Fluctuations and Latitude Effect of Cosmic Rays at High Altitudes and Latitudes*

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(Received December 22, 1952)

Using a newly developed ionization chamber, which transmits its information by radio, simultaneous balloon flights were made from widely separated stations in the summer of 1951. Bismarck, North Dakota (geomagnetic latitude, λ_m, 56°N) was used as a base station. Four flights were made from shipboard going north from Boston and five were made from Thule, Greenland ($\lambda_m=88$°N), simultaneous with those at Bismarck. In all, 28 successful flights were made by the two expeditions. In seeking to determine the geomagnetic effects on the low energy primaries, considerable information was gathered on the radiation that fluctuates from day to day. The following are the chief experimental findings together with some of the conclusions that may be drawn.

(1) The fluctuations in the primary radiation at 90 000 feet were as much as 10 percent in a few days. (2) These were simultaneous (except as noted in the text) and very close to the same amount at the two stations. (3) The magnitude of the fluctuations at high altitudes was considerably larger than the geomagnetic effect between Bismarck and Thule. (4) The radiation that fluctuated contained both high (>15 Bev/c) momentum and low (down to 1.5 Bev/c) momentum particles. (5) There was a good correlation between the fluctuations in the radiation at high altitudes and the fluctuations in the neutron and meson components at ground level. (6) The fact that no particles fluctuated at Thule that did not also fluctuate at Bismarck leads us to conclude that there are few, if any, low energy particles coming in at Thule that are not also present at Bismarck, otherwise they too would be expected to vary. (7) From the manner in which the fluctuating radiation is absorbed in the atmosphere, it is concluded that the fluctuations cannot be due to heavy primaries alone. Rather it appears that the particles that fluctuate are of the same nature as the other incoming particles but have somewhat less energy per particle. (8) Varying magnetic fields of the geomagnetic axially symmetrical type are discarded as being able to produce the kind of fluctuations observed. A more satisfactory mechanism appears to be varying electric fields. (9) There was a negative latitude effect in the total ionization at intermediate altitudes (30 000 to 50 000 feet) at high latitudes. This we attribute to the greater importance of μ-meson decay in the warmer air of the stratosphere which exists at the more northerly latitudes. The temperature coefficient arrived at is -0.19 percent °C^{-1}. (10) There was a positive latitude effect in the total ionization above 60 000 feet at high latitudes. Evidence is presented to show that this is not likely to be due either to atmospheric effects or to low energy particles admitted by the earth's magnetic field above 66°N. We attribute this increase to the shadow effect of the earth. (11) The absence of particles with momenta in the range 1.5 to 0.6 Bev/Zc (0.8 to 0.14 Bev for protons), shown by (a) a lack of increase of ionization at very high altitudes between geomagnetic latitudes 58° and 66°N, (b) the absence of an increase of area under the ionization-depth curve at latitudes north of $\lambda_m=58$°N, and (c) the absence of any particles that fluctuate at Thule that do not also fluctuate at Bismarck, indicates a cutoff of the primary particles. (12) This cutoff we attribute to a general solar magnetic field. The magnetic moment required is 0.65×10^{34} gauss-cm^3 corresponding to a field at the solar equator of 19 gauss. (13) Any diurnal effect on cosmic rays due to such a magnetic moment would normally be hidden by the daily fluctuations of the primary particles.

I. INTRODUCTION

A. The Latitude Effect at High Latitudes

IN studying the geomagnetic latitude effect in cosmic rays in the hope of being able to determine the energy distribution of the primary radiation at intermediate and high latitudes, it became evident a number of years ago[1] that simultaneous balloon flights would have to be made at two stations, because of the fluctuations in the primary radiation that take place from day to day. While not completely fulfilling this requirement, the B-29 airplane flight[2] made in 1948 from geomagnetic latitude 64°N[3] to the equator at 30 000 feet elevation did cover the high latitudes in the space of a few hours, and it was known that the fluctuations are usually not important in this period of time. This flight made it possible to normalize our former balloon flight curves, taken with counter telescopes, to agree with the airplane data at 310 g cm^{-2} air pressure. After so doing, an 8 percent increase in intensity at the maxima of the curves and a 2.2 percent increase in area was shown in going from Omaha (geomagnetic latitude, $\lambda_m=51$°N) to Saskatoon ($\lambda_m=60$°N).

Among earlier attempts to measure the latitude effect near the "knee" of the curve may be mentioned that of Cosyns[4] in 1935. He allowed a counter telescope, carried by a balloon, to drift at 204 g cm^{-2} air pressure over the range of geomagnetic latitude 47° to 51°N. The curve he obtained of intensity *vs* geomagnetic latitude showed a leveling off at 50°N.

In 1937 Carmichael and Dymond[5] made two good balloon flights near the geomagnetic pole; one with a counter telescope and another with an ionization chamber. Not having made comparison flights, the telescope data were fitted to those of Pfotzer[6] taken at $\lambda_m=49$°N at ground level. The ionization data were fitted at 125 g cm^{-2} air pressure to those of Bowen, Millikan, and Neher,[7] taken also with ionization chambers at 60°N ten days later. After so fitting, each of

* Assisted by the joint program of the U. S. Office of Naval Research and the U. S. Atomic Energy Commission.

[1] Biehl, Montgomery, Neher, Pickering, and Roesch, Revs. Modern Phys. **20**, 366 (1948).

[2] Biehl, Neher, and Roesch, Phys. Rev. **76**, 914 (1949).

[3] In all cases in this paper only geomagnetic latitudes will be used.

[4] Max Cosyns, Nature **135**, 313 (1935).

[5] H. Carmichael and E. G. Dymond, Proc. Roy. Soc. (London) **A171**, 321 (1939).

[6] G. Pfotzer, Z. Physik **102**, 41 (1936).

[7] Bowen, Millikan, and Neher, Phys. Rev. **53**, 855 (1938).

their curves was about 6 percent higher than the corresponding reference curve at the maxima.

A more recent attempt to determine the latitude effect at high latitudes has been made by Pomerantz.[8] Counter telescope balloon flights, using a 7.5-cm lead absorber, were made at Swarthmore, Pennsylvania ($\lambda_m = 52°$N). A trip was next made to Churchill, Canada ($\lambda_m = 69°$N), and two months later further data were taken at Swarthmore. Using no absorber, only data taken at Churchill and on the return to Swarthmore have been reported. In each case a 40 to 60 percent increase in the intensity at very high altitudes was found in comparing the two sets of data.

In attempting to determine the number of primary particles alone, Van Allen and Singer[9] have used rockets carrying either single Geiger counters or counter telescopes beyond the atmosphere. Aside from the fact that only a few minutes are available for measurement, these experiments suffer from the same disadvantage as others where simultaneous flights are not made from some base station. Since, as will be shown later, the fluctuation in the ionization at 90 000 feet is from 5 to 10 percent from day to day, this also means that there will be a change in the numbers of primary rays. In fact, the percentage change in ionization at 90 000 feet should be approximately the same as the percentage change in the number of primaries.

In evaluating the experiments above summarized, it must be borne in mind that, as pointed out many times before,[1,10–12] rather large fluctuations occur in the primary radiation and the agreement of flights made at a given location at different times may be fortuitous and that considerable caution must be used in drawing conclusions from data taken at different times at different locations, especially when the geomagnetic effects are expected to be of the same order of magnitude as the fluctuations themselves.

The importance of determining accurately the energy distribution of the primary radiation at the lower end of the energy spectrum lies in the implications involved from the standpoints of (a) the mechanism or mechanisms of origin of the radiation, and (b) the bearing on the problem of the general magnetic field of the sun. If it should be established that few if any primary cosmic-ray particles reach the earth with momenta less than a certain value, a cut-off mechanism would need to be found. This might exist either during the acceleration process or subsequently, but before they reach the influence of the magnetic field of the earth. One such mechanism, first suggested by Janossy,[13] is that a general solar magnetic field would, if its strength were of the proper magnitude, prohibit particles whose momenta were less than a certain value from reaching the vicinity of the earth. The bearing upon this problem of the experiments, to be described, will be discussed later.

B. The Role Played by Fluctuations

Considerable information on fluctuations that exist in the primary radiation has been accumulated over the years. Forbush[14] in 1938, in analyzing ground level data, drew attention to the world-wide character, not only of the large changes in cosmic rays that occur during magnetic storms, but also to the small changes that take place from month to month. There is also a correlation between these smaller changes and fluctuations in the earth's magnetic field. In each case the algebraic sign of the ratio of the change of cosmic-ray intensity to the change in the magnetic field is positive and of approximately the same value, thus indicating that the mechanism giving rise to the changes is the same in each case.

Recently, Simpson *et al.*[15] have reported the results obtained from monitoring neutron intensities at several stations. It was shown by Neher and Forbush[16] that these fluctuations were well correlated with the changes in the penetrating component as measured by ionization chambers at Cheltenham, Maryland and Huancayo, Peru, the ratio between the fluctuations of the neutrons and mesons being approximately 3 to 1.

Fluctuations at high altitudes have been measured with both ionization chambers[10–12] and counter telescopes.[1] For the series of flights made in 1947 using counter telescopes (reference 1) the fluctuations as measured at the maxima of the curves were compared with Forbush's sea level data. The ratio of the fluctuations at the peaks of the curves then found was 10 to 1. For the series of flights with ionization chambers made from Bismarck, North Dakota, in the summer of 1951, the ratio between the fluctuations found from day to day at 50 g cm^{-2} air pressure (about 70 000 feet) to the meson component at sea level was approximately 7 to 1.[16] This increase of the fluctuations with altitude indicates that the average energy of the particles (if singly charged) responsible for the changes is somewhat less than the average energy of the total radiation, yet sufficiently great to get through the earth's magnetic field at the equator and give changes of about the same amount as are found at the higher latitudes. This is in keeping with the behavior reported by Forbush[14] who found that the percentage change at mountain altitudes was somewhat greater than at sea level. Jesse[17] also has reported fluctuations in the primary radiation as measured with ionization chambers carried up by balloons from Chicago. The ratio of the fluctuations

[8] M. A. Pomerantz, Phys. Rev. **77**, 830 (1950); M. A. Pomerantz and G. W. McClure, Phys. Rev. **86**, 536 (1952).
[9] J. A. Van Allen and S. F. Singer, Phys. Rev. **78**, 819 (1950).
[10] R. A. Millikan and H. V. Neher, Phys. Rev. **56**, 491 (1939).
[11] R. A. Millikan and H. V. Neher, Proc. Am. Phil. Soc. **83**, 409 (1940).
[12] Millikan, Neher, and Pickering, Phys. Rev. **66**, 295 (1944).
[13] L. Janossy, Z. Physik **104**, 430 (1937).
[14] S. E. Forbush, Phys. Rev. **54**, 975 (1938).
[15] Simpson, Fonger, and Wilcox, Phys. Rev. **85**, 366 (1952).
[16] H. V. Neher and S. E. Forbush, Phys. Rev. **87**, 889 (1952).
[17] W. P. Jesse, Phys. Rev. **58**, 281 (1940).

shown by his data to that obtained by the Carnegie instrument at Huancayo, Peru, as determined from his published data, was about 6 to 1.

In addition to the above discussed fluctuations that occur from day to day in the high energy radiation, sudden increases have been measured by a number of observers[18] at or near sea level which are apparently due to lower energy particles. These increases are characterized by (1) they do not occur at the geomagnetic equator,[19] (2) the increase in the neutron component is many times the increase in the ionizing component,[18] (3) the increase is much more pronounced at mountain altitudes than at sea level,[19] and (4) there seems to exist a "spottiness" in that for about the same geomagnetic latitude but different longitudes the increase measured by different observers varies over wide ranges.[18]

It is particularly important to study these fluctuations at high altitudes because (1) atmospheric effects play a much less prominent role, (2) some of the radiation that fluctuates does not extend its influence to sea level, and (3) considerable information about the composition of the primary radiation that fluctuates may be obtained by the way in which it is absorbed in the atmosphere.

To gain information on the true latitude effect these fluctuations need to be taken into account. Consequently, a series of simultaneous flights was carried out at Bismarck, North Dakota (geomagnetic latitude, $\lambda_m = 56°$N) and Thule, Greenland ($\lambda_m = 88°$N). Four intermediate latitude flights were also made from shipboard going north. All of these latter flights and five of those made in Greenland were made simultaneously with similar flights at Bismarck.

C. Discussion of Instruments

Of the various types of instruments that can be used to attack the problem of fluctuations at high altitudes, the field is narrowed immediately by the following requirements: (1) Since the fluctuations are usually of the order of 5 to 10 percent, errors in measurement should be no more than $\frac{1}{10}$ of this at the most. (2) A large number of flights need to be made, and this demands a simple instrument. While the ionization chamber is omnidirectional and yields no direct information on the kinds of particles, it does have the advantage of measuring a quantity proportional to the energy per unit area falling on the atmosphere at the location where it is used, it is light in weight and simple to construct.

The ionization chamber may be compared with Geiger counters that are sent above the atmosphere in rockets as follows: First let us estimate the average ionization per particle at high altitudes. The curve given in Fig. 4 for Bismarck on August 3, 1951 becomes nearly horizontal at the lowest pressures of 15 to 30 g cm^{-2}. Assume the intersection of this curve with the axis is at $I=400$ ions cm^{-3} sec^{-1} atmos^{-1} of air, and take Van Allen's and Singer's data for the numbers of incident particles at about this latitude, namely, 0.28 particle cm^{-2} sec^{-1} sterad^{-1}. For 2π solid angle we would expect a number $J=1.8$ particles cm^{-2} sec^{-1}. If $\bar{\sigma}$ is the average specific ionization per particle, then the ionization will be

$$I=\bar{\sigma}J$$

or

$$\bar{\sigma}=400/1.8=220 \text{ ions cm}^{-1} \text{ atmos}^{-1} \text{ of air.}$$

This is to be compared with 180 arrived at for the average ionization throughout the atmosphere in comparing counter telescope and ionization chamber flights at Saskatoon.[20] Bursts and stars should be relatively unimportant in this connection.

Next, consider the ionization chamber at 10 to 20 g cm^{-2} down into the atmosphere. If we assume the same value of $\bar{\sigma}$ as before for the particles that change from day to day, then the percentage change in the ionization at these altitudes will be the same as the change in the numbers of primary particles. In this case stars and showers will give some contribution at large zenith angles, but it is evident from the way the curve flattens off at high altitudes that any such contributions are balanced by the effect of new particles as one goes to lower pressures.

The possibility that the fluctuations in the primary radiation are due only to particles of large atomic number should be considered. In such a case the changes as measured by Geiger counters in rockets would be much smaller than those observed with ionization chambers. It will be shown later that if one takes the number distribution given by Kaplon, Peters *et al.*[21] for particles of all atomic numbers Z and assumes that the constants by which the number distributions are multiplied are the quantities that change, then it is unlikely that Z can be larger than three times that for the average of all primaries. It is perhaps more reasonable to assume that the mechanism that causes the fluctuations affects all incoming particles.

We thus arrive at the conclusion that the ionization chamber, compared with the rocket-borne Geiger counter, will show a relative change at least as large for changes in the primaries. The advantages of using the balloon-borne ionization chamber are (1) for equal times the ion chamber gives much better statistics, and (2) the length of time available for measurement is the order of hours compared with minutes when rockets are used.

[18] See *Progress in Cosmic-Ray Physics* (North-Holland Publishing Company, Amsterdam, 1952), pp. 502–510 for summary.
[19] Forbush, Stinchcomb, and Schein, Phys. Rev. **79**, 501 (1950).
[20] See reference 18, p. 260.
[21] Kaplon, Peters, Reynolds, and Ritson, Phys. Rev. **85**, 295 (1952).

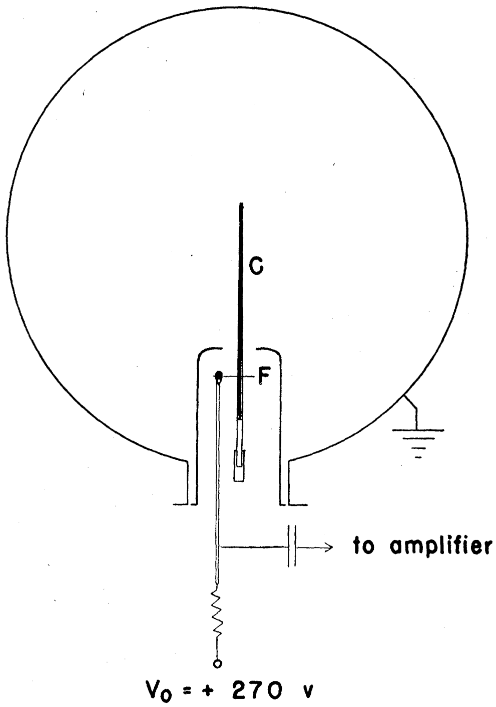

FIG. 1. Schematic drawing of the automatic ionization chamber. Ion collector *C* is a quartz rod made conducting by a coating of graphite except at the lower end, where the bare quartz serves as an insulator. Quartz fiber *F* recharges *C* when the potential of the collector reaches a definite value.

II. INSTRUMENTS AND EXPERIMENTAL PROCEDURES

A. The Ionization Chamber

In planning for flights near the geomagnetic pole an instrument was devised whose information could be transmitted by radio since the problem of recovery was a serious one.

The ionization chamber, described in detail elsewhere,[22] consisted of a steel spherical shell, 25 cm in diameter, having a wall thickness of 0.5 mm (0.4 g cm^{-2}), and filled to a pressure of 8 atmos of argon. The ion collector was a conducting quartz rod, the lower end of which was left uncoated for insulation purposes. A small conducting quartz fiber automatically touched the collector when the potential of the latter dropped to a definite value of about $V_0/1.5$, where V_0 was the potential applied to the quartz fiber. When contact was thus made a pulse was generated across a series resistor and this pulse was amplified and transmitted.

The device is represented schematically in Fig. 1. The fiber *F* is normally maintained at a potential of 270 volts. As the collector *C* loses charge by collecting negative charges from the ionized gas, the fiber moves closer until it becomes unstable due to image forces, rapidly touches *C*, charging it again, and flies away. The process is then repeated. At the maximum rate of ionization during a balloon flight, this recharging occurs every 15 to 20 seconds.

The rate of recharging for a constant ionization depends on the potential V_0 applied to the fiber. In practice this dependence was about 0.7 percent $volt^{-1}$ change of V_0. The battery used was the commercial 300-volt unit. To determine the potential of the batteries for the standard instruments, a potentiometer was used which was sensitive to less than 0.1 volt. Tests were made on the constancy of this potential for the current drains used and for the temperature changes expected. In each case the changes of potential were negligible. (The temperature coefficient determined was +0.02 percent $°C^{-1}$.)

For calibration purposes one instrument was chosen as a standard and two others as secondary standards. Before leaving Pasadena a comparison was made between these new instruments and the older photographically recording balloon ionization chambers used in past years to gather data in various regions of the world.[23] The walls of both instruments were steel and very close to the same thickness. In comparing the two, an ionization of approximately the maximum value to be expected during a flight was used. The source of radiation consisted chiefly of the gamma-rays from thorium C'' filtered through 3.7 cm of steel. This procedure should then tie our new results in with those obtained in past years.

Each group, the one that went to Bismarck, North

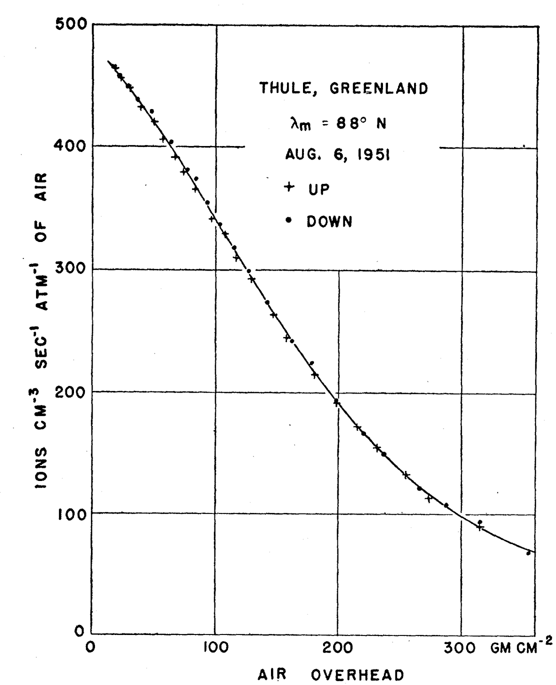

FIG. 2. Example of a single flight using the automatic ionization chamber showing the consistency of the individual points as well as the agreement between the flight going up and coming down.

[22] H. V. Neher, Rev. Sci. Instr. 24, 99 (1953).

[23] Bowen, Millikan, and Neher, Phys. Rev. 53, 855 (1938).

TABLE I. Data for the four flights at Thule, Greenland at definite atmospheric pressures (columns a) have corrections applied for the fluctuations as measured during simultaneous flights at Bismarck, North Dakota (columns b). The resulting corrected data (columns c) show a consistency better than ±0.5 percent from flight to flight.

	20 g cm^{-2}			40 g cm^{-2}			60 g cm^{-2}			80 g cm^{-2}			100 g cm^{-2}		
Date	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
Aug. 3, 1951	424	+24	448	406	+23	429	380	+20	400	351	+18	369	321	+15	336
Aug. 4, 1951	437	+15	452	414	+15	429	387	+10	397	358	+11	369	326	+12	338
Aug. 5, 1951	457	−10	447	435	− 6	429	404	− 8	396	372	− 6	366	342	− 7	335
Aug. 6, 1951	455	− 6	449	430	+ 1	431	400	− 2	398	367	0	367	334	+ 2	336
Average			449±1			430±1			398±1			368±1			336±1

Dakota, and the one that went to Thule, Greenland, took a standard and two secondary standards. These were used to calibrate the instruments sent aloft. In so doing an ionization about equal to the maximum expected was again used.

The group that went to Bismarck, for example, using 2 cm of steel as a filter for the gamma-rays, found that the intensity for the geometry there was 1.1 percent greater than for the arrangement in Pasadena. For the geometry at Thule, Greenland, the calibration intensity was 1.3 percent less than in Pasadena before leaving. In Pasadena the calibration intensity was 566 ions cm^{-3} sec^{-1} per atmosphere of air. Hence, at Bismarck it was 572 and at Thule, 559.

As a further check on the calibration rates, the rate at Thule was carefully noted just before leaving and was then compared with the standard used at Bismarck after returning to Pasadena. A calculation of the intensity at Thule, assuming the Bismarck instrument correct, gave 561 ions cm^{-3} sec^{-1} instead of 559 given above.

We therefore believe that the relative calibration intensities at Bismarck and Thule are known to one percent or better.

The instrument to be used was checked, just prior to being sent aloft, with the battery employed during the flight.

B. The Barometer Unit

The measurement of barometric pressure, giving the mass of air overhead, is a most important quantity. Where the curve of ionization *vs* air mass is the steepest, an error of 1 mm of mercury pressure is approximately equivalent to an error of 0.6 percent in ionization. The barometer unit used on these flights has been described elsewhere.[24] Briefly, it consists of a good commercial, three-section bellows whose expansion is measured by a series of contacts. No mechanical magnification is used, and friction is such that no effect due to it may be detected. Approximately 20 barometer signals are received for a change of one atmosphere pressure.

In calibrating the barometer unit the pressure was changed at about the rate to be expected during a flight, both for decrease and increase of pressure. This tends to make the hysteresis effect in the bellows nearly the same in the two cases.

[24] H. V. Neher, Rev. Sci. Instr. 24, 97 (1953).

A temperature effect was looked for in the barometer unit. No detectable effect was found between 0° and 25°C.

The slightly larger value for the acceleration of gravity near the pole, *viz.*, 980.6 at Bismarck *vs* 982.6 cm sec^{-2} at Thule, introduces a slight correction amounting to 0.1 percent in the value of the ionization at 100 g cm^{-2} pressure. This increases to 0.4 percent at 300-g cm^{-2} and to 0.7 percent at 500-g cm^{-2} pressure. This correction, because of its small size at the higher altitudes, has not been taken into account.

C. Performance of the Equipment

In Fig. 2 the results of a single flight are given as measured at Thule, Greenland (geomagnetic latitude 88°N) on August 6, 1951. The ordinates, in ions cm^{-3} sec^{-1} atmos^{-1} of air, are in terms of our old ionization measurements[23] and may be directly compared. The rates of ascent and descent on this flight were approximately the same, and a good record was obtained throughout.

Perhaps the best indication of the consistency of the flights at the two locations is afforded by the following comparison. On August 3, 4, 5, and 6 simultaneous flights were made at the two stations. The Greenwich times when the flights reached their maximum height are given in Tables V and VI. If it is assumed that the absolute values of the fluctuations are the same at the two stations, then the measured values at Thule may be corrected for the fluctuations as measured at Bismarck simply by adding or subtracting from the Thule flights the change measured at Bismarck. The flight of July 17 at Bismarck is arbitrarily taken as a reference and the departures of the other flights at Bismarck from the flight of July 17 are then applied to the corresponding flights at Thule.

The data given in Table I are taken from the smooth curves drawn through the points for the different flights at Thule, Greenland ($\lambda_m = 88°$N).

The column designated "a" gives the ionization at the indicated depth in the atmosphere for that particular day. Column "b" gives the correction as determined from the corresponding flight at Bismarck as explained above. Column "c" gives the corrected values at Thule.

If the fluctuations are actually simultaneous and if the instruments are functioning relative to one another as they should, then one would expect agreement

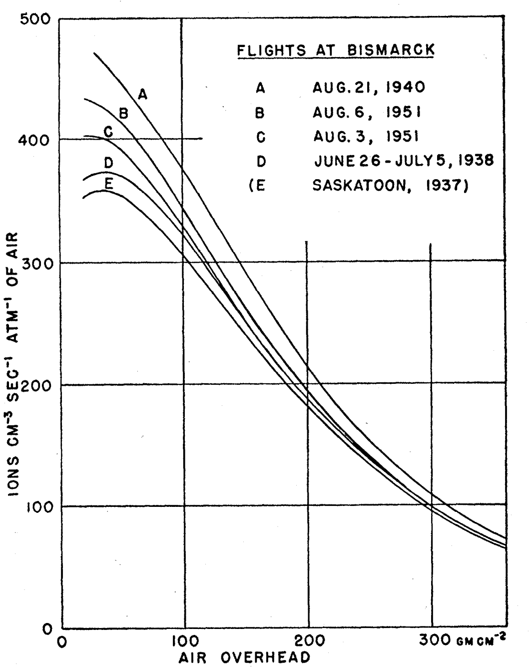

FIG. 3. Extremes of ionization *vs* depth in the atmosphere measured thus far at Bismarck, North Dakota. Curve E taken at Saskatoon is included since Bismarck at the same time should in no case have been higher.

between the various flights as given in column "c." It is seen that the corrections are not small, amounting at 20 g cm^{-2} to a plus 5.5 percent correction on August 3 and a minus 2.2 percent on August 5. Yet when the corrections are made for the fluctuations as measured at Bismarck, the corrected Thule values agree to less than 0.3 percent. The errors given are merely determined by the scatter of the corrected data and do not in any way represent the estimated error in the absolute value of the numbers.

In evaluating the results given in Table I, it should be borne in mind that not only errors in the calibration, both of the ionization chambers and barometers, together with errors in the individual flights, enter at the one station but similar errors enter for the corresponding instrument sent up at the other station.

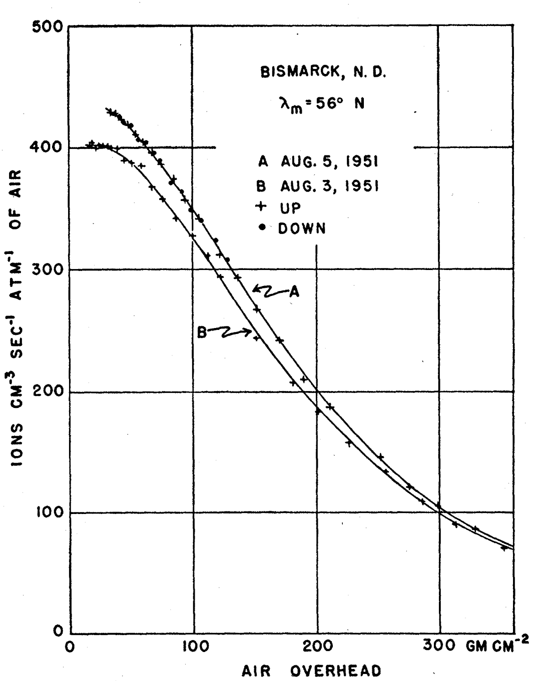

FIG. 4. Representative curves for two particular days at Bismarck, geomagnetic latitude, λ_m, 56°N.

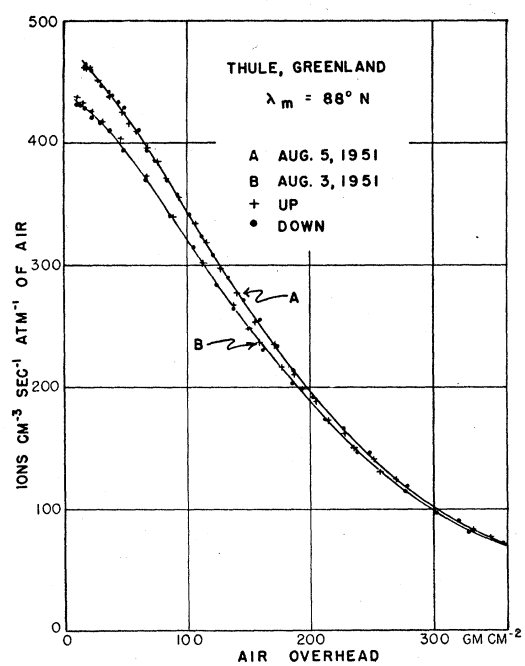

FIG. 5. Curves at Thule, Greenland (λ_m=88°N) for the same two days as those at Bismarck in Fig. 4. Note the similarity in the change that took place at the two stations.

III. EXPERIMENTAL RESULTS

A. Fluctuations

As pointed out previously, before the latitude effect can be determined at high latitudes, it is first necessary to determine the fluctuations. Since data had been obtained at Bismarck in past years, we shall first compare two typical flights, using the present equipment on different days, with flights made with our older, photographically recording ionization chambers. These old and new chambers have very closely the same wall thickness (0.5 mm of steel) and were compared with each other in the laboratory with hard gamma-rays using an intensity of radiation about equal to the maximum to be expected during a flight.

Figure 3 shows how radically different the atmospheric absorption curves can be at a given location at different times. Curve A is the average of three flights[25] made on the same day on August 21, 1940. Curves B and C are flights made on August 6 and 3 of 1951 with the present equipment. Curve D is the average of four flights[26] made during the period June 26 to July 5, 1938. In addition to these four curves, curve E is given which is the average of 3 flights[7] at Saskatoon ($\lambda_m = 60°$N) on August 14, 16, and 17, 1937. Since the intensity due to geomagnetic effects should in no case decrease with increasing latitude, the fact that curve E falls below D is taken to mean a real increase took place in the primary intensity between 1937 and 1938 for the times the flights were made. Curves A to E represent then, the extremes of the fluctuations at Bismarck as measured thus far and, from arguments given in the Introduction, represent a change in the numbers of primary particles of about 30 percent.

TABLE II. Data from ionization-depth curves for each simultaneous flight from the U.S.S. Wyandot (column W) and Bismarck (column B). Ionization is in terms of ions cm^{-3} sec^{-1} $atmos^{-1}$ of air. Values given in parentheses are extrapolated, based on the other, similar flights. July, 1951.

	July 17		July 22		July 23		July 24	
g cm^{-2}	W 55°N	B 56°N	W 58.5°N	B 56°N	W 62.5°N	B 56°N	W 68°N	B 56°N
15	···	(430)	409	···	434	402	421	412
20	418	429	408	···	430	401	420	412
30	418	427	407	···	421	393	417	411
40	416	423	402	397	411	385	412	406
50	408	415	395	390	400	375	403	397
60	395	401	384	381	388	363	391	386
80	366	375	357	353	360	339	360	360
100	336	344	328	323	328	312	328	332
120	···	313	298	294	298	282	297	302
140	···	282	268	265	269	254	267	272
160	···	252	241	237	242	226	240	242
180	···	224	216	210	216	202	214	216
200	···	198	191	185	191	178	190	191
220	···	175	168	164	168	158	167	167
240	···	154	148	145	146	139	146	147
260	···	136	131	128	128	121	129	130
280	···	120	115	112	111	105	113	113
300	···	106	100	99	98	92	101	99
340	···	81	74	76	76	70	79	76
380	···	60	56	57	60	54	61	59
420	···	46	44	44	48	42	46	45
460	···	35	···	34	···	32	36	35
500	···	26	···	27	···	···	···	26

It is of interest that the ionization-depth curve obtained near Thule by Carmichael and Dymond[5] in 1937 passed through a maximum as did also our own curves taken at Saskatoon ten days later. Whether or not such a curve passes through a maximum will depend on the ratio of the numbers of particles that do not multiply appreciably as they strike the atmosphere to those that do. In other words, the presence of a sufficient number of primary nuclei of momenta around 1 Bev/c will explain the difference between the upper parts of curves A and E.

[25] Millikan, Neher, and Pickering, Phys. Rev. **66**, 295 (1944).
[26] R. A. Millikan and H. V. Neher, Proc. Am. Phil. Soc. **83**, 409 (1940).

TABLE III. Data from ionization-depth curves for each simultaneous flight at Thule, Greenland (T), 88° geomagnetic north and Bismarck, (B) at 56°N. Ionization in terms of ions cm^{-3} sec^{-1} $atmos^{-1}$ of air. Values given in parentheses are extrapolated but based on other similar flights. August, 1951.

g	August 2		August 3		August 4		August 5		August 6	
cm^{-2}	T	B	T	B	T	B	T	B	T	B
15	448	401	427	405	442	···	461	···	461	438
20	445	401	424	405	437	414	457	(439)	455	435
30	436	401	416	404	426	411	447	(436)	443	431
40	427	398	406	400	414	408	435	429	430	423
50	416	394	394	393	401	401	421	419	416	414
60	404	383	380	381	387	391	404	409	400	403
80	375	361	351	357	358	364	372	381	367	375
100	343	334	321	329	326	333	342	352	334	343
120	310	304	290	298	295	300	307	320	301	309
140	281	274	260	268	267	271	277	289	269	278
160	252	244	232	236	242	243	248	257	241	248
180	224	216	207	210	214	216	220	228	213	220
200	198	193	185	188	189	190	193	202	187	193
220	175	171	164	166	166	167	170	178	164	169
240	154	153	145	148	145	144	150	157	143	147
260	135	135	127	131	127	127	132	137	125	131
280	121	119	112	115	111	112	115	120	109	115
300	106	105	98	101	97	99	101	105	96	101
340	81	82	76	77	74	76	79	81	74	78
380	62	64	59	60	58	57	60	62	57	59
420	47	50	46	45	44	42	46	47	44	44
460	36	···	35	···	33	31	35	···	34	···
500	28	···	26	···	27	···	27	···	25	···

It is significant that while curve A as compared with D or E shows the presence of radiation that is rapidly absorbed in the upper part of the atmosphere, there was also present on August 21, 1940, more penetrating radiation as compared with July of 1938. In fact, curve A continues to lie above the others throughout the atmosphere. A more complete discussion of the character of the radiation at high altitudes and latitudes that fluctuates from day to day will be given later.

Figures 4 and 5 give the data obtained for August 3 and 5 at Bismarck and Thule. The curves given hereafter will not, in general, contain the plotted points but only the smooth curves or the data taken therefrom will be given. For most of the flights, records were obtained for both the descent as well as the ascent, and in most cases agreed very well. A particular case where the two did not agree will be discussed later.

The data taken from the individual curves are given for each of the simultaneous flights in Tables II and III. In Table IV are given the results after correcting the data taken from shipboard and at Thule for the fluctuations as measured at Bismarck, using the data at the latter station on July 17 as a reference.

In Tables V and VI are given the times when the instruments reached their maximum height, the minimum pressures and the locations where the flights were made. While the Greenwich times for launching were not identical, it will be seen from the tables that the times when the instrument reached the maximum height did not usually differ by more than 1 hour. The fact that the points on the descent nearly always agreed with those taken on the ascent means that, in general,

TABLE IV. Corrected values of ionization for shipboard and the four simultaneous flights at Thule, using July 17 at Bismarck as a base. Column b gives corrections as obtained from departures of the particular Bismarck flight from that on July 17. Column c gives the corrected values of ionization in ions cm^{-3} sec^{-1} $atmos^{-1}$ of air.

g cm^{-2}	July 17 W 55°N	July 17 B 56°N	July 22 58.5°N b	July 22 58.5°N c	July 23 62.5°N b	July 23 62.5°N c	July 24 68°N b	July 24 68°N c	Aug. 3, 4, 5, 6 88°N c (Av)
15	···	(430)	···	···	(28)	462	(17)	438	454
20	418	429	(27)	435	27	457	17	437	449
30	418	427	(26)	433	34	455	16	433	441
40	416	423	26	428	38	449	17	429	430
50	408	415	25	420	40	440	18	421	417
60	395	401	20	404	38	426	15	406	398
80	366	375	22	379	36	396	15	375	368
100	336	344	21	349	32	360	12	340	336
120	···	313	19	317	31	329	11	308	304
140	···	282	17	285	28	297	10	277	274
160	···	252	15	256	26	268	10	250	247
180	···	224	14	230	22	238	8	222	218
200	···	198	12	203	19	210	7	197	193
220	···	175	10	178	16	184	7	174	170
240	···	154	9	157	15	161	7	153	151
260	···	136	8	139	15	143	6	135	132
280	···	120	8	123	15	126	7	120	116
300	···	106	7	107	14	112	7	108	102
340	···	81	5	79	10	86	5	84	79
380	···	60	3	59	6	66	2	63	59
420	···	46	2	46	4	52	1	47	46
460	···	35	1	···	3	···	0	36	36
500	···	26	−1	···	···	···	0	···	···

the radiation did not change appreciably in a period of 1 to 2 hours.

To give a better idea of where the various flights were made, Fig. 6 is given showing a map of the regions of interest. Three of the four flights from shipboard were made in foggy weather. The flight of July 17 was incomplete because of radio interference from equipment on the ship.

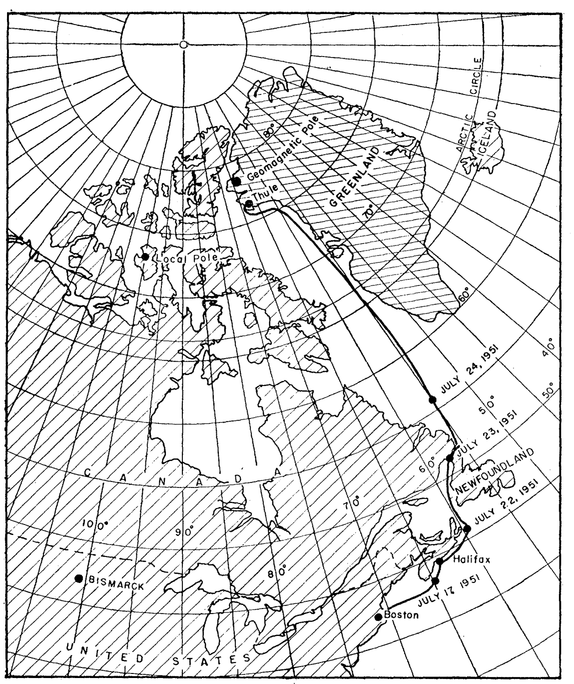

FIG. 6. Map of the region where simultaneous flights were made.

At Thule, the flights during the first week of August were made in very good weather. Toward the middle and end of August more fog and clouds were present. The winds at both the surface and at high altitudes were in general low. The result was that only on one occasion was any difficulty experienced in filling and launching the balloons even though this was done out-of-doors. The winds above 30 000 feet during the month of August were low and variable. The total distance of drift of the instruments during a 4 to 5 hour flight was from 30 to 150 miles. A summary of the weather observations at both surface level and high altitudes at Thule may be obtained from the U. S. Weather Bureau.[27]

To illustrate the simultaneity of the fluctuations at Bismarck and Thule, Fig. 7 is given. Here the ionization for certain pressures as taken from Table III for August 3, 4, 5, and 6 are plotted for these stations. The data for August 2 will be discussed later.

TABLE V. Data for individual flights at Bismarck, North Dakota, geomagnetic latitude 56°N.

	Time at p_{min} GCT	p_{min}		Time at p_{min} GCT	p_{min}
July 17	14:22	22 g cm^{-2}	Aug. 2	15:38	23 g cm^{-2}
July 22	16:37	45	Aug. 3	14:24	17
July 23	14:08	12	Aug. 4	14:20	25
July 24	13:57	21	Aug. 5	13:38	33
			Aug. 6	14:35	23

TABLE VI. Data for individual flights from shipboard and at Thule.

	λ_m	Time at p_{min} GCT	p_{min}		Time at p_{min} GCT	p_{min}
July 17	55°N	13:14	22 g cm^{-2}	Aug. 2	13:40	16 g cm^{-2}
July 22	58.5°	12:54	17	Aug. 3	13:08	10
July 23	62.5°	12:55	11	Aug. 4	13:20	8
July 24	68°	12:55	9	Aug. 5	13:25	16
				Aug. 6	13:05	13

In addition to the fact that for these particular days, the intensity of the radiation went up and down simultaneously at these two stations that are 2300 miles apart, two other characteristics are apparent from an examination of the values given in Fig. 7. These are (1) the relatively large difference between Thule and Bismarck in the ionization at 20 g cm^{-2} and (2) the reversal of the intensities at the intermediate pressures. These effects are brought out more fully in curves to follow.

Not only do the fluctuations near the north geomagnetic pole appear to be simultaneous with fluctuations at Bismarck but it also appears to be true that these

[27] *Climatological Summary*, Thule, Greenland, U. S. Weather Bureau, Washington, D. C.

are simultaneous with changes in the ionizing component and neutron intensities as measured at ground level. For completeness we reproduce in Fig. 8 a series of curves already published[16] showing these changes during the period of July 17 to August 14, 1951. The balloon flight data are taken at 50 g cm^{-2}, or about 70 000 feet, primarily because some of the flights did not go above this altitude.

These data emphasize the fact pointed out before by Forbush[14] that these changes are world wide. The present experiments which demonstrate the simultaneous nature of the fluctuations in the radiation at high altitudes between the north geomagnetic pole and intermediate latitudes together with the correlation of changes at high altitudes and ground elevations at both intermediate and equatorial latitudes, gives added support to Forbush's suggestion and places on a firmer basis the world-wide character of these fluctuations.

The ratio of the percentage change in ionization at 70 000 feet to that found at sea level from these data is about 7 to 1. It is obvious that the mean energy of the particles responsible for these fluctuations is less than for the total radiation, since, if the total radiation changed by a given amount, the percentage change would be independent of altitude. Nevertheless, these changes are measured at the equator, although, as Forbush has pointed out,[14] the percentage variation there is somewhat less than at Cheltenham ($\lambda_m = 50°$N).

The ratio of 7 to 1 between changes in the ionizing component at 70 000 feet to those at sea level here found may be compared with the ratio of 10 to 1 found by Biehl *et al.*[1] with counter telescopes at about 50 000 feet and a ratio of 6 to 1 found by Jesse.[17] Some further information bearing on the ratio of changes in ionization at high altitudes as compared with sea level is as follows. On July 27, 1946 (data unpublished) a balloon flight was made from Ft. Worth, Texas with our photographically recording ion chambers. This was two days after the large solar flare of July 25 which caused an oft-cited increase in cosmic rays. By July 27 the cosmic-ray intensity at Mt. Wilson had dropped to 5.5 percent below its pre-flare value, while the ionization at 70 000 feet over Texas was 22 percent less than its pre-flare value. This gives a ratio of about 4 to 1. These data indicate that as one proceeds toward the equator, i.e., as the average energy of the primaries increases, the ratio between the fluctuations at high to low altitude decreases.

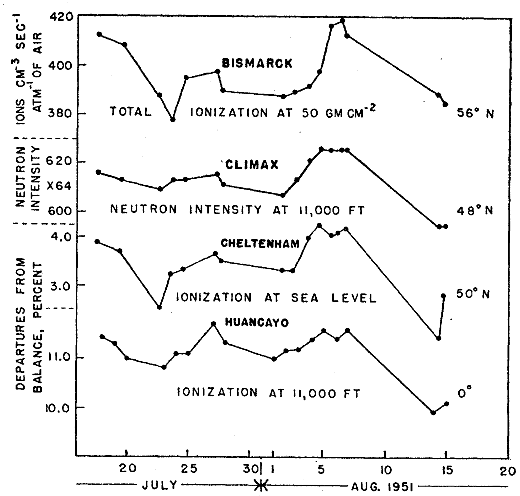

FIG. 8. During July and August, 1951, there was a good correlation between the ionization as measured at 70 000 feet at Bismarck, the neutron intensity at Climax, Colorado, the ionization at Cheltenham, Maryland, and the ionization at Huancayo, Peru.

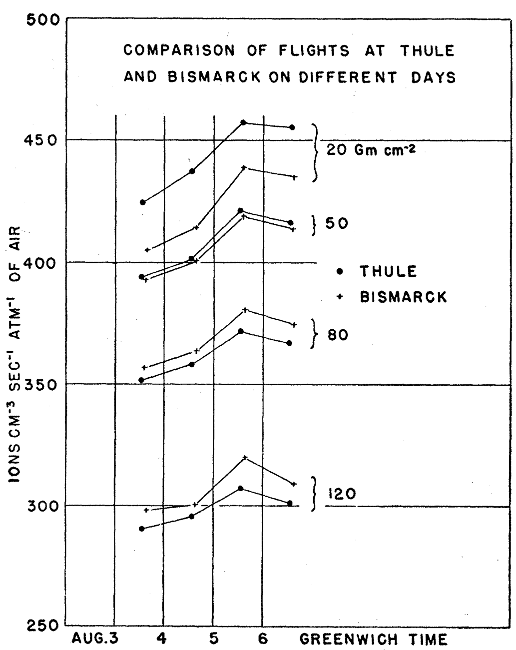

FIG. 7. At given depths in the atmosphere at Thule and Bismarck the ionization changed very close to the same amount for these particular days.

Since fluctuations in the ionizing component of the order of 1 percent at ground level, which are not attributable to atmospheric effects, are quite common, we conclude from this information that fluctuations of 7 to 10 percent in the ionization are just as frequent at high altitudes and latitudes. From the arguments given in the Introduction, we conclude that the corresponding change in the numbers of primary particles is also of the order of 10 percent.

The percentage change in neutron intensity at Climax, Colorado is roughly three times the change in ionization at Cheltenham. As pointed out previously,[16] the fluctuations shown in Fig. 8 are not due to solar flares such as that which occurred on November 19, 1949. On this occasion the change in neutron intensity at Manchester, England[28] was 60 times the change in

[28] N. Adams, Phil. Mag. 41, 503 (1950).

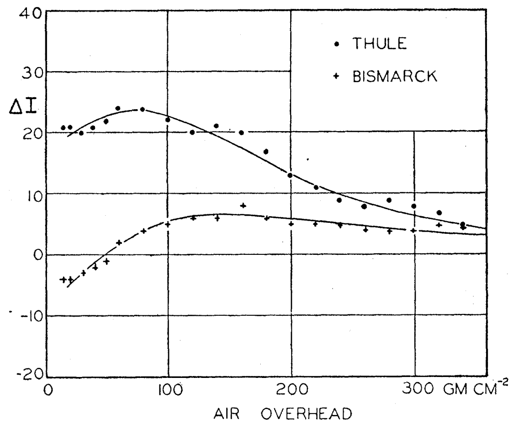

FIG. 9. Differences at Bismarck and at Thule, August 2–August 3, 1951. August 2, 1951 appeared to be anomalous in that the change measured at Thule compared with August 3 was not the same as at Bismarck.

ionizing particles, both measurements being made at ground level.

While it seems reasonable to assume from the above discussion that the fluctuations, at such widely separated stations as Bismarck and Thule, are usually simultaneous, there are some important exceptions to this rule.

A study of Table III will show some of these differences. Comparing the difference between Thule and Bismarck on August 2 with those on August 3, 4, 5, and 6 it is seen that while the former difference tends to disappear at the higher atmospheric pressures, the difference at the low pressures is very much larger than for the other simultaneous flights. We do not believe the difficulty is instrumental. The most likely instrumental failure is that the constant by which the rate of recharging is multiplied, to convert to ions cm^{-3} sec^{-1} $atmos^{-1}$ of air, somehow changed. If this were so, one would not expect the Bismarck and Thule curves to agree at pressures around 300 g cm^{-2}. Furthermore, the points coming down for both flights agreed with those taken going up. Plotted in Fig. 9 are the curves of the differences between August 2 and 3 at both stations.

The above indicates that on August 2 there was present at Thule radiation that was not present at Bismarck. Further, the manner in which it is absorbed in the atmosphere indicates that the particles should have had sufficient momentum to get through the earth's magnetic field at Bismarck.

A further indication that the radiation changes may be different at two widely separated stations is afforded by the flight from shipboard on July 23, 1951. Not allowing for any fluctuations as measured at Bismarck, the upper parts of the three curves taken on July 22, 23, and 24 while proceeding north by ship from Boston are plotted in Fig. 10. These curves show very well what can happen to the shape of the curve at high altitudes from one day to the next. It is evident that on July 23 there were present low energy particles that were not present in such copious numbers on July 22 or July 24. The effect of these particles seems to die out completely in the first 50 g cm^{-2}.

The corresponding Bismarck flight was made about one hour after the July 23 flight from shipboard. The upper part of the curve from this flight we give in Fig. 11. Two facts stand out when this flight is compared with other flights and the July 23 flight from shipboard. (1) The points coming down, in the upper part of the atmosphere, do not agree with those going up. (2) The whole curve is lower than the flight from shipboard.

The "hysteresis" effect shown by the Bismarck curve is interpreted as being due to a more intense incoming radiation while the instrument was coming down than when going up. Since the points coming down agree with those going up at depths greater than 100 g cm^{-2}, we conclude that these particles, if protons, had energies of not more than 0.6 Bev. A search for solar phenomena which may have been present at this time indicates that a flare of magnitude 1 occurred at 1130 Greenwich time. This time is to be compared with 1255 and 1408 when the flights from the ship and at Bismarck reached their maximum heights, respectively. It appears that the effect of the solar flare, while present over Newfoundland was delayed in arriving at North Dakota, its influence being felt only while the instrument was going down.

Spatial dependence on increases in cosmic rays have been reported previously. The increase of February 28,

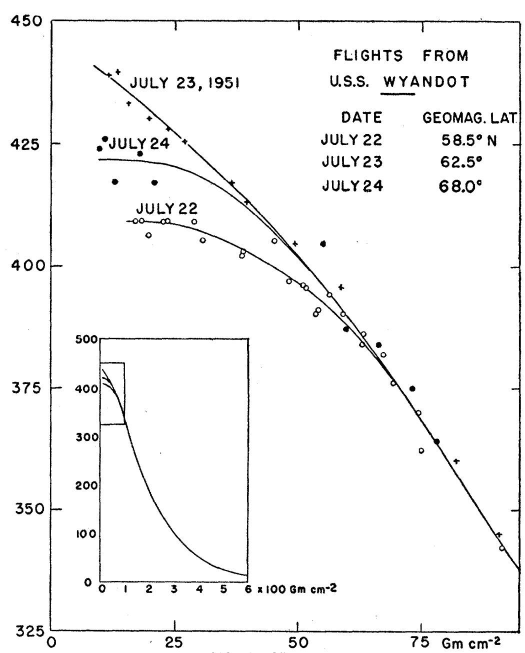

FIG. 10. On July 23 considerably more absorbable radiation was present at high altitudes near Newfoundland than on July 22 or July 24.

1942 amounted to 7 percent at Cheltenham, Maryland,[29] but only a one percent increase in London[30] was observed. The cosmic-ray flare of November 19, 1949 was of different magnitude also at different locations. At Ottawa,[31] Rose reported a 70 percent increase in the ionizing component, while only a 3.6 percent increase was noted by Dauvillier[32] in France. Furthermore, differences in times of an hour for the increase to reach its maximum are reported by various observers.

The indications from the present data are that even small solar flares may give rise to increases in low energy charged particles, whose effects never reach down to sea level and that there are spatial and time differences, which, at the present time, are not well understood.

B. The Geomagnetic Effect at High Latitudes

Having made simultaneous flights at Bismarck and Thule and at points in between, and having eliminated the effect of fluctuations by so doing, it now becomes possible to determine a true geomagnetic effect in going north from 55° geomagnetic latitude, to essentially the geomagnetic pole.

In Fig. 12 the resultant ionization-depth curves are plotted for Bismarck and Thule. The Bismarck curve is that obtained for July 17, 1951, while the Thule curve is the average of the four coincident flights (August 3, 4, 5, and 6) at Thule after having been corrected for the fluctuations as measured at Bismarck, using the flight of July 17 as reference. These two curves cross at about 60 g cm^{-2} (65 000 feet) and also at about 400 g cm^{-2} (25 000 feet). In between these two pressures the maximum difference is about 2.5 percent.

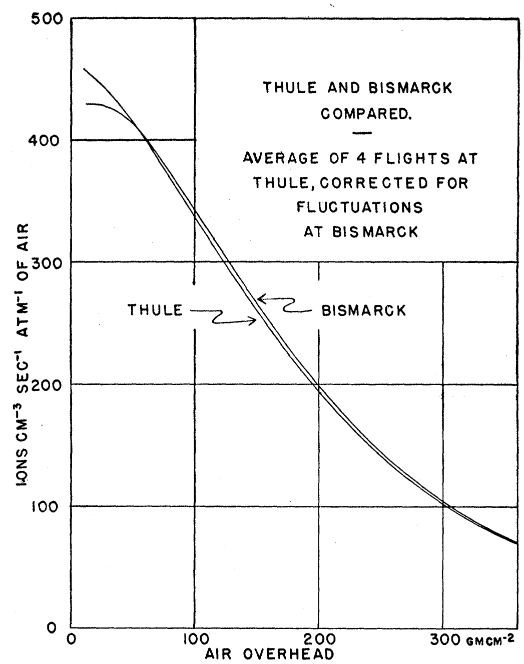

FIG. 12. When the Thule flights are corrected for the fluctuations as measured at Bismarck the resultant ionization-depth curves at the two stations can be compared. The increase of Thule over Bismarck at low pressures is attributed primarily to the shadow effect of the earth. The decrease of Thule over Bismarck at intermediate pressures is ascribed to a temperature effect.

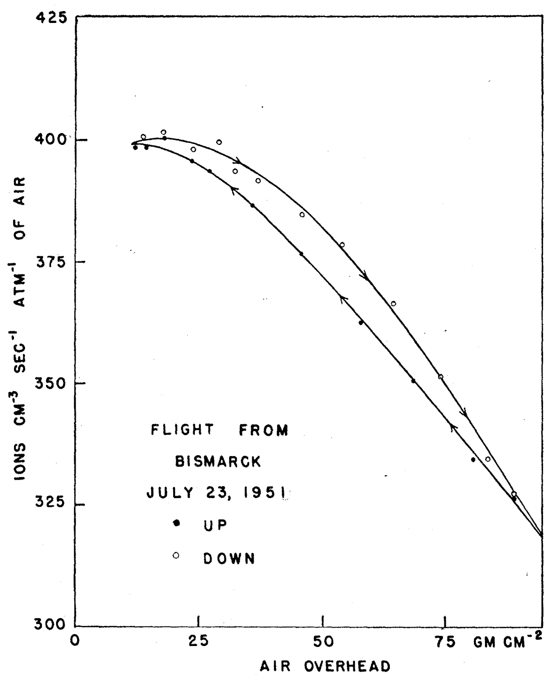

FIG. 11. Flight from Bismarck on July 23 showed an interesting "hysteresis" loop. There is a possible connection of this behavior with that exhibited in Fig. 10.

To determine the manner in which the ionization changes with latitude, the flights from shipboard are used. Figure 13 illustrates the necessity of correcting for fluctuations. Here we have plotted the ionization for given depths in the atmosphere for each of the flights as a function of geomagnetic latitude. The points for a given pressure have arbitrarily been connected by straight lines. The uncertainties given at Thule (λ_m = 88°N) are merely the extremes of the four flights made on August 3, 4, 5, and 6.

In Fig. 14 we plot the same data as in Fig. 13 but now corrected for the fluctuations as measured at Bismarck, again using the flight of July 17 at Bismarck as a reference. The flight of July 23 at λ_m = 62.5°N, as discussed previously, is considered anomalous and is omitted. The uncertainties indicated at 88°N are the remaining extremes of the four simultaneous flights after having been so corrected. The somewhat larger disagreement between the Thule flights at pressures greater than 100 g cm^{-2} may be due to variable atmospheric conditions from day to day. The meteorological data for Thule show considerably larger day-to-day fluctuations in temperature for August 3, 4, 5, and 6

[29] I. Lange and S. E. Forbush, Terr. Mag. Atm. Elec. **47**, 331 (1942).
[30] A. Duperier, Proc. Phys. Soc. (London) **57**, 473 (1945).
[31] D. C. Rose, Can. J. Phys. **29**, 227 (1951).
[32] A. Dauvillier, Compt. rend. **229**, 1096 (1949).

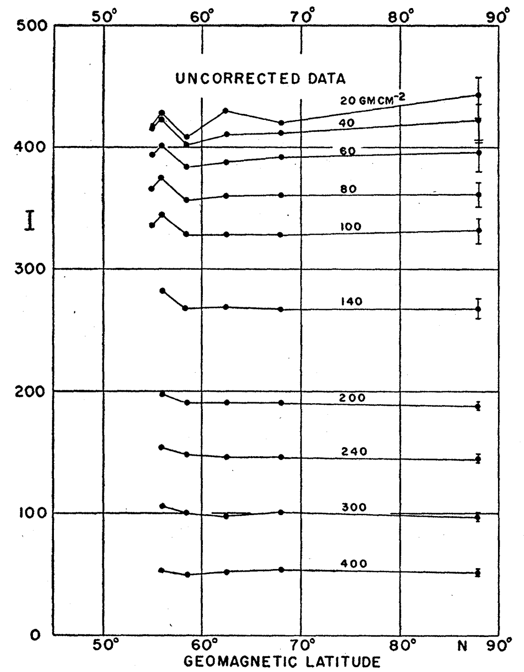

FIG. 13. Ionization for given depths in the atmosphere for each flight as a function of geomagnetic latitude. Before corrections are made to the data obtained at intermediate latitudes and at Thule for the fluctuations measured at Bismarck, very little consistency is evident when ionization at given depths is plotted against geomagnetic latitude.

at the intermediate altitudes compared with those at the higher altitudes. The data for the different flights should then become more consistent at high altitudes and this they appear to do.

The present results may be compared with some previous data taken by Biehl and Neher[33] with an unshielded ionization chamber while on a B-29 airplane flight at 30 000 feet from 64° geomagnetic north to the equator, along longitude 80°W. This ionization chamber had an average wall thickness of 8 mm of steel. The contribution of showers from this amount of material plus additional matter close by, due to its location in the plane, probably accounts for the somewhat larger value of ionization shown in Fig. 14 as compared with the present data, taken with thin-walled ionization chambers (0.5-mm steel), for the same atmospheric pressure. However, the agreement as to the slopes of the lines seems to be quite satisfactory.

The two outstanding characteristics, evident from both Figs. 12 and 14 are (1) the negative latitude effect at intermediate latitudes and altitudes and (2) the positive latitude effect at very high altitudes.

Effect (1) appears to be due to the influence of the warmer atmosphere over northern Greenland in the summer compared with that over North Dakota. Weather data, furnished by the U. S. and Danish Weather Bureaus, show that the average temperature

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

for August 3, 4, 5, and 6, 1951 at the 100-mb level at Thule was −42°C and at Bismarck −63°C. At the 50-mb level the temperatures were −41°C and −54°C, respectively (see Fig. 15). In the warmer, and hence more attenuated, atmosphere the μ-mesons will decay, on the average, with more kinetic energy than in the denser atmosphere and hence more energy, on the average, will go into the two resulting neutrinos. Assuming that no new particles get through the earth's magnetic field between Bismarck and Thule, whose influence can penetrate to these intermediate altitudes, we calculate a temperature coefficient on the above basis, assuming an effective temperature difference of 16°C,

$$\alpha=(1/I)(dI/dT)=-0.19 \text{ percent } {}^{\circ}\mathrm{C}^{-1},$$

for altitudes of 30 000 to 50 000 feet. The value found at sea level by various observers is close to this for intermediate latitudes but it is not clear just how they are related.

At high altitudes the atmospheric temperature situation becomes somewhat different. Studies of Kellogg and Schilling[34] indicate that in the summertime the temperature from about 30 to 50 km altitude should be lower over northern Greenland than over Bismarck. At a height of about 30 km (100 000 feet) their analysis indicates

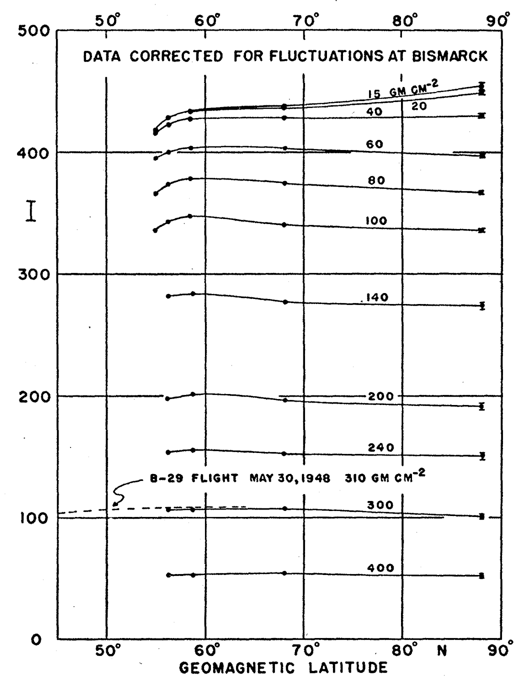

FIG. 14. After corrections are made to the flights at intermediate latitudes and at Thule, the data show much more consistency than is evident in Fig. 13. The uncertainties indicated at 88°N are the resultant extremes of the 4 simultaneous flights after corrections are made.

[34] W. W. Kellogg and G. F. Schilling, J. Meteorol. **8**, 222 (1951); also, W. W. Kellogg, *Physics and Medicine of the Upper Atmosphere* (The University of New Mexico Press, New Mexico, 1952), Chap. IV, page 71.

that there is little, if any, change of temperature with latitude, during the summer months, from intermediate latitudes on to the pole. The actual situations for August 3, 4, 5, and 6, as determined from the weather data, for the two stations, are shown in Fig. 15. The solid lines give the average temperatures for these four days. The dashed parts represent the probable extensions of these curves to higher altitudes from the analysis of Kellogg and Schilling. We infer, then, that the effects of decay, in causing a difference in the ionization at Bismarck compared with points north, should disappear for pressures of 10 to 15 g cm^{-2}.

As to the increase in ionization with increasing latitude at very high altitudes mentioned above as effect (2), it will be noticed from Fig. 14 that an increase of 5 percent in the ionization occurs at 15 g cm^{-2} between 66° and 88°N. The minimum energy allowed by the Stoermer cone for protons at 66°N is approximately 140 Mev. Protons of this energy have a range in air of about 16 g cm^{-2} and hence would just penetrate to the instrument. The increase from 66° to 88° should then not be due to new particles let in by the opening of the Stoermer cones.

At a given geomagnetic latitude only part of the sky is accessible to particles of a given momentum. The boundary that separates the accessible from the forbidden regions, forms what is known as the Stoermer cone. An application of Liouville's theorem implies that over the accessible region, particles of this momentum come in with uniform intensity. At latitudes where the Stoermer cone has opened up completely for particles of a given momentum, one might expect the whole sky to be uniformly illuminated by these particles. The presence of the earth, however, prevents some of the particles from arriving due to the fact that their trajectories have intersected the earth elsewhere.

Schremp[35] has calculated this shadow effect and has presented his results in the form of orthogonal projections for every 10° of latitude. For positive particles in the northern hemisphere, the boundaries to these shadow cones are at zenith angles greater than 45° and extend from the northwest quadrant around toward the southeast. The theory indicates that particles of high momentum are affected most. Thus at 70°N even some particles of momentum 14 Bev/Zc are not present near the eastern horizon due to the fact that they have struck the earth before reaching the point of observation.

Using Schremp's calculations and the energy distribution of the primary radiation given in a previous paper,[36] the effect of these shadow cones has been determined by graphical integration. The results show (1) that the magnitude of the increase calculated between geomagnetic latitudes 56° and 88° is about 4 times that observed and (2) that the increase in the numbers of particles between 66° and 88° should be about four times that between 56° and 66°. As far as the discrepancy in magnitude is concerned, some of it can be explained by the greater length of path for the particles coming in at the large zenith angles which will result in secondaries that lose a considerable portion of their energy in neutrinos. More work needs to be done, however, both from the experimental and theoretical points of view.

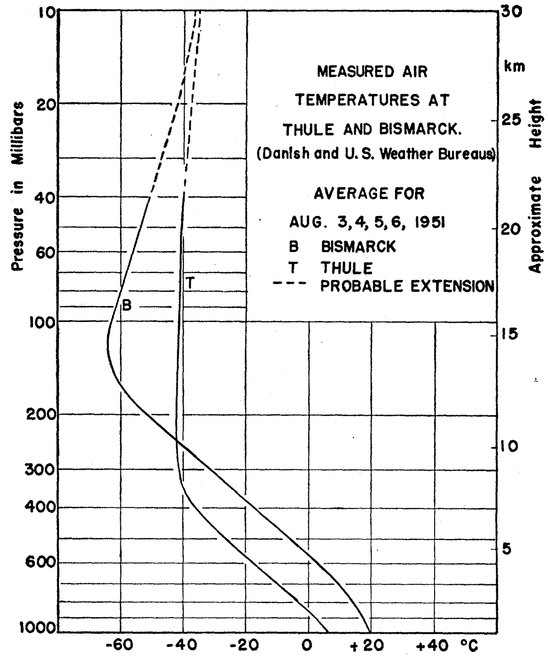

FIG. 15. Temperature data at the two stations were furnished by the U. S. and Danish Weather Bureaus. The extensions indicated are based on the analysis of Kellogg and Schilling. (See reference 34.)

We may, then, divide the distance, at very high altitudes, between Thule and Bismarck, into two regions, (1) that between 56° and 66°N where the increase in ionization at 15 g cm^{-2} may be due to both the increase in the number of low energy particles admitted by the earth's magnetic field and the decrease of the shadow cones, and (2) that between 66° and 88° where the increase must be due to the shadow effect alone since new low energy particles admitted above 66° cannot reach down to the instrument. We may then take the increase from 66° to 88°N as an experimental determination of the shadow effect at these latitudes. The increase in ionization between these latitudes is 4 percent, at 15 g cm^{-2}, from Fig. 14. Assuming the latitude dependence as calculated for the shadow cones as correct we would then expect a 1 percent increase in the ionization due to the shadow effect between 56° and 66°. From Fig. 14 it will be seen that the increase in ionization is about 1 percent between 58° and 66°N. We therefore conclude that the shadow effect can account for all the increase measured, at the highest

[35] E. J. Schremp, Phys. Rev. 54, 158 (1938).
[36] H. V. Neher, Phys. Rev. 83, 649 (1951).

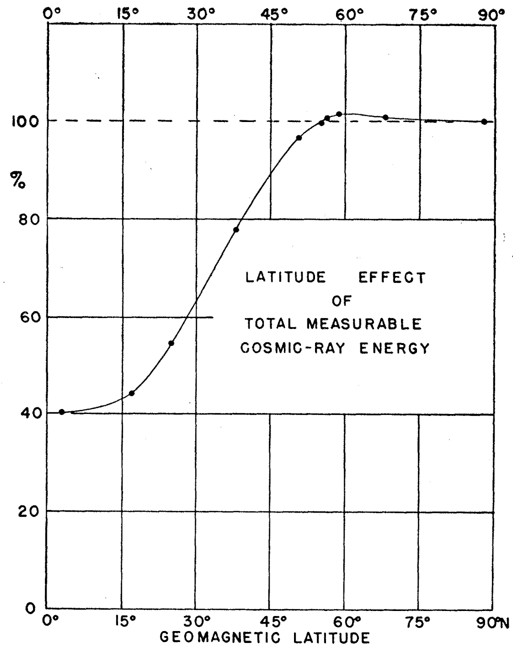

FIG. 16. The latitude effect of the total measurable cosmic-ray energy per unit area dissipated in the atmosphere.

altitudes, from about geomagnetic latitude 58°N to the pole.

The latitude effect may be defined also in terms of the energy dissipated in the atmosphere per unit of horizontal area as a function of latitude. It is easily shown that, except for loses in particles, such as neutrinos, which never reappear in the form of ionizing radiation, the area under the ionization-depth curve gives the total energy dissipated in a vertical column of air of unit cross section. If we call the total area under the Thule curve 100 percent, then the areas at the other latitudes may be expressed in terms of this. In so doing we arrived at the values given in Fig. 16.

In determining the area at 55°N, some interpolation was necessary in drawing the curve, since the data extended down only to 100 g cm^{-2}. The curve was completed by running it into the corresponding Bismarck curve at a somewhat higher pressure. To extend the curve of Fig. 16 to lower latitudes our data taken in past years were used. The point at 51°N was obtained from the data taken at Saskatoon and Omaha[7] in 1937. A decrease in area of 4.7 percent was found at that time[37] in going from 60°N to 51°N, and this is the difference between the Omaha point and the value at 60°N in Fig. 16. The point at 38°N is at San Antonio, Texas and is taken from our data[7] of 1936. The point at 3°N is from our balloon flights in India in 1936 which agreed with those made[38] in 1940. That at 17°N is from the Agra flights in December, 1939. The above flights were all made with similar, carefully compared, photographically recording ionization chambers. The point at 25°N is for Peshawar, India from data obtained with single Geiger counters. Single counter flights were also made at 17°N and 3°N and a comparison made with our ionization chambers at these latitudes.

While the points from 51°N to the equator in Fig. 16 were not taken simultaneously the few percent error that might have been introduced into this relative comparison will not alter the principle features of this curve.

It should be pointed out that the lower three points of Fig. 16 were taken at longitudes 70° to 77°E while all the other points were taken at about 95°W. The effect of change of longitude on the area is such[39] that approximately 16 percent should be added to the values at 70°E longitude near the equator to obtain the expected values at 90°W. It should further be pointed out that all of these data at the intermediate and higher

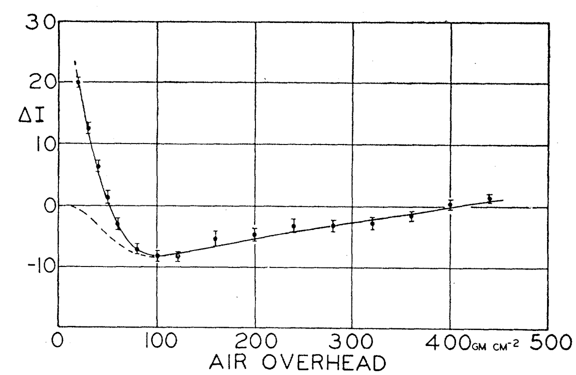

FIG. 17. Difference between Thule and Bismarck as shown in Fig. 12. (Average of four flights.) The dashed line represents an estimate of the temperature effect extended to higher altitudes.

latitudes were taken in the summer months and may not quite represent the conditions prevailing during the winter.

The behavior of the curve of Fig. 16 from 56° on north is determined by the same effects discussed previously, namely, (1) any new particles that are permitted to enter by the earth's magnetic field, (2) new particles admitted by the closing of the shadow cones, and (3) differences in losses in neutrinos throughout the atmosphere because of the different density of the air. To gain an estimate of the magnitudes of these effects on the areas under the ionization depth curves, we have plotted Fig. 17 giving the difference between the curves of Fig. 12 which are the averages obtained for Bismarck and Thule. The negative part of the curve we have attributed to μ-meson decay effects in the middle part of the atmosphere. As pointed out

[37] Reference to the Cheltenham data of the Carnegie Institution of Washington shows that the ground level ionization was very close to the same for these Saskatoon and Omaha flights. [See I. Lange and S. E. Forbush, Carnegie Institution of Washington Publication No. 175, p. 130, 1948.]

[38] H. V. Neher and W. H. Pickering, Phys. Rev. **61**, 408 (1942).
[39] H. V. Neher, Phys. Rev. **78**, 674 (1950).

previously, this difference should disappear at the higher altitudes where the temperature of the air becomes nearly equal at the two stations. We have drawn a dashed line in Fig. 17 to represent what seems to be a reasonable extension to lower pressures for this temperature effect. The sharp upturn of the curve we attribute primarily to new particles admitted by the disappearance of the shadow effect at Thule, although there may be some effect of added particles let in by the opening of the Stoemer cones. The negative area of Fig. 17, which we assume is due to the temperature effect, is 2 percent of the total area under the ionization-depth curve. The positive area added is 1 percent. Since some of this must be due to the shadow effect, it is evident that very little can be due to the addition of lower energy particles. It appears from Fig. 16, however, that there is an increase in energy up to about geomagnetic latitude 58°N. This is consistent with the ionization shown by the top curve of Fig. 14.

Recapitulation on the latitude effect at high altitudes and latitudes: We have shown (1) that any new particles admitted by the earth's magnetic field, if protons, should reach down to our instrument at least up to a latitude of 66° geomagnetic north, (2) that at these altitudes (90 000–100 000 feet) the temperature of the atmosphere should be approximately independent of latitude and hence temperature differences should not affect the relative ionization at these altitudes at latitudes above 56°N because of losses due to neutrinos, (3) that the shadow effect alone can account for all new particles that appear at very high altitudes from 58° to 88° geomagnetic north, and (4) that the temperature and shadow effects will account for the difference in the areas under the ionization-depth curves from 58° to 88°N.

In addition to the above experimental evidence for a cutoff of primary particles, another argument can be made in terms of the fluctuations measured at Bismarck and Thule. When corrections are made to the Thule flights for fluctuations as measured at Bismarck, it is found that on 4 out of the 5 days when simultaneous flights were made, the corrected values at Thule showed a remarkable consistency from day to day. This is illustrated in Table I. The interpretation we placed on this is that no radiation fluctuates at Thule that does not also fluctuate at Bismarck. If any low energy primary particles were present at Thule which were not also present at Bismarck, one would expect them to fluctuate also. From Table I the corrected data for the 4 flights are consistent with each other to less than ±0.5 percent down to an atmospheric depth of at least 100 g cm^{-2}. Hence, within rather narrow limits, there are no lower energy particles, which could penetrate the atmosphere down to our instrument and which would be admitted by the earth's field, from geomagnetic latitude 56° to 88°N.

Giving somewhat less weight to this latter argument than those given previously, we conclude that a real cutoff of the primary particles exists and we place the latitude at which this occurs at 58°±1° geomagnetic north. Because of the omnidirectional character of our instrument, particles of a given momentum will be effective until the allowed cone is nearly completely open. We shall take a zenith angle of the allowed cone of 45°E in the E-W plane and assume that any further opening will not appreciably affect our results. The limiting momentum at this angle at 58° is found to be[39] 1.5±0.2 Bev/Zc, which for protons represents an energy of 0.8±0.2 Bev. The errors indicated in the energy and momentum give the estimated uncertainties arising from both the experimental errors and those in estimating the effective opening of the allowed cone.

IV. DISCUSSION

A. The Fluctuating Radiation

In Fig. 3 we have given the curves obtained at Bismarck and at Saskatoon on various occasions. In Fig. 18 we have plotted the difference between Bismarck in August, 1940 and Saskatoon in August, 1937. This latter curve represents the absorption in the atmosphere of the radiation present in 1940 that was not there in 1937. At the highest altitudes reached the ionization in 1940 was about 33 percent higher than in 1937, corresponding to a similar increase in the number of primary particles. A reasonable extension of the original curves to higher altitudes would certainly increase this number.

The additional radiation present in 1940 consisted mostly of low energy particles that were rapidly absorbed in the atmosphere. In addition, however, there were also present particles whose effects extended down through the whole atmosphere. If we compare the increase, as measured at 50 g cm^{-2}, of the 1940 Bismarck data over that at Saskatoon in 1937 with similar data at Cheltenham and Huancayo[40] for the

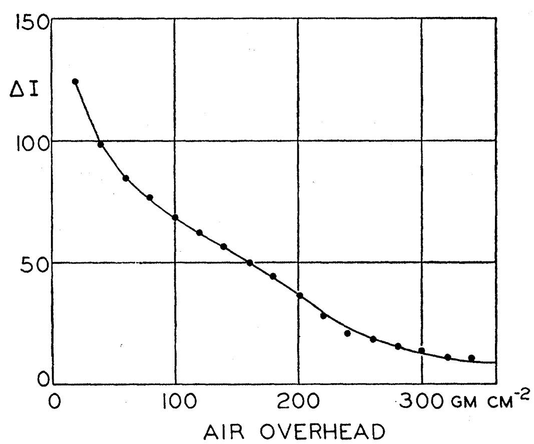

FIG. 18. The difference between curves *A* (Bismarck, Aug. 21, 1940) and *E* (Saskatoon, Aug. 14, 1937) of Fig. 3. This curve represents the way in which the additional radiation at Bismarck in August, 1940 over that present in 1937 is absorbed in the atmosphere.

[40] I. Lange and S. E. Forbush, Carnegie Institution of Washington Publication No. 175, 1948.

same days, we find a ratio of about 10 to 1, if we take the average shown by these two ground stations. This is consistent with the ratios previously determined for this latitude. (The reason for taking the average for Huancayo and Cheltenham is that over a period of years there seems to be a gradual drift of the instruments which is different at the two stations.)

A similar curve is obtained by taking the difference between August 6 and August 3, 1951. In Fig. 19 this difference for both Thule and Bismarck has been plotted. This curve emphasizes again the usual similarity in the fluctuations at the two locations. There is a striking resemblance of this curve with that given in Fig. 18 and discussed above. The chief difference is in the magnitude of the ordinate. We shall assume that the same agency is at work in causing these changes in each case.

As pointed out in the Introduction, a clue as to the nature of the particles that fluctuate may be obtained

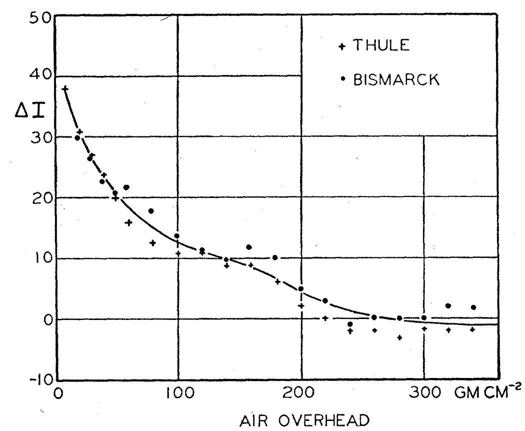

FIG. 19. Differences at Bismarck and at Thule, August 6–August 3, 1951. The difference at Thule on August 6 compared with August 3 is quite similar to the difference shown at Bismarck for the same two days.

by comparing the change in ionization at very high altitudes with the change in area that they produce. For the total incoming particles, as obtained from Fig. 3 curve C, the ratio of the ionization at very high altitudes to the total area they produce is 4.2×10^{-3} g^{-1} cm^2. With a reasonable extrapolation to zero pressure, the average for this quantity as obtained from Figs. 18 and 19 is 12×10^{-3} g^{-1} cm^2. We interpret this to mean, that for these occasions, either the average particle that fluctuated ionized 3 times as much along its path as the average for all cosmic-ray particles, or that the particles that fluctuated were essentially the same as the total but that their average energy was one-third as great. There might, of course, have been a mixture of these two possibilities.

It is evident, however, that the fluctuations could not have been in heavy nuclei alone. Kaplon *et al.*[21] found that the dependence of the number distribution on the energy per nucleon is approximately the same for all atomic numbers Z. The ionization of a high velocity nucleus varies as Z^2, while the energy brought in by a nucleus of a given momentum (pc/Z) varies as Z. The ratio of these two is Z. It is clear then that if the energy distribution of the particles remains unaltered, and the fluctuations were only in particles heavier than protons, that their average Z could not have been greater than three times that for the average of all primaries. We think it more likely that, whatever the mechanism causing the fluctuations, it affects particles of all Z but alters the energy distribution, so that particles of low energy are changed more than those with higher energy.

In seeking an explanation for these fluctuations, one may assume (1) that the source itself fluctuates and/or (2) that the fluctuations are due to some agency between the source and the earth.

If the intensity changes at the source, then the number of sources must be small and near at hand. The reason for the small number of sources is as follows: Suppose the number were large and scattered throughout the galaxy. Then one would hardly expect any one or even a few to predominate in their effects on the earth. Since the fluctuations are large we conclude, from probability considerations, that if the sources fluctuate their number must be small and, from energy considerations, they must be relatively close.

The other possibility, that the fluctuations are due to some agency between the source and the earth, has been treated by a number of authors. One such agency discussed by Meixner[41] might be a fluctuating solar magnetic field. The effect of such a varying field has been discussed by Alfven.[42] Briefly, the arguments are as follows. The effect of a general magnetic field of the sun whose dipole moment is in the neighborhood of 0.5×10^{34} gauss-cm^3 is to eliminate all particles whose momentum is less than about 1 Bev/Zc from arriving at the earth. However, no changes would be expected at the equator if only particles with momentum of less than a few Bev/Zc were so affected. This is contrary to the world-wide changes in cosmic rays that appear to exist.

Another possible agency that has often been discussed is a fluctuating magnetic field set up by a ring current surrounding the earth. Although such a mechanism has many attractive features from the point of view of interpreting magnetic fluctuations, serious objections have been raised by those attempting to explain cosmic-ray fluctuations by any such ring current. Johnson long ago[43] pointed out that the changes in cosmic rays were many times greater than could be expected from the measured change in the magnetic field during a magnetic storm. Furthermore, the calculations of Hayakawa[44] indicate that if the radius of this

[41] W. Heisenberg, Editor, *Cosmic Radiation* (Dover Publications, New York, 1946), p. 178.
[42] H. Alfven, Nature **158**, 618 (1946).
[43] T. H. Johnson, Revs. Modern Phys. **10**, 193 (1938).
[44] See S. Hayakawa, reference 18, p. 496 for discussion.

ring current is greater than 1.3 earth radii, the effect on incoming cosmic-ray particles of 15 Bev/Zc momentum is opposite to that observed.

A further objection to the ring current as explaining cosmic-ray fluctuations seems to be as follows: The axis of the ring presumably coincides with that of the geomagnetic axis. Along this axis all directions should be allowed for all energies of incident particles. For an isotropic distribution at great distances, this means the sky at the geomagnetic north pole should be equally illuminated with particles of all energies in all directions. A changing magnetic field should have no effect on this intensity. At the equator or at intermediate latitudes, changes in intensity would, however, occur. This is contrary to the experimental fact that changes are definitely observed near the pole.

Another mechanism suggested by Alfven[42,45] is that of electrical fields being built up in the ionized streams ejected from the sun. Cosmic-ray particles passing through these streams would not only lose or gain energy, changing the energy dissipated in the atmosphere, but the latitude for cutoff for particles of a given original momentum would also change.

Nagashima[46] has investigated the effect of changing electric fields on the distribution in numbers of particles arriving at the earth at various latitudes when Liouville's theorem is applied in the generalized form to apply to electric as well as magnetic fields.[47] He finds that changing potentials, at some distance from the earth, of the order of 0.1 Bev can cause changes in the ionization at high altitudes of a few percent at the equator and 5 to 10 percent at the higher latitudes. This proposed mechanism has the advantage of giving changes at the equator as well as at the poles which are roughly in agreement with experiment.

In seeking an explanation for these fluctuations in the primary cosmic rays, any proposed mechanism or mechanisms must satisfy the requirement first, that, in general, the changes are world wide; second that the changes in the ionizing component at sea level are nearly independent of latitude; third, that the changes in the ionizing component increase with increasing latitude; fourth, that the fluctuations in the ionizing component at high altitudes are larger than at intermediate altitudes or at ground level; fifth, that the changes in the neutron component are several times those in the ionizing component.

B. The Latitude Effect at High Altitudes and Latitudes

We have presented experimental evidence to show that there is a cutoff of the primary cosmic-ray particles at about 58° geomagnetic north. Briefly, this conclusion is based on the following arguments: (1) The small increase in ionization (Fig. 14) of one percent at 15-g cm^{-2} air pressure from 58° to 68°N can be accounted for entirely by shadow effects due to the interception of particles of relatively high energy by the earth. (2) The behavior of the curve (Fig. 16) giving the total energy dissipated in the atmosphere *vs* geomagnetic latitude from 58° to 88°N can be accounted for entirely by atmospheric temperature and shadow effects. (3) No particles fluctuate at 88°N, in general, that do not also fluctuate at 56°N. We interpret this to mean that, with certain exceptions, no low energy particles are present at the one station that are not also present at the other. We have given more weight to the first two arguments and have set the cut-off latitude at 58°±1°. Because of the omnidirectional character of our apparatus the cut-off momentum is not that for the vertical direction. Taking as an effective zenith angle, 45°E, we found the cut-off momentum to be 1.5±0.2 Bev/Zc. This corresponds to an energy for protons of 0.8±0.2 Bev.

In a recent discussion of their own measurements with rockets compared with the results of Pomerantz,[8] and Van Allen and Singer[48] have shown that within experimental errors their rocket flight at 58°N shows the same primary flux as Pomerantz's balloon flights with Geiger counters at 69°N. The experimental errors are given by Van Allen and Singer as ±10 percent for their own measurements and ±8 percent for those of Pomerantz. These two sets of experiments were performed at different times. Those of Pomerantz were in August, 1949, while Van Allen and Singer made their rocket flight in January, 1950. In view of the fluctuations discussed above one must add to the experimental uncertainties those due to possible changes in the radiation also, since no monitoring station was used. On the basis of the fluctuations given in Figs. 7 and 8, we conclude that in each case the uncertainties for each set of experiments would need to be increased to ±15 or 20 percent. Thus, barring any large changes, such as occurred at Bismarck and given in Fig. 3, there could be a 30 to 40 percent increase in the numbers of primary particles in going from 58° to 69°N at any given time and a comparison of these two experiments would stand a good chance of not revealing such an increase.

Several mechanisms have been invoked to account for the cutoff of low energy particles in cosmic rays. Janossy's[13] suggestion that the general magnetic field of the sun turns away particles below a certain momentum from the earth is still a distinct possibility. Alfven's[49] discussion of the effect of turbulence in the photosphere of the sun on the Zeeman pattern for such a weak field, has thrown some doubt on the interpretation of such measurements as a means of arriving at the general magnetic field of the sun. The magnetic moment of the sun that would cause a cutoff of cosmic-ray particles in the neighborhood of 58° geomagnetic

[45] H. Alfven, Phys. Rev. **75**, 1732 (1949).
[46] K. Nagashima, J. Geomag. Geoelec. **3**, 100 (1951).
[47] W. F. G. Swann, Phys. Rev. **44**, 224 (1933).
[48] J. A. Van Allen and S. F. Singer, Nature **170**, 62 (1952).
[49] H. Alfven, Nature **168**, 1036 (1951).

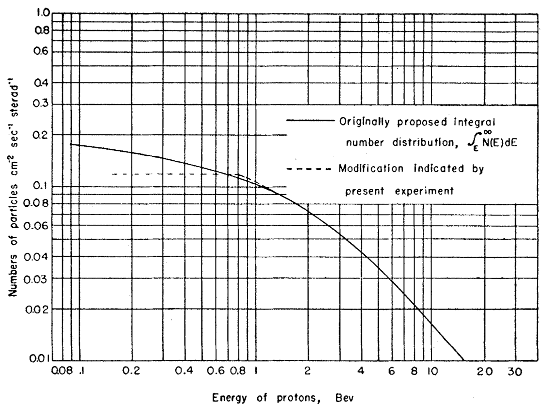

FIG. 20. The present experiments indicate a cutoff of the primary radiation at 58°±1° geomagnetic north. A modification to the number distribution proposed previously (see reference 36) is here indicated.

north is 0.65×10^{34} gauss-cm^3. This corresponds to an equatorial solar magnetic field at the photosphere of 19 gauss.

The diurnal effects to be expected from such a dipole of the sun have been discussed by Epstein,[50] Kane, Shanley, and Wheeler,[51] Dwight,[52] and Singer.[53] On the basis of Epstein's and Dwight's calculations one might expect a diurnal effect at geomagnetic latitude 51° for the above solar dipole moment. The expected magnitude would be 5 to 8 percent, depending on the energy distribution of the primary particles, with a maximum at about 6 A.M. and a minimum at 6 P.M. Bergstralh and Schroeder[54] made two balloon flights at 56°N which were intended primarily to test for a diurnal effect. None was found, either in the total ionizing radiation, the low energy gamma-rays or the fast neutrons at high altitudes. It is evident, however, that if the solar magnetic field keeps any new particles from coming to the earth above 58°N that only a small diurnal effect might be found at 56°N. A more appropriate geomagnetic latitude would be 51° to 53°N.

On the other hand, while no serious attempts have apparently been made to detect any systematic differences at different times of the day, it is difficult to understand how such large changes from 6 A.M. to 6 P.M. could have escaped detection. Alfven[55] proposed a mechanism which would decrease the expected diurnal effect, and the detailed calculations of Kane, Shanley, and Wheeler[51] have shown that this mechanism would result in a maximum diurnal change of only a few percent of that calculated by Epstein. Alfven considered the scattering of incoming particles by the magnetic field of the earth. Depending on the magnitude of the solar magnetic field, particles within a certain momentum range that came within the influence of the earth's magnetic field but did not hit the earth would be deflected into trapped orbits about the sun. Eventually these would hit the earth but would come from directions that were initially prohibited. It seems reasonably certain that the absence of a large diurnal effect is not an argument against a solar cutoff.

The residual systematic diurnal effect found by Kane *et al.* would be difficult to establish in view of the much larger random diurnal effects discussed earlier in this paper.

Unsöld[56] has proposed that the cutoff is due to low energy charged particles being stopped by losing their energy through ionization in passing through interstellar matter which, on the average, he estimates at 50 g cm^{-2}. If there is a uniform distribution in the energies of the initial primaries, one would expect that by this same mechanism other particles with slightly higher energies would end up in the lower energy group and thus no cutoff would occur.

With the present information it is now possible to revise the number spectrum proposed by one of us.[36] In Fig. 20 the originally proposed integral spectrum derived from balloon-borne ionization chamber and counter telescope data is represented by a solid line while the modification indicated by the present experiments is given by the dashed line. The cutoff of the primary radiation we have placed at 0.8 Bev for protons as discussed above.

V. SUMMARY

Using a new type of integrating ionization chamber, whose information is transmitted readily by radio, a series of balloon flights was made from shipboard going north from Boston in the summer of 1951. These were made from geomagnetic latitudes 55°, 58.5°, 62.5°, and 68°N. Another series of flights was made from Thule, Greenland at geomagnetic latitude 88°N. Five of these latter and the 4 shipboard flights were made at approximately the same Greenwich time as similar flights from Bismarck, North Dakota (56°N) made by another expedition. The major experimental results and conclusions drawn therefrom may be stated as follows:

1. The ionization-depth curves at Bismarck in July and August, 1951 did not pass through a maximum as was the case in 1938. They were, in fact, intermediate between the 1938 flights and those obtained in 1940.

2. The fluctuations in the radiation at high altitudes, measured during the present series of flights, were simultaneous at the two stations. Two of the nine simultaneous flights were exceptions to this statement. On at least one of these occasions, a small solar flare may have been responsible for this difference.

3. During the period of observation, the magnitude

[50] P. S. Epstein, Phys. Rev. **53**, 862 (1938).
[51] Kane, Shanley, and Wheeler, Revs. Modern Phys. **21**, 51 (1949).
[52] K. Dwight, Phys. Rev. **78**, 40 (1950).
[53] S. F. Singer, Nature **170**, 63 (1952).
[54] T. A. Bergstralh and C. A. Schroeder, Phys. Rev. **81**, 244 (1951).
[55] H. Alfven, Phys. Rev. **72**, 88 (1947).
[56] A. Unsöld, Phys. Rev. **82**, 861 (1951).

of the fluctuation in the ionization from day to day amounted to from 5 to 10 percent at the highest altitudes.

4. The fluctuations at high altitude in the ionizing component showed a good correlation with ground level measurements of the ionizing component both at 50°N and at the geomagnetic equator. The changes at 70 000 feet were approximately 7 times as large as the changes in penetrating component at sea level. Since changes of the order of 1 percent at sea level are quite common, that are not ascribable to atmospheric effects, we conclude that changes of 7 to 10 percent at very high altitudes and high latitudes are also common.

5. There was a similar correlation between the ionization at 70 000 feet and the neutron component as measured at ground level at intermediate latitudes. The ratio of the fluctuations in this case was about 2 to 1.

6. On only 2 occasions out of a total of 14 at the two stations, where such an effect should have been detected, was the curve obtained on the down flight significantly different than on the up flight. Since the time spent at the high altitudes was from 1 to 2 hours, we conclude that changes in the radiation are not likely to occur in this period of time.

7. The particles that fluctuate cannot be those of high atomic number only. This we deduce from the ratio of the change in the ionization at very high altitudes to the change in area under the ionization-depth curve they produce, compared with a similar ratio for all cosmic-ray particles. If the fluctuations are due to particles with atomic number Z, larger than 1, evidence is cited to show that Z is probably not larger than 3. We conclude that the most reasonable explanation for the factor 3 is that some mechanism affects the energy distribution of the primary particles in such a manner that the average energy of the particle that fluctuates is about $\frac{1}{3}$ of the average for all primaries.

8. A negative latitude effect in the ionization at high latitudes and intermediate altitudes was found. This we have ascribed to a temperature effect due to the warmer air above Thule as compared with Bismarck for that time of year. The coefficient obtained is -0.19 percent per degree Centigrade for altitudes around 40 000 feet.

9. At pressures less than 40 g cm^{-2} we find a positive latitude effect at high latitudes. This we have ascribed to the disappearance of the earth's shadow cones as one goes north. The increase beyond 66°N at the highest altitudes reached (about 15 g cm^{-2}) cannot be due to new low energy particles being admitted by the earth's magnetic field, since their energy is too low to penetrate the residual atmosphere above the instrument.

10. At altitudes corresponding to 15 g cm^{-2} there appears to be no latitude effect in the total ionization between 58° and 66° geomagnetic north. Arguments are presented to show that differences in ionization cause by temperature differences between these two latitudes and at this altitude should be small. The sum of the effects due to the earth's shadow and new particles appears to be less than 1 percent. We therefore conclude that the number of new low energy particles whose energy, if protons, lies between 0.8 and 0.14 Bev must be less than 1 percent of the total number of incident particles.

11. A similar conclusion is drawn from the areas under the ionization curves *vs* geomagnetic latitude. The slightly smaller area at 88°N compared with 58°N is assigned to a difference in energy loss due to neutrinos, while the absence of a significant change from 58° to 66°N is interpreted as meaning that no new particles come to the earth in the above energy interval.

12. The simultaneous nature of the fluctuations at Bismarck and Thule, together with the fact that they usually were closely of the same amount, shows that, in general, no particles fluctuated at Thule that did not also fluctuate at Bismarck. We interpret this to mean again that no new particles were entering north of Bismarck, since if there were, they too would have fluctuated. Weighing the experimental evidence we have placed the latitude of cutoff of the primary particles at $58°\pm1°$ geomagnetic north.

13. To account for this cutoff of low energy particles, which for protons is about 0.8 Bev, we think a general solar magnetic field is the most reasonable mechanism. If so, the magnetic moment necessary would be 0.65×10^{34} gauss-cm^3. This would correspond to 19 gauss at the solar equator.

In conclusion, we want to acknowledge the aid and cooperation of persons and agencies who made the carrying through of these experiments possible. The local Pasadena U. S. Office of Naval Research as well as the main ONR office in Washington were of great assistance in making many of the arrangements. The U. S. Navy and the Military Air Transport Service we wish to thank for furnishing the necessary transportation. We are also grateful to Captain F. W. Laing and the officers of the U. S. S. Wyandot for their cooperation in making the flights from shipboard in going north from Boston.

We are particularly grateful to the U. S. Weather Bureau for the assistance rendered. Through Chief of the Bureau, Dr. F. W. Reichelderfer, arrangements were made for helium supplies at Bismarck, Thule and on shipboard. Also through his office arrangements were made for accommodations at the Weather Bureau station at Thule. We also want to thank Mr. Robert B. Sykes, Jr., Chief of the Arctic Operations Project, Mr. J. Glenn Dyer, Assistant Chief, and Mr. George Rabbitt, all of the Weather Bureau, for much needed assistance. The help of Mr. John T. Crowell, Officer in charge of the Weather Bureau station at Thule, and of Mr. F. J. Bavendick, in charge of the Bismarck Office, is gratefully acknowledged.

We want also to express our appreciation to the Danish Government for permission to go to Greenland to make these flights. The assistance of the Thule Colony Manager, Mr. Krough in enlisting the help of the Eskimos and Danish residents in locating instruments is also appreciated. By this means, two instruments were found, one, 150 miles north of Thule on the ice cap.

Finally we want to thank Dr. Robert A. Millikan who assisted in making the arrangements and who was greatly interested in the project. Also we are grateful for the able assistance of Dr. Bernard Steenson and Mr. Alan Johnston in making the equipment, in its calibration, and in carrying out the flights. Our thanks are also due Dr. Oliver Wulf for valuable discussions on the properties of the upper atmosphere.

PHYSICAL REVIEW VOLUME 90, NUMBER 4 MAY 15, 1953

Nuclear Interactions of 210-Mev π^- Mesons in Emulsions

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(Received December 11, 1952)

A study has been made of the interactions of 210±20-Mev π^- mesons with the nuclei of photographic emulsions which were exposed to the University of Chicago synchrocyclotron. Detailed classification of the events into elastic and inelastic scatterings, stops and stars, permitted some discussion of the mechanisms involved. The mean free path for a nuclear interaction was found to be 25.7 cm, as determined from an examination of 2823 cm of track. The increase in this mean free path over that observed at lower energies at Columbia appears to be primarily due to a decrease in the probability for π^- meson absorption in a nuclear collision.

INTRODUCTION

At Bristol,[1] analysis of photographic emulsions exposed to the cosmic radiation has permitted investigation of the nuclear interactions of π-mesons in the energy interval 50 to 1100 Mev. In such studies, the number of observations in any given energy interval is small, and the events examined are usually confined to stars with at least 2 or 3 heavy (or black) prongs. The production of fairly intense, monoenergetic, well-collimated π-meson beams by the large accelerators, now permits a more detailed study in the lower energy region. At Berkeley,[2] observations on 35-Mev π^- mesons and 45-Mev π^+ mesons have been made, while at Columbia,[3] more extensive experiments up to energies of 110 Mev have been performed. Further, many complementary experiments using pure materials instead of emulsion have been carried out at Berkeley, Cornell, Columbia, and Chicago.[4]

This communication reports on a study of 227-Mev (nominal value) π^- meson interactions in emulsions. A stack of Ilford G5 plates, 400 microns thick, and 6 in.×3 in. was placed in the high energy pion beam from the University of Chicago synchrocyclotron. A description of the channels, analyzing magnet, and the scintillation counter detection system has been published by Martin.[5] The plates were exposed one foot from the pole pieces of the analyzing magnet, with the emulsion plane roughly parallel to the beam. They were developed with an amidol bisulfite solution using the well-known temperature method.

TECHNIQUE

An individual meson track was followed from the point the meson entered the emulsion to the point where either it left the emulsion, left the scan area, or produced an interaction. Observations showed that about 95 percent of the mesons entered the emulsion from the glass surface; it was therefore considered desirable and convenient to restrict the observations to the tracks of these mesons. Further selection was made by requiring that the mesons enter the emulsion within 10° (in horizontal projection) of the mean incident direction; in practice it was found that the vast majority entered within 3° of this direction. Finally, in order to reduce the possibility of large energy loss, no scanning was performed further than 3 cm from the edge of the plate that faced the beam during the exposure. The average length of individual meson tracks in the emulsion was about 7 mm. In all, 4483 tracks were followed, for a total track length of 3003.4 cm.

Scattering and grain density measurements were made on about 1 percent of the tracks selected at

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