in the nose of a type B47 jet aircraft. The material in the vicinity of the detector also contributes to a small extent to the neutron counting rate ($<3\%$). We verified, by flying southbound and northbound with continuously decreasing fuel load, that the contribution of neutrons, locally produced in the aircraft fuel, was too small to be detectable. Counting rates were approximately 13 000 counts per minute at 30 000 feet pressure altitude (310 g/cm^2) for high magnetic latitudes.

In order to have an independent check for our measurements, we installed a counter telescope in the same aircraft for measuring the near vertical meson intensity. The instrument consisted of three trays of two Geiger counters each, with an absorber of 10-cm Pb between the second and third tray. The telescope had a length of 15 inches, a width of 3 inches, and a height of 9 inches. Triple coincidences were recorded at a rate of approximately 350 per minute at 30 000 feet pressure altitude and high magnetic latitudes.

All flights were made at the constant atmospheric depth of 310 g/cm^2. The pressure altitude could be kept within ±50 feet and short periods were discarded from the data when this limit was exceeded. Possible errors due to navigation, the aircraft velocity, the load distribution, and the position error of the static pressure line were taken into account. Such corrections, however, turn out to be so small that they do not influence our results.

As an indication of the rate at which data were obtained, we note that it took approximately 10 minutes to fly over 1° of latitude. The total range of latitudes covered in the flights extended from approximately 40° to 65° N geomagnetic latitude. This range is sufficient for the identification of the cut-off latitude, and, at the same time, provides information on changes in the slope of the latitude curve, which is a measure of changes in the primary particle spectrum.

The data of 1948 and 1951 had been obtained at different longitudes; since we wish to exclude any possible ambiguities due to the longitude effect we have repeated the exact courses flown in both these years.

In 1948 and 1954, the data were obtained at times when there were no large scale intensity variations, such as the 27-day variation or Forbush-type intensity decreases, which would interfere with our measurements. The ionization intensity measured for May, and June, 1948 was kindly provided by Forbush, and the neutron monitor intensity for 1954 was used to check the 1954 flight periods. In fact, 1954 represents the period of minimum intensity variations and the minimum solar activity in the present solar cycle.

III. CHANGE OF LOW RIGIDITY CUTOFF

The nucleonic component latitude curves for 1948 and 1954 at 80° west longitude are shown in Fig. 2

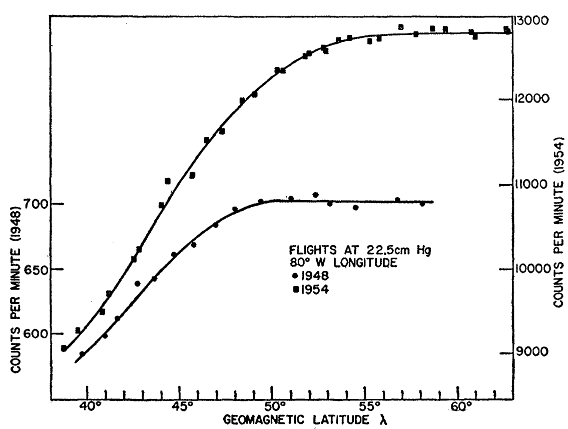

FIG. 2. The nucleonic component latitude curves for 1948 (reference 4) and 1954 at 80° west longitude 310 g/cm^2 atmospheric depth. The data for the 1954 flights are for November 13, 14, and 15th, 1954.

[3] J. Simpson, Phys. Rev. **94**, 426 (1954).
[4] J. Simpson, Phys. Rev. **83**, 1175 (1951).
[5] Simpson, Fonger, and Treiman, Phys. Rev. **90**, 934 (1953).

along with their respective counting rates. Similarly, in Fig. 3, we show the same measurements for 1951 and 1954 (the 1951 curve is the average of several flights) at approximately 90° west longitude. The size of the experimental points in both these figures represents the magnitude of the error of each point.

In Fig. 4(a), we have arbitrarily normalized the 80° west longitude data at the highest magnetic latitudes in order to display more clearly the approximately 3° shift of the cut-off latitude between 1948 and 1954.

In Fig. 4(b), on the other hand, the 90° west longitude data are arbitrarily normalized at high magnetic latitudes. We note that the shift in cutoff between 1951 and 1954 was less than ~1° latitude.

Although the large change in cut-off rigidity was evident by 1951, we were not certain of the influence which the longitude effect might have upon the curves at 80° and 90° west longitude. For this reason, and to search for further shifts of the cutoff, the 1954 flights were required.

Before attempting to interpret these measurements, it is essential to explore the basic question—are these changes in latitude curves in fact due to changes of the primary particle spectrum? Different geometries were used in 1948, 1951, and 1954 to measure nucleonic component intensity; namely, in 1948 most of the locally produced neutrons came from the vicinity of the detector (aircraft structure and paraffin); in 1951 and 1954 lead was the principal local producer. Simpson and Uretz[6] show in their Table II that the latitude response of such different detectors is the same, and we therefore conclude that all three detector geometries have the same "response" for incoming nucleons produced by the primary radiations. The only differences among the detectors is the counting rate for a given primary intensity.

It is obvious from Figs. 2 and 4(a) that the cutoff observed in 1948 could not be due to the inability of the detector to measure the effect of lower rigidity particles; otherwise, the shift in cutoff between 1948 and 1954 could not have been observed. (We shall show later that it is unlikely this shift could be produced by changes in the geomagnetic field.) On the other hand, we cannot show that the 1954 cutoff at 57° represents the lowest rigidity particles that can arrive at the top of the atmosphere. Consequently, our measurements represent the *lower limit* of the change in cutoff which could have occurred in the primary radiation between 1948 and 1951.

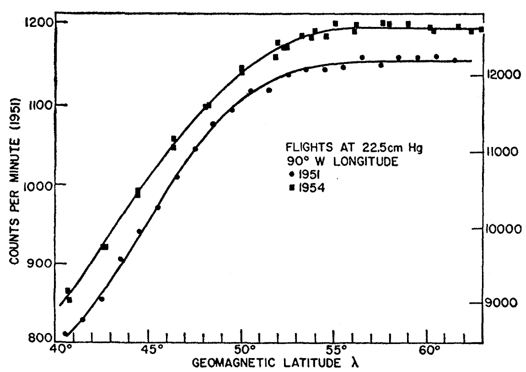

FIG. 3. The nucleonic component latitude curves for 1951 (reference 3) and 1954 at 90° west longitude and 310 g/cm² atmospheric depth. The data for the 1954 flights are for November 3 and 4, 1954.

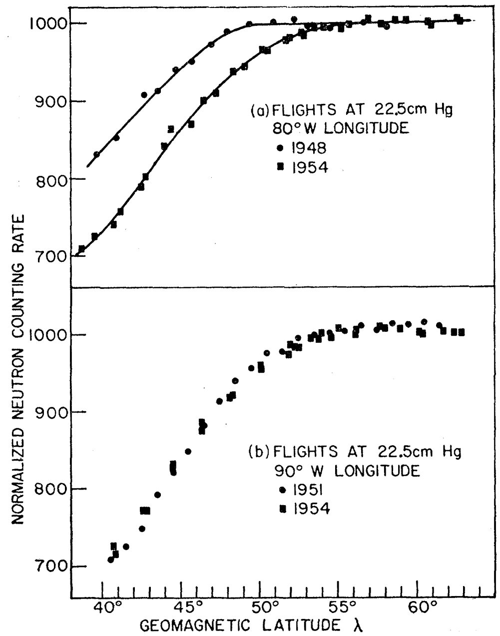

FIG. 4. (a) and (b). The nucleonic component latitude curves are *arbitrarily* normalized at latitudes greater than 58° N in order to display clearly the magnitude of the northward shift in the low-rigidity cutoff. However, it is shown in Sec. V that there was, indeed, an increase of intensity between 1948 and 1954 arising from a change in primary spectrum in addition to the shift in low-rigidity cutoff.

Although atmospheric absorption certainly becomes an increasingly important factor at higher latitudes, the cut-off latitude does not appear to be appreciably altitude dependent within the range of altitudes attained by aircraft. This is shown in Fig. 5, where latitude curves, obtained at different altitudes, are compared.

The position of the low-rigidity cutoff near the top of the atmosphere in 1951 was established by Neher[7] by means of balloon-borne ionization chambers. For the range of atmospheric depths 15–100 g/cm² the cutoff was at 58°±1°. Thus, at least for the year 1951 we see that the cutoff measured at the top of the atmosphere is very close to the cutoff determined by a nucleon detector within the atmosphere.

The telescope latitude curves also reveal a shift in cutoff rigidity with time. The data for 1948 were obtained in aircraft by Biehl and Neher[8] and are com-

[6] J. Simpson and R. Uretz, Phys. Rev. **90**, 44 (1953).

[7] Neher, Peterson, and Stern, Phys. Rev. **90**, 655 (1953).

[8] A. T. Biehl and H. V. Neher, Phys. Rev. **78**, 172 (1950).

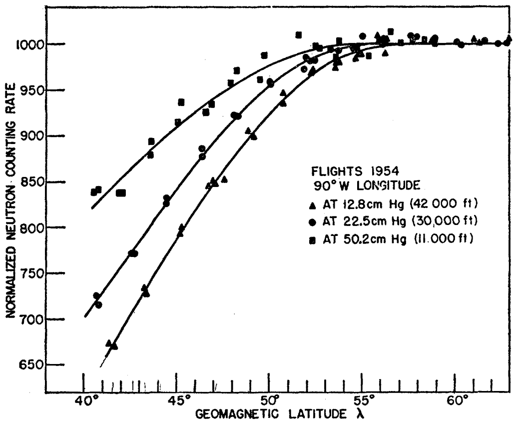

FIG. 5. The nucleonic component latitude curves observed with a neutron detector at different altitudes. The data are arbitrarily normalized at high latitudes.

pared in Fig. 6 with our corresponding curve for 1954. All data are for 80° west longitude and 310 g/cm^2 atmospheric depth. Although a shift in cutoff rigidity is quite apparent, the latitude effect measured with a counter telescope is too small and the counting rates too low to give precise information on its magnitude and on the slopes of the latitude curves.

IV. CHANGES IN PRIMARY SPECTRUM DEDUCED FROM THE MEASUREMENTS

Our problem is to utilize the observed changes in the nucleonic component latitude curves to describe the changes which have occurred in the primary spectrum. It has been shown earlier than the measured intensity within the atmosphere arises principally from primary particles arriving from the vertical direction at the top of the atmosphere.[5] We shall, therefore, call the observed counting rate, R,

$$R(\lambda,x,t)=\int_{(p/z)_\lambda}^{\infty} S(x,p/z)j(p/z,t)d(p/z),$$

where j is the differential primary spectrum, p/z is proportional to the magnetic rigidity of particles with charge ze, and S is the average specific yield function which gives, at atmospheric depth x, the observed counting rate for incoming primary particles of rigidity p/z. $(p/z)_\lambda$ represents the cut-off rigidity at latitude λ.

The slope of the latitude curve is given by

$$dR/d\lambda \equiv R' = -Sjd(p/z)/d\lambda.$$

The ratio of the slopes for curves measured at times t_1, t_2 for any given λ, x will be

$$\frac{R'(t_2)}{R'(t_1)}=\left[\frac{S(t_2)j(t_2,p/z)}{S(t_1)j(t_1,p/z)}\right]_\lambda,$$

since $d(p/z)/d\lambda$ is independent of time provided the permanent geomagnetic field does not undergo large changes between t_1 and t_2.

We now introduce the assumption that the relative abundances of particles of different z and mass is invariant with time. Thus, the average yield function $S(t_2)=S(t_1)K$, where K is the ratio of the counting efficiencies of the respective geometries used to measure the latitude curves at t_1 and t_2. It then follows that if we know K, we may determine the relative change of the primary rigidity spectrum from the measurements of the slopes of the latitude curves.

Using the above relations, we shall consider the change of primary spectrum within the period 1948 (t_1) to 1954 (t_2) by using the data in Fig. 2 obtained at 80° west longitude. The ratio $R'(1954)/R'(1948)$ was measured graphically at $\lambda=40°$, 42°, 44°, 46°, 48° and 60°. To describe the differential spectrum $j(1954)$, we must know $j(1948)$. In the period 1948–1950, there were measurements made near the top of the atmosphere by several observers to determine the low-rigidity primary spectrum.[9] Their results are best described in the form

$$j=C(p/z)^{-2},$$

shown as the solid line in Fig. 7 extended to the low-rigidity cutoff observed in 1948. Using the spectrum for 1948, we have computed the rigidity spectrum for 1954. The points are shown in Fig. 7. The dashed curve, which represents the 1954 spectrum, has been fitted to the 1948 spectrum at a particle rigidity corresponding to minimum-rigidity particles arriving from the vertical at $\lambda=40°$. We shall show below that this fit at $\lambda=40°$ represents the *lower* limit for the change of total primary intensity which occurred between 1948 and 1954. In this way we dispose of the unknown constant K.

The dashed curve through the calculated points in Fig. 7 is well represented by a straight line and, hence, by a new spectrum,

$$j(1954)=C'[p/z]^{-2.7}.$$

Rather large errors must be assigned to the exponent 2.7; in fact, it is likely that the exponent is a function of particle rigidity. It should be noted that the change of exponent is independent of the value K. The shaded portion of the 1954 curve is indeterminate because

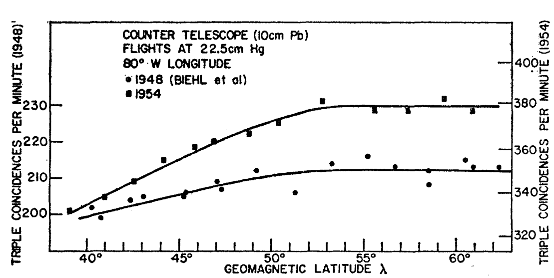

FIG. 6. The charged particle intensity as measured by vertical, triple-coincidence counter telescopes with 10-cm Pb absorber. The 1948 data were published by Biehl and Neher.[8] The 1954 data were obtained on the aircraft flights described in Figs. 2 and 3. All data are for atmospheric depth 310 g/cm^2.

[9] Winckler, Stix, Dwight, and Sabin, Phys. Rev. **79**, 656 (1950); M. L. Vidale and M. Schein, Nuovo cimento **8**, 774 (1951).

particles of these low rigidities were not present in 1948.

As noted earlier, the particles which are responsible for the change in spectrum between 1948 and 1954 must have already been present by 1951 since there is no appreciable difference between the shapes of the 1951 and 1954 latitude curves, as shown in Figs. 3 and 4(b). Consequently, the major changes in the portion of the spectrum covered by our experiment took place in the earlier period.

V. CHANGE IN TOTAL COSMIC-RAY INTENSITY BETWEEN 1948 AND 1951

We now inquire into the possible change of total cosmic-ray intensity between 1948 and 1951 arising from this change in spectrum. If we assume that the total intensity had been constant in this period—as represented by the arbitrary normalization of the curves in Fig. 4(a) at high latitudes—then, in order to agree with observations, an intensity decrease would have to be observed at intermediate and low latitudes. But this is in contradiction with the experimental evidence recently published by Forbush[10] wherein he measured mean cosmic ray intensities with shielded, Compton-type ionization chambers which detect the intensity changes of primary particles of higher mean energy than in our experiment. From his data, shown in Fig. 8, it is clear that a world-wide increase in intensity occurred between 1948 and 1951. To relate this change of intensity to the lower energy portion of the primary spectrum we made the assumption that the exponent of the differential power law spectrum did not decrease between 1948 and 1951 for particle rigidities $\gtrsim 4$ Bv. It then follows that, since the ionization chamber intensity increased in this period, the differential intensity for $j(1951)$ at 40° must not be less than for $j(1948)$. Thus, from matching the neutron intensities at 40° latitude and 80° west longitude, Figs. 2 and 7, we see that there is an observed increase of total cosmic ray intensity of at least 13% at 310 g/cm² within the three-year period, and that this represents the minimum total intensity change.

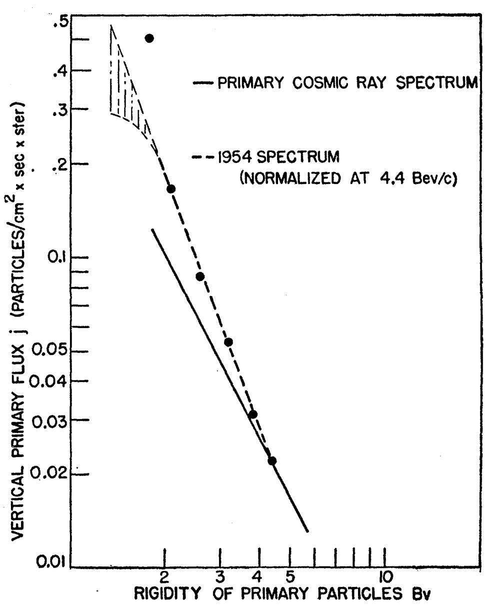

FIG. 7. The change in spectrum deduced from latitude curve measurements indicates that if the differential spectrum in 1948 was represented[9] by $j=C(p/z)^{-2}$ then the 1951 spectrum is well represented by $j=C(p/z)^{-2.7}$, except perhaps at very low particle rigidities. The normalization at 4.4 Bv, as shown in Sec. V, will give the *minimum* value for the change of total intensity which occurred between 1948 and 1951.

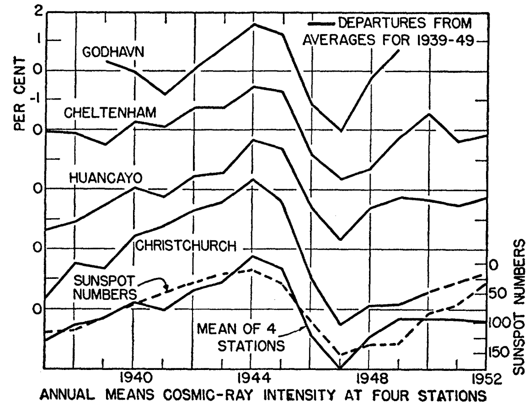

FIG. 8. Annual means of cosmic-ray intensity measured with shielded ionization chambers by Forbush.[10]

It is probable that in addition to this total intensity increase brought about by changes in the spectrum, there may have been further total intensity changes in the period 1951–1954 without changes in the spectrum —such a change would not be measured with our apparatus without determining the constant K.

VI. CONCLUSIONS

In the introduction we divided the regions in which the cut-off mechanism might be operative into (a) the earth and its immediate vicinity, (b) the solar system, and (c) the space outside the solar system. Using our new experimental evidence for the change in low rigidity cutoff and change in shape of the primary spectrum with time, we shall now explore which of these regions most probably is associated with the basic mechanism.

First, let us assume that the mechanism is of terrestrial origin (region *a*)—that is, the effect exists only as a result of the presence of the earth and its electromagnetic field systems. The geomagnetic field which interacts with incoming charged particles arises principally from the earth's permanent field with smaller, additional contributions from external current systems, such as a ring current. These currents are assumed to be axially symmetric with respect to the earth's equivalent permanent dipole moment. It is the latter kind of magnetic field system which is invoked by Chapman and Ferraro to explain magnetic storms. Additional current systems in the ionosphere at present appear to

[10] S. E. Forbush, J. Geophys. Research **59**, 525 (1954).

produce fields of too short a range to appreciably influence the geomagnetic cutoff.

If we assume that the geomagnetic field undergoes a change with time, the total cosmic-ray intensity as observed at high latitudes (above the "knee" of the latitude curve) should not change as illustrated by the arbitrary fitting of the two curves in Fig. 4(a). But we know that this is contrary to experimental evidence since no cosmic-ray intensity decrease was observed at intermediate latitudes. (An independent argument supporting this view is that the change in dipole moment required to account for the observed shift in cutoff latitude would amount to about 30%. Changes of this magnitude are not known to exist.)

The shadow cone of the earth at high magnetic latitudes influences the total intensity of particles arriving at large zenith angles. Since the main contribution to the total nucleonic component intensity at 310 g/cm^2 arises from those primaries which arrive within a zenith angle of approximately 45°, it is clear that changes in the shadow cone which might be brought about by the changes in quadrupole or higher order contributions to the magnetic field have little influence upon the observed total intensity.

Although there is no evidence that geoelectric fields of the order of 0.1–1 Bv exist, this possibility has been frequently discussed. If the particles from a primary spectrum, with or without a cutoff of low rigidity, pass through a geoelectric accelerating field (approximately 1 Bv) the lowest rigidity particles will appear near the cutoff observed in 1948. A subsequent decrease of the proposed field would be required to account for the observed 3° northward shift of the cutoff. But this decrease in field will be associated with a decrease of cosmic-ray intensity at intermediate latitudes in contradiction with the facts. Thus, no geoelectric field can be invoked to account for this effect.

We, therefore, conclude that neither known terrestrial magnetic fields nor assumed geoelectric fields produce the changes in the properties of the low-energy primary particles described in this paper and we, therefore, discard possibility (a).

It might then be argued that the cutoff in the primary spectrum is a fundamental characteristic of the cosmic radiation throughout our galaxy (region *c*) and is not an effect restricted to the solar system. If there were some property of the accelerating mechanism which could introduce a cutoff, it would even then be difficult to keep the spectrum free of lower rigidity particles after the radiations have reached equilibrium, since particles near 1 Bv may suffer losses in energy. It appears probable that the particle spectrum would extend to near zero energy. Likewise, if there is a mechanism within our galaxy which removes low-energy particles, the same difficulty would exist unless we are making our observations at some very special position in the galaxy. A further objection is that the time scale for spectral changes of galactic origin is orders of magnitudes longer than the time scale encountered in our measurements.

We are led, therefore, to consider the cutoff as a mechanism operative within the solar system (region *b*). If it should subsequently develop, as may well happen that the long-time changes of total cosmic-ray intensity shown by Forbush[10] to be related to the general level of solar activity, is also related to the change of cutoff which we report here, this would be further evidence that the mechanism is a property of the solar system.

Ellis and Van Allen[11] find that the low-rigidity cutoff in 1953 appears to be the same, within the experimental errors, for both protons and heavy nuclei. If subsequent experiments show that a common rigidity cutoff persists throughout the changes in cutoff with time then a mechanism involving magnetic fields will be required.

As mentioned before, Janossy[1] had, as early as 1937, invoked a perfect, general magnetic dipole field on the sun to account for the observed cutoff which, at that time, was thought to be at geomagnetic latitude $\sim$50°. During the past eight or nine years, however, it has become apparent that the general field of the sun is an order of magnitude lower than had been assumed in earlier years. It seems to be highly doubtful that the general solar field at present has an intensity on the sun's surface of more than 5 gauss. Thus, solar observations lead to a dipole moment far too small to account for the range of cutoffs observed in our studies. Even if the solar magnetic moment were sufficiently large it would be necessary to postulate both a perfect dipole field and a change in its magnetic moment with time to account for our experimental evidence. There is an additional difficulty with the solar field hypothesis in that a large cosmic ray diurnal effect at high latitudes is expected but is not found by experiments.[12]

At the present time, therefore, we have the possibility that the cut-off mechanism, and its change with time, is a property of a volume in space having roughly the dimensions or scale length of our solar system. It is quite possible that a distribution of magnetic fields may be found in the interplanetary space of the solar system which will prevent low-energy particles present within the galaxy from entering the solar system near the position of the earth's orbit. For example, if the level of general solar activity controls the configuration of outlying magnetic fields—such as outgoing clouds of ionized matter containing magnetic fields—the eleven year changes of cosmic-ray intensity and the changes in the low rigidity cutoff reported here, could have a common origin.

VII. SUMMARY

High-altitude measurements over the years 1948 through 1954 have revealed the fact that the lowest

[11] Ellis, Gottlieb, and Van Allen, State University of Iowa Report S.U.I.-54-3, 1954 (unpublished).

[12] D. I. Dawton and H. Elliot, J. Atm. and Terrest. Phys. **3**, 217 (1953).

rigidities for particles which reach the earth have changed significantly between 1948 and 1951. This effect was measured by observing a shift of 3° in cut-off latitude. Thus, additional, low-rigidity particles have been admitted to the top of the atmosphere since 1948. The measurements were obtained by observing nucleonic component intensity and were independently confirmed by vertical counter telescope measurements.

In addition, we found that the power-law spectrum of the form

$$j=C(p/z)^{-n}$$

assumed to be represented in the low-rigidity spectrum in 1948 by $n\approx 2$ must have a new exponent $n\approx 2.7$ in 1951, within an interval of particle rigidities ~1–4 Bv. The change in cutoff appears to be associated with a change in the shape of the primary spectrum. Finally, this change in spectrum and cutoff is accompanied by an increase in total cosmic-ray intensity amounting to more than 13% between 1948 and 1951. Also, there may have been additional intensity increases during times of no spectrum change (probably after 1951) which could further increase the total intensity.

From these experimental facts it is deduced that the low-rigidity cutoff in the primary spectrum is not of terrestrial origin. Measurements of the general solar magnetic field over the past decade indicate that the solar dipole field does not account for this effect. The evidence, therefore, points at the present time to a mechanism which is operative within the volume of our solar system.

Note: Neher and Stern[13] have repeated in 1954 the same type of high altitude ionization chamber measurements they reported in 1951. They find in 1954 that new, low-energy particles are arriving at latitudes above about 58°N. and that there was in July–August, 1954 no low-rigidity cutoff, at least down to proton energies of ~0.15 Bev. They find evidence for even lower energy radiation near the top of the atmosphere at the geomagnetic pole. Below 58° the total change of intensity between 1951 and 1954 was small. Thus, we note that not only was the low-rigidity cutoff changing between 1948 and 1951, but, from these recent data, is found to recede further. In 1954, the existence of any cutoff at all is in doubt. From these new measurements of Neher's it turns out that the onset of the absorption cutoff for the nucleonic component at aircraft altitudes is in the region of 57–58°.

For assistance in preparing the electronic apparatus and detection systems, we wish to thank Mr. Rochus Vogt, Mr. John Erwood, and Mr. John Horton. We appreciated the help of the men of W.C.U., Wright Air Development Center for installing the equipment. For remarkable assistance in carrying out the flights and for handling the aircraft, we are especially indebted to the pilot and co-pilot, Captain T. M. Sumner and Captain R. Rice, and the men of bomber operations and maintenance, Directorate of Flight and All-Weather Testing, W.P.A.F.B.

[13] H. V. Neher and E. A. Stern, Phys. Rev. **98**, 845 (1955). We wish to thank the authors for sending us their communication in advance of publication.

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Production of π^+ Mesons at 0° by 335-Mev Protons on Deuterium and Complex Nuclei*

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The relative yield of π^+ mesons has been determined for 335-Mev protons on several elements. Specifically, the relative differential cross section, $d^2\sigma/dE\,d\Omega$, was measured at 0°±4° in the reaction $p+A\rightarrow\pi^++A'$ for D, Be^9, B^{10}, B(natural), C, Al, Cu, Fe, Ag, and Pb. The π^+-meson energies ranged from 34 to 147 Mev. They were counted electronically from signals generated in a *trans*-stilbene crystal telescope. Identification of the π^+ meson depended upon a coincidence in the first two crystals plus the $\pi^+-\mu^+$ decay in the third crystal of the telescope.

No special isotope effects were observed for the π^+-meson spectra from the isotopes Be^9, B^{10}, B(natural), and C.

For C, Cu, and Pb the relative π^+-meson yield per nucleus is proportional to the product of two factors, (*a*) the number of protons in the nucleus, (*b*) an attenuation factor F which is derived from proton and meson mean free paths in nuclear matter. These mean free paths are consistent with those calculated from measured interaction cross sections of protons and mesons with C, Cu, and Pb.

The importance of meson scattering within nuclear matter is discussed in the case of carbon. Also the total π^+-meson production is estimated for carbon from the experimental proton-proton cross section and is compared with the experimental results for carbon.

I. INTRODUCTION

THE dependence upon atomic number of the production of π mesons by proton bombardment of complex nuclei has been partially investigated.[1–7] Except for references 2 and 7, the yield has been meas-

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