# The Primary Cosmic Radiation at High Latitudes*

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Various properties of the new group of low energy primary cosmic-ray particles ($E<1.6$ Bev for protons) which enter the top of the atmosphere at geomagnetic latitudes north of 52° were investigated during the summer of 1950. Measurements at both 52°N (Swarthmore, Pennsylvania) and 69°N (Fort Churchill, Manitoba) were obtained with the same quadruple-coincidence counter trains used previously, oriented either horizontally or vertically, and with pulsed ionization chambers biased to detect bursts exceeding 1.0 Po-$\alpha$.

No diurnal or temporal variations in the cosmic-ray intensity were detected, and no change between 1949 and 1950 was indicated. Flights were conducted with counter trains containing various thicknesses of interposed Pb absorber.

In contrast with the 46 percent increase in the vertical intensity between the two stations, no latitude effect was revealed either in the flux of cosmic rays traveling in the horizontal direction or in the frequency of bursts detected by the ionization chambers, at the highest altitudes attained ($\sim$9 mm of Hg).

The data permit conclusions to be drawn regarding the horizontal component, the solar dipole-moment, the nature of the low energy spectrum, as well as nuclear disintegrations and primary heavy nuclei.

## I. INTRODUCTION

EXPERIMENTS which have revealed the presence in the primary cosmic radiation of particles having momenta below that required for entrance at geomagnetic latitude 50°N have been described previously.[1] The original conclusions were based upon a direct comparison, by identical instruments, of the vertical cosmic-ray intensity near the "top of the atmosphere" at Fort Churchill, Manitoba (geomagnetic latitude 69°N), during the summer of 1949 with that at Swarthmore, Pa. (geomagnetic latitude 52°N).

After it had thus been established that a new group of particles was reaching the earth north of the previously-assumed knee of the latitude effect which had heretofore been attributed to a cut off imposed by the magnetic field of the sun, it was of interest further to investigate certain other features of these particles. In particular, it was considered desirable:

(a) to determine whether any change of conditions such as might be produced by a variable solar magnetic dipole-moment had occurred subsequent to the initial observations;

(b) to conduct additional attempts to detect either diurnal variations or short-time temporal variations (over a period of weeks);

(c) to obtain measurements of the intensity *vs* altitude curves with an interposed absorber of thickness intermediate between those utilized previously (4 cm of Pb);

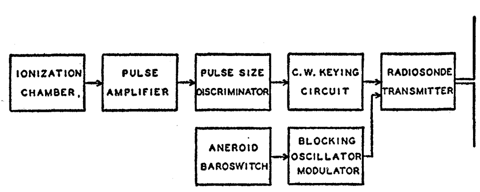


FIG. 1. Block diagram of circuits associated with ionization chamber.

(d) to compare the intensity in the horizontal direction at 69°N with that at 52°N in order to secure additional information regarding the nature of the new group of primary particles entering at the higher latitude;

(e) to observe the effect of the new low energy group of primaries upon the rate of bursts produced within the walls of an ionization chamber at high altitudes.

Under the sponsorship of the National Geographic Society, a second expedition to Fort Churchill, Manitoba, was therefore conducted during the summer of 1950. Two types of instruments, a burst-detecting ionization chamber and a quadruple coincidence counter train, were utilized to accomplish the aforementioned objectives.

## II. EXPERIMENTAL PROCEDURE

### A. Ionization Chamber Apparatus

A block diagram of the ionization chamber and associated circuitry is shown in Fig. 1. The instrument functions as follows: Voltage pulses produced in the ionization chamber (mainly by primary heavy nuclei and by nuclear disintegrations occurring in the chamber walls) are amplified by a linear pulse-amplifier and fed into a pulse-height discriminator. The latter permits the passage only of those pulses having amplitudes exceeding a predetermined size. Each discriminator output pulse triggers a keying univibrator, thereby causing the transmitter to emit a 75 megacycle C. W. signal for a period of 0.06 sec.

The telemetering system as well as the method for the determination of atmospheric pressure and temperature within the gondola during the balloon flights have already been described in detail elsewhere.[2]

The ionization chamber (Fig. 2) is composed essentially of an outer cylindrical pressure vessel, a concentric cylindrical cathode, and a central electron-collecting wire. The cathode, which operates at a potential of

* Assisted by the joint program of the ONR and AEC.
[1] M. A. Pomerantz, Phys. Rev. 77, 830 (1950).
[2] M. A. Pomerantz, Electronics 24, 88 (1951).

$-300$ v relative to the wire, is closed at the ends by copper guard disks having $\frac{1}{2}$-inch center holes to pass the collector wire. The collector connects directly to the first grid of the linear amplifier and is maintained at dc ground potential by means of a $10^8$-ohm grid-leak resistance. To eliminate the possibility of leakage from the high voltage cathode to the collector wire, the insulators supporting the wire are mounted on the grounded outer case.

In all measurements made to date, the chambers have been filled with 5 atmospheres of tank argon rated 99.9 percent pure. Before assembly, the internal parts are cleaned with an acid rinse, and immediately after the soldering operation, the chambers are evacuated for 24 hours while being maintained by an oven at a temperature of 125°C. The outgassing and filling procedures are accomplished on a special pressure-vacuum system, which permits both operations to be performed without the intervening admission of air into the chamber. A pressure gauge mounted permanently on each ion chamber permits the detection of leaks which might develop subsequent to sealing-off the unit.

For the purpose of calibration, each chamber contains a Po-$\alpha$ source plated onto an insulated silver electrode. The source protrudes slightly through a hole in the cathode and is "turned on or off" by connecting the probe to the cathode supply ($-300$ v) or to ground, respectively. In the "off" state, the $\alpha$-particle ionization electrons are collected on the grounded source probe and are thus not permitted to reach the central wire.

The Po-$\alpha$ pulses reach voltage saturation at a cathode potential of $-200$ v immediately after a chamber is filled. However, the saturation voltage drops to an equilibrium value some 50 volts lower in the course of a few days. This tendency, which is probably caused by the "getter" action of the clean copper walls, insures that the normal operating potential of $-300$ v is adequate for saturation even long after the chambers are filled. The calibration source is used only for setting the discriminator and checking the over-all stability of the instrument in preflight tests. During flight the source is turned off so as not to interfere with the detection of cosmic-ray bursts. In the case of every instrument which has been recovered immediately after landing, postflight checks have revealed no detectable change in calibration.

The linear amplifier comprises three stages of amplification with 0.015 percent inverse feedback and has an over-all gain of $5\times10^3$. This amount of feedback, although not large, is sufficient to reduce to 2 percent the change in amplifier gain resulting from battery voltage drops during the normal (five hour) flight duration. The interstage coupling components of the amplifier are chosen to give a rise time (5 $\mu$sec) comparable to the electron collection time of the ionization chamber, and a decay time (100 $\mu$sec) sufficiently small that the inductive effect of positive ion motion is not amplified. Through careful selection of vacuum tubes, the amplifier output noise level is approximately 0.2 v, which is 5 percent of the amplitude of the smallest pulses allowed past the discriminator in the measurements reported here.

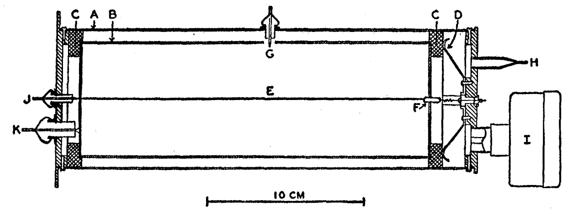


FIG. 2. Constructional details of ionization chamber. **A**, pressure vessel (0.032-in. Cu); **B**, cathode (0.032-in. Cu); **C**, cathode insulating rings (Mykroy); **D**, retaining spring; **E**, electron collector (0.010-in. Kovar); **F**, glass insulator; **G**, Po-$\alpha$ source electrode; **H**, pinch seal; **I**, 0–100 lb/in.[2] pressure gauge; **J**, connection to amplifier; **K**, $-300$ v cathode connection.

The discriminator stage is a triode biased beyond cut off by a variable potentiometer adjustment. The (positive) amplifier output pulses reach the discriminator plate circuit (and thence trigger the subsequent keying univibrator) only when their amplitudes exceed the difference between the negative bias potential and the triode cut off potential. For all of the flights reported in the present paper, the discriminator was adjusted so that only bursts $>1.0$ Po-$\alpha$ were relayed to the ground station.

### B. Quadrupole Coincidence Counter Train

The counter trains utilized in measurements of the intensity both in the vertical and horizontal directions were identical with those used in 1949[1] and previously.[3] The complete balloon-borne apparatus, as well as the ground receiving station, have also been described in detail.[2]

## III. RESULTS

### A. Search for Diurnal and Temporal Variations

The detection of a small diurnal variation had not been specifically attempted in 1949, although the data obtained in flights conducted at different times of the day revealed no indication of any marked differences which could be attributed to a diurnal effect. If the sun possesses a permanent dipole-moment of the magnitude which had previously been assumed, a diurnal variation of the intensity of the primary cosmic radiation must necessarily occur, for reasons which have already been discussed.[1] Observations conducted at a high northern latitude are optimum from the point of view of the magnitude of the change expected during the course of a day, since the variation is maximum at locations appreciably north of the previously-assumed knee of the latitude effect. Furthermore, the extreme change expected at high latitudes occurs during daylight hours,

[3] For details regarding geometry, see M. A. Pomerantz, Phys. Rev. 75, 1721 (1949).

TABLE I. Summary of balloon flights.

| Geomag. lat. | Flight date | Instrumental arrangement | Ceiling altitude, feet | Time of arrival at ceiling altitude, local solar time |
|---|---|---|---|---|
| 69°N | 8– 6–49 | Vertical counter train containing 7.5 cm of interposed Pb absorber. | 96,000 | 10:32 A.M. |
| | 8– 9–49 | | 85,500 | 8:40 A.M. |
| | 8–11–49 | | 74,000 | 4:24 P.M. |
| | 8–16–49 | | 81,000 | 10:17 A.M. |
| | 8–21–49 | | 73,500 | 10:13 A.M. |
| | 7–24–50 | | 67,000 | 8:31 A.M. |
| | 7–25–50 | | 100,500 | 9:07 A.M. |
| | 7–26–50 | | 76,000 | 10:18 A.M. |
| | 7–31–50 | | 74,800 | 9:04 A.M. |
| | 8– 5–50 | | 84,500 | 1:37 P.M. |
| | 8–12–50 | | 97,000 | 12:43 P.M. |
| 52°N | 7–26–47 | | 89,000 | 6:39 A.M. |
| | 7–20–49 | | 83,000 | 8:33 A.M. |
| | 9–27–49 | | 112,000 | 10:52 A.M. |
| | 5–25–50 | | 94,000 | 8:52 A.M. |
| 69°N | 8– 2–50 | Vertical counter train containing 4.0 cm of interposed Pb absorber. | 91,000 | 8:17 A.M. |
| | 8– 5–50 | | 81,800 | 8:15 A.M. |
| | 8–29–50 | | 74,500 | 4:16 P.M. |
| | 8–30–50 | | 100,000 | 9:44 A.M. |
| 52°N | 6–24–48 | | 95,000 | 8:24 A.M. |
| | 10– 6–49 | | 68,000 | 10:26 A.M. |
| | 10–14–49 | | 81,500 | 10:33 A.M. |
| 69°N | 8–18–50 | Horizontal counter train containing no interposed Pb absorber. | 80,000 | 6:14 P.M. |
| | 8–19–50 | | 97,000 | 2:28 P.M. |
| | 8–24–50 | | 83,000 | 10:00 A.M. |
| 52°N | 7– 7–50 | | 105,000 | 9:37 A.M. |
| | 10–17–50 | | 102,200 | 10:43 A.M. |
| | 10–27–50 | | 104,200 | 11:13 A.M. |
| | 11– 7–50 | | 108,000 | 3:22 P.M. |
| 52°N | 7– 9–48 | Horizontal counter train containing 1.0 cm of interposed Pb absorber. | 109,500 | 9:51 A.M. |
| | 10– 7–48 | | 109,000 | 11:18 A.M. |
| | 10–28–49 | | 117,500 | 11:02 A.M. |
| 69°N | 8– 9–50 | Horizontal counter train containing 7.5 cm of interposed Pb absorber. | 83,000 | 9:26 A.M. |
| | 8–16–50 | | 72,500 | 10:25 A.M. |
| | 8–18–50 | | 87,500 | 9:14 A.M. |
| | 8–29–50 | | 85,400 | 9:29 A.M. |
| 52°N | 7– 7–48 | | 104,000 | 8:24 A.M. |
| | 10–29–48 | | 102,000 | 11:03 A.M. |
| | 11–23–48 | | 115,000 | 10:59 A.M. |
| 69°N | 9– 2–50 | Ionization chamber biased to record events exceeding 1 Po-$\alpha$. | 78,500 | 6:01 P.M. |
| | 9– 3–50 | | 91,500 | 4:59 P.M. |
| | 9– 4–50 | | 110,500 | 10:46 A.M. |
| 52°N | 4–30–50 | | 83,000 | 9:50 A.M. |
| | 6– 2–50 | | 103,500 | 9:00 A.M. |
| | 6– 9–50 | | 94,000 | 8:25 A.M. |
| | 3– 7–51 | | 80,000 | 12:35 P.M. |

to which the present flights were necessarily confined owing to technical limitations imposed by the absence of heating by solar radiation at night. Finally, and most important of all, the intensity at the higher latitude should actually be lower than that at Swarthmore in the early morning, and equal in the late afternoon, according to Dwight's calculations.[4]

Therefore, the flights in 1950 were released over a wider range of times to broaden the scope of this important phase of the investigation. For reasons cited earlier,[1] measurements were obtained principally with counter trains containing 7.5 cm of interposed lead absorber. Table I contains a summary of the 1950 series at Fort Churchill, and as may be seen in Figs. 3 and 4, there is no detectable dependence of the results upon the time of day.

Furthermore, it is apparent in Fig. 3 that the present measurements have quantitatively confirmed the earlier data, thus indicating no observable difference in the conditions existing during the summers of 1949 and 1950. Finally, it is to be noted that, during the course of continuous observations extending over a period of more than a month, no changes sufficient to be detected by the instruments utilized in these investigations are manifested.

### B. Intensity *vs* Altitude Curve with 4 cm Pb

The nature of the dependence of the intensity upon altitude at 69°N in the case of particles capable of penetrating 4 cm of Pb is of particular interest. The fact that a definite maximum in the curve is observed at 52°N for 4 cm but not 6 cm provided a basis for the prediction that the maximum with 4 cm would disappear at the higher latitude. Low energy primaries, such as were presumably entering at Fort Churchill, were expected, through their progeny, to contribute appreciably to the intensity only near the top of the atmosphere.

This hypothesis is supported by the results plotted in Fig. 4. It is observed that, at Fort Churchill, the intensity of particles having a residual range of 4 cm of Pb is essentially constant throughout the upper seven percent of the atmosphere.

This latitude dependence of the critical thickness of interposed absorber for which the maximum in the intensity *vs* altitude curve disappears, arising from the change in the minimum allowed primary energy, would result in the appearance of a maximum at low latitudes even for thick absorbers. Thus, Rao *et al.*,[4a] at 3°N, have observed a distinct peak in the vertical intensity of cosmic radiation penetrating 10 cm of Pb, at a pressure of 90 mm of Hg. This is entirely in accord with expectations on the basis of the present considerations. Furthermore, as a consequence of this effect, the atmospheric pressure at which the maximum occurs for any particular amount of absorber would increase as the latitude is decreased.

### C. Intensity in the Horizontal Direction

Investigations[5–7] of the cosmic-ray intensity at various zenith angles have revealed an appreciable

[4] K. Dwight, Phys. Rev. 78, 40 (1950).

[4a] Rao, Balasubrahmanyam, Gokhale, and Pereira, Phys. Rev. **83**, 173 (1951).

[5] Swann, Locher, and Danforth, Natl. Geographic Soc. Contributed Tech. Papers, Stratosphere Series **2**, 13 (1936).

[6] M. A. Pomerantz, Phys. Rev. **75**, 1335 (1948).

[7] Winckler, Stroud, and Shanley, Phys. Rev. **76**, 1012 (1949).

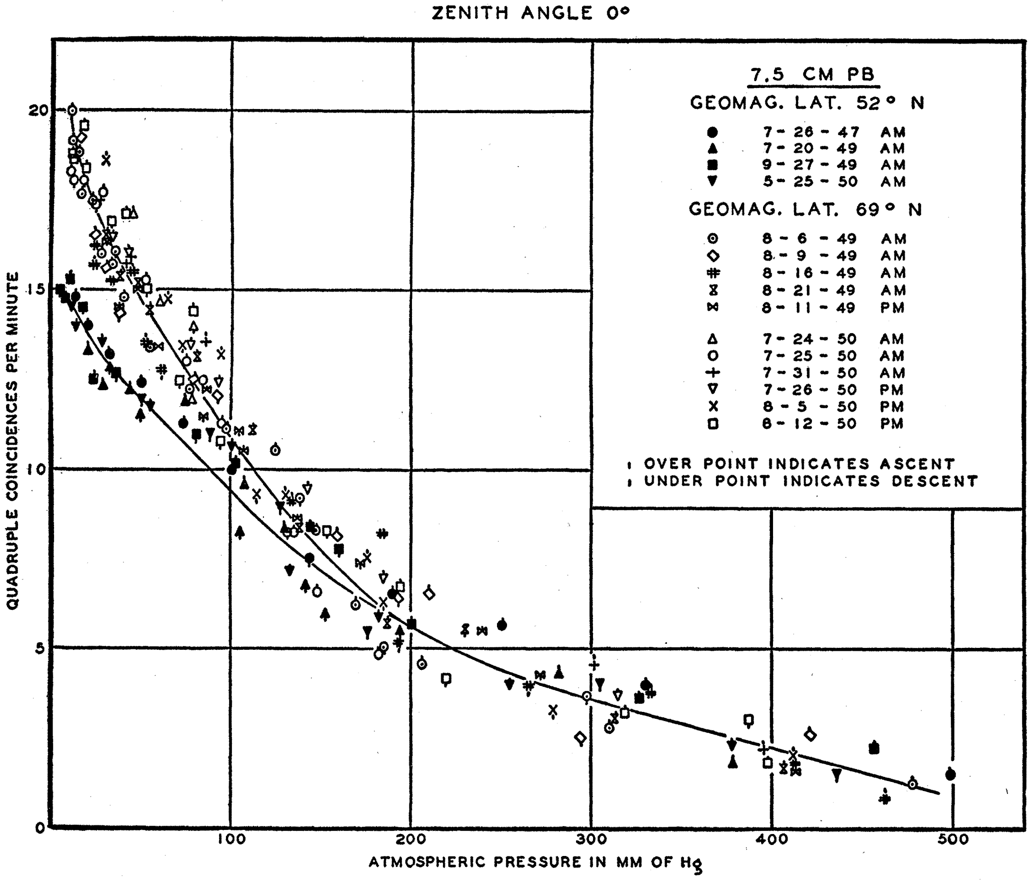


FIG. 3. Intensity *vs* altitude curves for cosmic rays arriving vertically, and penetrating 7.5 cm of Pb at $\lambda=52°$N (Swarthmore, Pennsylvania) and $\lambda=69°$N (Fort Churchill, Manitoba). Note the absence of detectable diurnal or temporal variations.

component at large angles. The observed horizontal intensity at very high altitudes appreciably exceeds that at the terminus of a corresponding effective atmospheric path in the vertical direction, and must consist predominantly of secondary particles emitted in acts in which the initial direction is not propagated. It was of interest to ascertain whether the new group of low energy primary particles entering at Fort Churchill would enhance the horizontal intensity at that station. Therefore, a direct comparison of the horizontal intensities at the two latitudes was conducted.

The measurements were obtained with the same counter trains used in the other phases of these experiments. When the instruments are oriented horizontally, the maximum aperture between the extreme ray and the horizontal plane is 4.5°. Telescopic observations of the swinging of the instruments during flight revealed that the maximum excursion was usually less than 2° from the vertical even during the more turbulent initial portions of the ascent.

In some of the flights, a 7.5 cm Pb absorber was interposed in the counter train. In others, no absorber was present other than the counter walls. In this case all particles capable of penetrating 4.4 g/cm$^2$ were detected. This corresponds to a minimum energy for mesons of approximately 20 Mev.

A detailed statistical analysis of flights under the latter condition is summarized in Table II. These

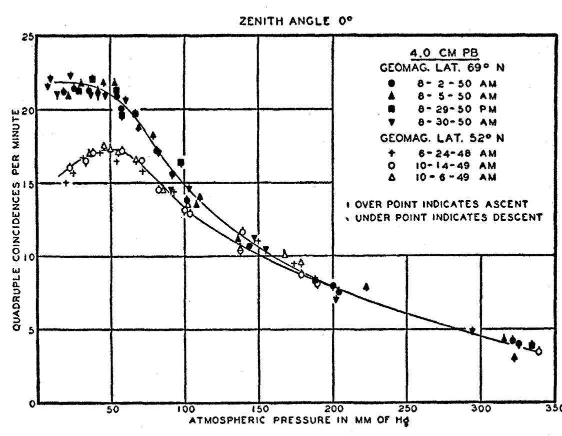


FIG. 4. Intensity *vs* altitude curves, obtained with concidence-counter trains containing 4 cm of Pb, for cosmic rays arriving vertically at $\lambda=52°$N and $\lambda=69°$N. The maximum disappears at the more northern station.

TABLE II. Summary of data obtained with horizontal quadruple-coincidence counter trains containing no interposed Pb absorber. Within the statistical uncertainties, no dependence upon latitude between 52°N and 69°N is indicated.

| Geomag. lat. | Flight date | Average counting rates, counts per minute, in indicated pressure interval | | | |
|---|---|---|---|---|---|
| | | 54–33 mm of Hg | 33–21 mm of Hg | 21–13 mm of Hg | 13–8 mm of Hg |
| 69°N | 8–18–50 | 19.3±0.8 | 25.4±1.1 | | |
| 69°N | 8–19–50 | 18.1±1.0 | 25.0±1.0 | 31.0±0.9 | 33.3±1.1 |
| 69°N | 8–24–50 | 17.9±0.9 | 28.1±1.1 | | |
| 69°N | Average | 18.5±0.5 | 26.3±0.6 | 31.0±0.9 | 33.3±1.1 |
| 52°N | 7– 7–50 | 17.7±1.1 | 25.8±1.1 | 29.5±1.0 | |
| 52°N | 10–17–50 | 17.2±0.9 | 27.1±1.9 | 28.8±1.1 | |
| 52°N | 10–27–50 | 18.0±0.8 | 23.1±1.2 | 29.7±1.2 | 32.1±1.0 |
| 52°N | 11– 7–50 | 18.1±0.9 | 29.0±2.1 | 33.6±1.2 | 34.5±1.1 |
| 52°N | Average | 17.8±0.5 | 25.7±0.7 | 30.9±0.6 | 32.5±0.6 |

experiments have indicated, as may be seen also in Fig. 5, that, unlike the situation in the vertical direction, even at the highest altitudes attained the horizontal intensity is not dependent upon latitude north of 52°.

Data obtained at 52°N with 1.0 cm of absorber are also included in Fig. 5 because these constitute a self-consistent set of measurements, with good resolution in zenith, of the intensity and the rate of absorption of the horizontal component of the cosmic radiation.

### D. Ionization Chamber Bursts

The data obtained in four ionization chamber flights at Swarthmore, Pennsylvania (52°N geomagnetic latitude) and in three flights at Fort Churchill (69°N geomagnetic latitude) are plotted in Fig. 6. Statistical errors (not shown in the figure) are approximately ±10 percent for points near the top of the atmosphere and ±20 percent for the lower points. A statistical analysis of the data from the seven separate flights at the two locations (Table III) shows that all individual flights agree within statistical expectation. Similarly, the combined average counting rates of the Fort Churchill flights agree with the combined average rates obtained at Swarthmore. Within the statistical uncertainties indicated in Table III the burst rates at the two locations are the same at all altitudes.

## IV. DISCUSSIONS

### A. Horizontal Intensity

The maximum residual range in air of the new particles which enter the top of the atmosphere at 69°N is approximately 150 g/cm$^2$. This is indicated by the fact that, as is shown in Figs. 3 and 4, no observable difference in the intensity at the two locations arises until the atmospheric pressure is somewhat less than 120 mm of Hg.

The ratio of the minimum amount of matter which a particle would have traversed through the spherical atmosphere before entering the geometrical arrangement utilized in these experiments in the horizontal direction to that in the vertical is 12. Thus, on the basis of mass-absorption alone, it is evident that none of the particles in this new group, which must have energies below 1.6 Bev, could be expected to penetrate to a horizontal detecting device of the present dimensions at an altitude lower than that corresponding to a maximum pressure of $120/12=10$ mm of Hg. In view of the fact that the particles observed at the greatest depths in the vertical direction may be mesons rather than primary nucleons, the effects of decay would make the situation even more drastic.

The particles which constitute the horizontal intensity are principally secondaries produced at wide angles from the forward direction by primaries moving essentially downward through the atmosphere. This is immediately evident from the comparison of the counting rates recorded at high altitudes in the horizontal direction with those predicted on the basis of measurements obtained with an identical instrument oriented vertically. The expected counting rate $I_H(p_0)$ of a horizontal train at pressure $p_0$ can be computed on the basis of the assumption that the contribution at angle $\zeta$ is $I_\zeta(p_0)=I_0(p_0f_\zeta)$, where $f_\zeta$ would be sec$\zeta$ for a flat atmosphere of infinite extent. $I_0(p_0f_\zeta)$ is obtained from the corresponding vertical intensity *vs* altitude

TABLE III. Summary of data obtained with ionization chambers biased to record pulse of height exceeding 1 Po-$\alpha$. Within the statistical uncertainties, no dependence upon latitude between 52°N and 69°N is indicated.

| Geomag. lat. | Flight date | Average counting rates, counts per minute, in indicated pressure interval | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 200–87 mm of Hg | 87–54 mm of Hg | 54–33 mm of Hg | 33–21 mm of Hg | 21–13 mm of Hg | 13–8 mm of Hg | 8–5 mm of Hg |
| 69°N | 9– 2–50 | 4.9±0.5 | 6.5±0.5 | 10.0±0.7 | 12.8±0.5 | | | |
| 69°N | 9– 3–50 | 4.0±0.7 | 7.3±0.9 | 8.1±0.8 | 12.6±0.8 | 17.1±0.8 | | |
| 69°N | 9– 4–50 | 3.5±0.4 | 7.3±0.5 | 11.2±0.6 | | 15.6±0.6 | 19.1±0.6 | 21.2±0.8 |
| 69°N | Average | 4.1±0.3 | 7.0±0.3 | 10.2±0.4 | 12.7±0.4 | 16.3±0.5 | 19.1±0.6 | 21.2±0.8 |
| 52°N | 4–30–50 | 5.0±0.3 | 6.8±0.6 | 10.0±0.6 | | 17.0±1.0 | | |
| 52°N | 6– 2–50 | 4.5±0.3 | 8.5±0.7 | 10.4±0.7 | 13.1±1.0 | 15.6±0.8 | 19.0±0.8 | 20.8±1.4 |
| 52°N | 6– 9–50 | 5.2±0.3 | 7.2±0.5 | 10.7±0.7 | 13.8±0.9 | 15.8±0.8 | 19.5±1.3 | |
| 52°N | 3– 7–51 | 5.6±0.4 | 9.1±0.6 | 12.4±0.8 | 13.2±1.2 | | | |
| 52°N | Average | 5.0±0.2 | 8.0±0.3 | 10.8±0.4 | 13.4±0.6 | 16.0±0.5 | 19.2±0.7 | 20.8±1.4 |

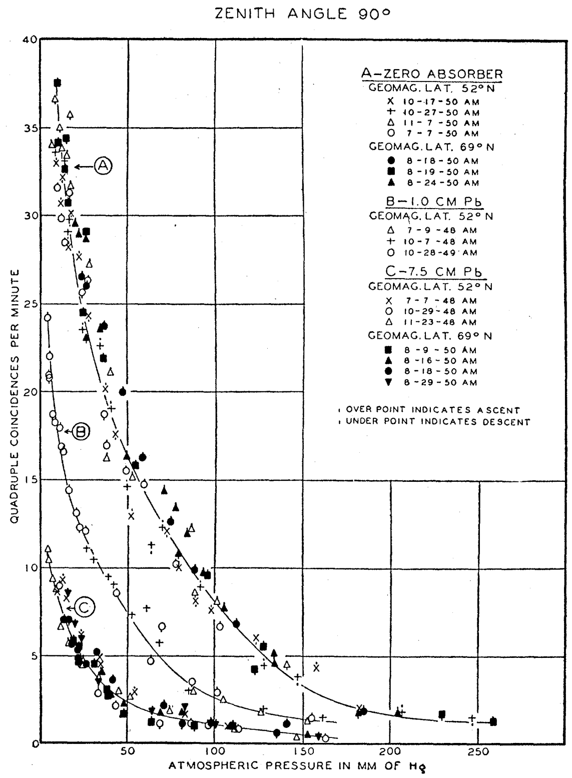


FIG. 5. Data obtained with counter trains oriented horizontally. No dependence upon latitude north of $\lambda = 52°$ is indicated.

curve. In the case of a spherical atmosphere, although $f_\xi$ remains finite at 90°, the calculated counting rates are far less than the observed even if the attenuation introduced by meson decay is not taken into consideration. For example, at $p_0 = 30$ mm of Hg, the maximum expected counting rate with the geometry utilized in these experiments is 2 counts per minute as compared with 24 counts per minute observed with no interposed absorber. Meson decay should reduce this expected rate by a factor of at least 1000, depending upon the assumptions made regarding the production of mesons. This general situation (becoming even more drastic at lower altitudes), prevails for all thicknesses of absorber for which data are available up to the highest altitudes attained, although the disparity between the expected and observed intensities with 7.5 cm of Pb is considerably reduced at 5 mm of Hg. Thus, the horizontal intensity is far in excess of that expected for rectilinear propagation of an isotropic primary beam incident at the top of the atmosphere.

It might have been expected that low energy primaries would be most productive of wide-angle events, principally through the formation of low energy mesons. Furthermore, the spectrum is richest at the low end, and intensity considerations seemed to favor the primaries having energies near the geomagnetic cutoff at 52°N as the source of the horizontal component.

The absence of an increase in the horizontal intensity

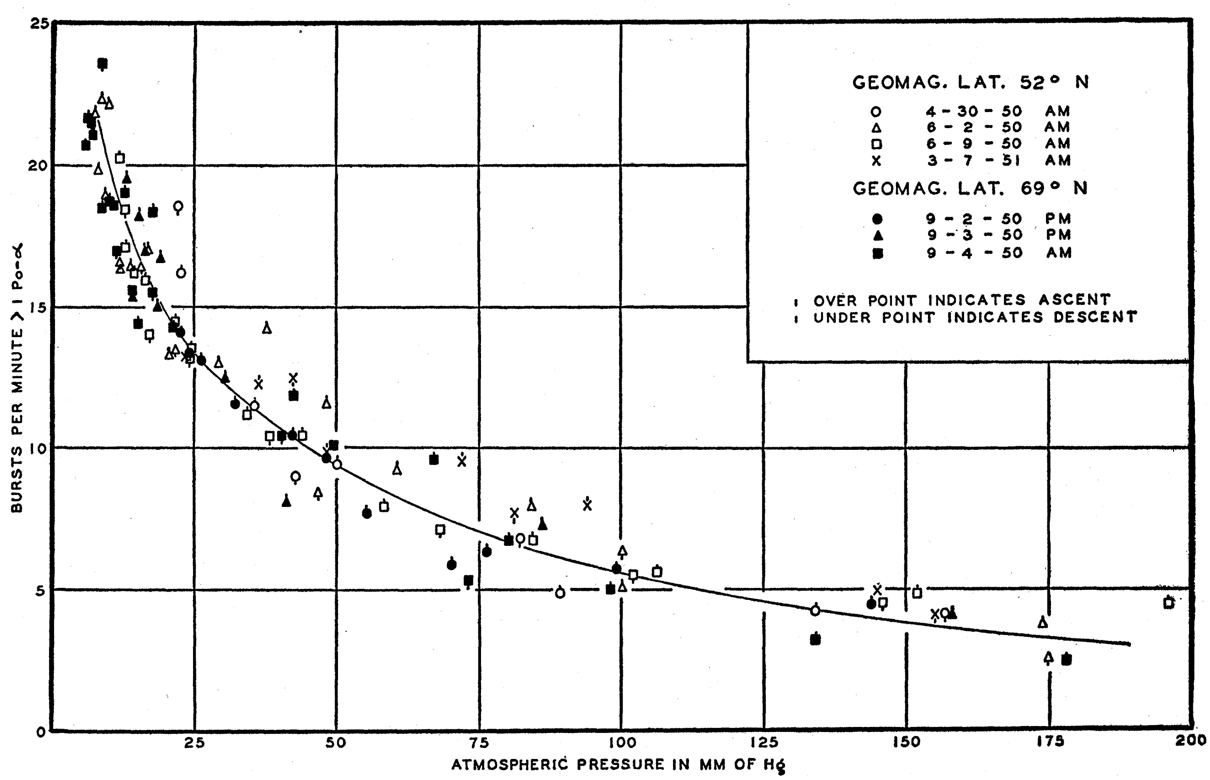


FIG. 6. Dependence of burst-rate upon altitude, as measured by ionization chambers biased to record events >1.0 Po-$\alpha$. No variation with latitude north of $\lambda = 52°$ is revealed.

at the highest altitude attained, corresponding to about 9 mm of Hg, is not consistent with this hypothesis. On the contrary, the results indicate that the secondary particles which constitute the horizontal component do not arise from primaries having energies near the minimum permitted at 52°N. Hence, they must be the progeny of the less numerous high energy primaries. The latter are particularly effective in contributing to the counting rate of a counter train inclined at a zenith angle of 90° because the total flux of vertically-directed particles which can produce wide-angle secondaries capable of actuating the horizontal instrument is, of course, much larger than the total flux through the same counter train oriented vertically.

### B. Solar Dipole-Moment

The original conclusion[8] that the maximum value of the solar dipole-moment does not exceed $6\times 10^{32}$ gauss-cm$^3$ remains unchanged. It must be emphasized that this deduction from the present experimental results presupposes an infinitely distant source for most of the cosmic radiation reaching the earth. The concept of a solar allowed-cone created at the earth by a permanent magnetic field of the sun certainly does not apply to particles produced at that body and proceeding more or less directly to the earth. Hence, if it had been independently demonstrated that the sun did possess a dipole-moment of the previously assigned magnitude during the period when these experiments were performed, the present results would have constituted direct evidence for a solar origin of a large fraction of the primary intensity. However, the most recent astrophysical determinations of the solar field by Thiessen[9] and von Klüber[10] using vastly improved methods have yielded values no higher than 1–2 gauss.

The observed isotropy of the high energy nonfield-sensitive radiation ($>10^{13}$ ev) reveals that the entire galaxy must be the source of such particles, as has been demonstrated by Cocconi.[11] On the other hand, the low energy portion of the spectrum ($<10^{10}$ ev) must have a local origin in order to avoid the necessity of traversing an excessive mass of matter, as a consequence of the action of the galactic magnetic field, during the journey through the galaxy to this planet. The isotropy of the total incoming radiation, as revealed by measurements of the zenith[6] and azimuthal distributions[7] at high altitudes as well as by the absence of a detectable diurnal variation as reported herewith, indicates that the particles of solar origin do not in general proceed directly from the sun to the earth Hence, after they are emitted from the sun, the particles must subsequently follow complicated trajectories as a consequence of which the intensity ultimately becomes isotropic. Thus, the primaries reaching the earth appear to arrive from a distant (virtual) source uniformly distributed about the earth.

This is evidently accomplished by interactions with magnetic fields within the solar system. The particles which are observed to come more or less directly from the sun,[12] in contrast with the isotropically-distributed radiation, can be consequently accounted for only by a tunneling through the trapping field resulting from a sort of degaussing effect produced by transient local magnetic fields, such as was first proposed by Forbush, Gill, and Vallarta.[13]

### C. Low Energy Spectrum

General considerations relating to the determination of the nature of the primary spectral distribution from the present results were discussed in reference 1. The exact value of $\gamma$ in a differential energy distribution law of the form $i(E)dE=kE^{-\gamma}dE$ cannot be deduced in the usual manner from the geomagnetic cut-off energies and the observed ratio of the intensities at the two latitudes in this case. At high latitudes, atmospheric absorption rather than the terrestrial magnetic field determines the minimum energy which a primary particle must possess in order to reach the detecting apparatus. This lower limit $\epsilon_n(t, \lambda)$, required by a primary particle (or its progeny) to penetrate the thickness $t$ of atmosphere above the detecting apparatus plus the counter walls, cannot be assigned a precise value.

Winckler, *et al.*,[14] have determined from measurements at low latitudes that the value of $\gamma$ is 1.9 for primary protons having energies between 4 and 14 Bev. If the power law with the same exponent still prevailed at latitudes north of 52°, the observed ratio of intensities $I_{69°}/I_{52°}=1.46$ would correspond to an absorption cut-off energy $\epsilon_n(t, 69°)$ of 1.1 Bev for primary protons at 69°N.

The maximum depth of penetration of particles having energies just below the geomagnetic cutoff at 52°N ($\approx 1.6$ Bev) is approximately 150 g/cm$^2$ of air (see Sec. IVA). Previous absorption measurements[15] have also revealed that 1.6-Bev particles are first absorbed[16] by something like the same amount of lead. Furthermore, from the location of the sea-level knee of the latitude effect, it is known that approximately 3 Bev are required for penetration of 1000 g/cm$^2$ of air. Although the effective range is falling off faster than directly proportional to the energy, it is inconceivable that primaries having an energy of 1.1 Bev would have a range $t\leq 20$ g/cm$^2$. In any event, after the particle

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[9] G. Thiessen (private communication).
[10] H. von Klüber, Proc. Roy. Ast. Soc. **111**, 8 (1951).
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[13] Forbush, Gill, and Vallarta, Revs. Modern Phys. **21**, 44 (1949).
[14] Winckler, Stix, Dwight, and Sabin, Phys. Rev. **79**, 656 (1950).
[15] M. A. Pomerantz, Phys. Rev. **83**, 459 (1951).
[16] Absorption is defined here as the reduction below unity of the probability that each primary, or at least one of its progeny created in the lead, always has sufficient residual range and is propagated in the proper direction to actuate the coincidence train.

has been slowed down to a velocity such that nuclear interactions are relatively improbable and ionization becomes the predominant mode of energy degradation, the residual range appreciably exceeds this amount. For example, the experimentally observed range of 340-Mev protons is 70 g/cm$^2$ in carbon.[17]

It is, therefore, necessary to conclude that the power-law spectrum observed for the primaries of higher energies does not apply at the low end. In fact, the differential spectrum may exhibit a maximum even south of 52°, followed by a rapid decrease toward the low energies which are permitted north of this latitude. This would not be inconsistent with either Winckler's results[14] or with those of Van Allen and Singer.[18]

A spectrum of this shape, poor in the low energy portion, would be expected if the regions where cosmic rays are being produced on the sun were distributed statistically uniformly over the surface. The low energy particles could, in general, move off toward infinity only near the poles, owing to the presence of the one gauss field, and the contribution from the polar regions would be a small part of the total. On the other hand, high energy particles, if indeed any are produced, would not be subject to trapping fields and could move off to infinity. The observed spectrum would, therefore, result from a combination of effects involving both the production and acceleration processes and the solar geomagnetic effects.

### D. Nuclear Disintegrations and Primary Heavy Nuclei

When biased as in the present experiments, the ionization chamber instrument responds to: (1) relativistic heavy nuclei of atomic number $Z>8$; (2) single slow protons and $\alpha$-particles; (3) nuclear disintegrations produced in the walls by fast protons and neutrons; (4) air showers in which at least 60 electrons traverse the chamber.

Of the above-listed events, air showers probably contribute the least to the observed counting rates. Chambers similar to those used in the present investigation have been operated in twofold coincidence as detectors of dense showers at mountain altitudes.[19] The results indicate that only a few percent of the bursts at these heights are produced by electron showers. Furthermore, the measurements of Kraybill and Ovrebo[20] show an altitude increase in the frequency of showers which is considerably less rapid than the observed altitude increase in the rate of ion chamber bursts.

In photographic emulsions exposed at atmospheric depths of 10 and 16 g/cm$^2$ at $\lambda=55°$, Bradt and Peters[21] have measured the collision mean free paths of heavy nuclei as a function of atomic number $Z$, and have calculated that the primary intensity of nuclei of $Z\geq 6$ is $1.4\times 10^{-3}$/cm$^2$/sec/sterad. The computation takes into account the absorption by nuclear collisions, but neglects a small fraction of the primary flux which is stopped as a consequence of ionization loss before reaching the depth at which the plates were exposed. On the basis of the above primary intensity value, and the $Z$-spectrum obtained by the same authors, the ionization chamber used in the present experiments should record 30 heavy nucleus counts per minute at the top of the atmosphere. In arriving at this result, isotropic incidence was assumed, and full account was taken of the rather complicated geometry of the chamber.

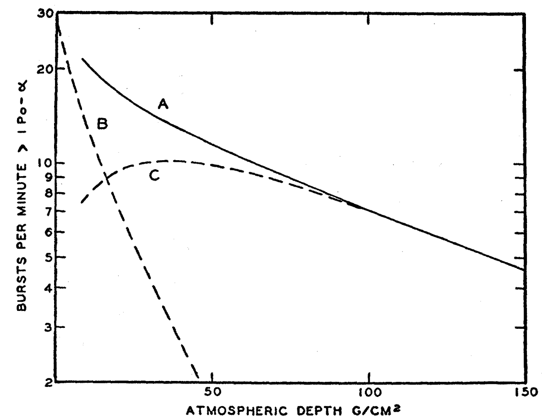


FIG. 7. Resolution of observed burst-rate, $A$, into the contributions by heavy primaries, $B$, and nuclear disintegrations, $C$.

If the emulsion observations[21] of the spectrum and the collision mean free paths of heavy nuclei are combined with a computation of the sensitivity of the ion chamber as a function of $Z$, the average collision mean free path in air for nuclei recorded by the chamber can be estimated as 30 g/cm$^2$. On the basis of this value for the absorption mean free path of the heavy primaries, and on the assumption of isotropic incidence above the atmosphere, the approximate heavy nucleus counting rate *vs* atmospheric depth curve labeled $B$ in Fig. 7 is deduced. Inasmuch as the same absorption mean free paths used by Bradt and Peters in calculating the primary flux from observations at about 15 g/cm$^2$ were used in obtaining curve $B$, the counting rate given by the latter at 15 g/cm$^2$ is probably quite accurate. At atmospheric depths exceeding 15 g/cm$^2$ the computed curve may be somewhat high because of the neglect of ionization loss. However, this effect is partially compensated by the assumption of an absorption mean free path equal to the collision mean free path, although actually some of the heavy nuclei are not completely broken up into fragments too small to be counted by the ionization chamber in their first collision.

Curve $C$ in Fig. 7 represents the difference between

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[18] J. A. Van Allen and S. F. Singer, Phys. Rev. **78**, 818 (1950).
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[20] H. L. Kraybill and P. J. Ovrebo, Phys. Rev. **72**, 351 (1947).
[21] H. L. Bradt and B. Peters, Phys. Rev. **77**, 54 (1949).

the calculated heavy nucleus counting rate and the experimental curve $A$. Within the uncertainties in the heavy nucleus rates, curve $C$ represents the variation with altitude of the total flux of protons, neutrons, and other particles capable of producing nuclear disintegrations in the chamber walls.

The maximum in curve $C$ at a depth of 35 g/cm$^2$ is indicative of the cascade multiplication of the nucleonic component and agrees in position with the maximum obtained by Whyte[22] in the analysis of Coor's[23] burst data for $\lambda=52°$. Photographic emulsion studies of the development of the nucleonic cascade as manifested in the rate of star production *vs* atmospheric depth seem to conflict with one another regarding the existence of a maximum in the flux of star-producing particles. Freier *et al.*[24] report evidence of strong maxima below 45 g/cm$^2$ in the production rates of stars of all sizes up to and including those with more than 10 prongs. On the other hand, Lord[25] finds that the frequencies of stars of all sizes from 3 to more than 16 prongs decrease monotonically at atmospheric depths greater than 15 g/cm$^2$. The present results are qualitatively in accord with the former, whereas there appears to be a definite inconsistency with the latter which is not as yet understood.

The absorption mean free path of the burst-producing radiation as determined by the best exponential representation of the counting rate *vs* altitude curve between 60 and 200 mm of Hg is $L=165$ g/cm$^2$. This is in reasonable agreement with the value $L=160$ g/cm$^2$ derived from Coor's ionization chamber data in the same altitude range. In a similar manner, the star production *vs* altitude curves of Lord between 60 and 200 mm of Hg yield absorption mean free paths $L=165$, 120 and 110 g/cm$^2$ for the radiations producing stars with 3, 4, 5 prongs, 6, 7, 8, 9 prongs and more than 9 prongs, respectively. It seems reasonable to expect that the $L$ value obtained from the ionization chamber results should lie somewhere within the above limits. However an exact comparison between ion chamber and emulsion data is precluded by inadequate knowledge of (1) the relative cross sections in Cu and emulsion for the production of stars of given size and (2) the burst-producing efficiency of stars as a function of size for the particular ion chamber geometry involved.

According to the emulsion work of Camerini, *et al.*[26] the integral cross section for production by neutrons and protons of stars with more than 2 prongs closely approximates the geometrical nuclear cross section. Assuming this to hold for primary cosmic rays incident upon copper, and using the value 0.17 particle/cm$^2$/sec/sterad as the primary intensity[3] at $\lambda=52°$, we find that stars with more than 2 prongs should occur in the ion chamber walls at the rate of 240 per minute at the top of the atmosphere. Comparison of this rate with any reasonable extrapolation of curve $C$, Fig. 7, to zero g/cm$^2$ shows that at most 3 percent of the stars produced in the wall by primaries give rise to bursts $>1.0$ Po-$\alpha$. Some knowledge of the extent to which this surprisingly small efficiency can be attributed to the absorption of low energy star fragments before their entry into the gas could be obtained by employing chambers with various wall thicknesses in future flights.

According to the curves $B$ and $C$ in Fig. 7, the heavy nuclei and nuclear disintegrations contribute 13 counts per minute and 8 counts per minute, respectively, at a depth of 10 g/cm$^2$ at geomagnetic latitude 52°N. The latitude effect between 52°N and 69°N at 10 g/cm$^2$ is $0\pm5$ percent. Considering the extreme case of a possible 5 percent increase (1.0 std. dev.) assignable solely to heavy nuclei, the increase in the latter at 10 g/cm$^2$ would be 8 percent. On the other hand, if the heavy nucleus flux were assumed to be unchanged, the corresponding increase in the nuclear disintegration rate would be 13 percent.

Extrapolation of the curves of Figs. 3 and 4 to the top of the atmosphere yields a lower limit of 45 percent for the increase in the vertical primary intensity between $\lambda=52°$ and $\lambda=69°$. Comparison of this result with the aforementioned $0\pm13$ percent latitude effect shows that primaries of energy below the geomagnetic cutoff at $\lambda=52°$ yield at a depth of 10 g/cm$^2$ less than one-third as many nuclear bursts per primary particle as the primaries entering at $\lambda=52°$.

It should be noted that the nuclear disintegration latitude effect deduced from the present measurements at 10 g/cm$^2$ does not necessarily apply at higher altitudes, for a considerable portion of the nuclear bursts at 10 g/cm$^2$ is produced by secondaries. (Note the shape of curve $C$, Fig. 7.) In addition, the primaries undergo some energy loss by ionization and nuclear collisions in the residual atmosphere. The magnitudes of these effects are undoubtedly quite different for the primary protons of energy $E>1.6$ Bev entering at $\lambda=52°$ and for those of energy $E<1.6$ Bev which comprise the additional proton intensity at $\lambda=69°$.

If the multiplicity of secondary nucleon production increases with the energy of the primary, and the probability of burst production in the chamber wall increases with the energy of the incident particles, a latitude effect should become apparent above 10 g/cm$^2$. In this case the low energy primaries at $\lambda=69°$ as they exist above the atmosphere could have a considerably higher burst-producing efficiency relative to the primaries at $\lambda=52°$ than the data at 10 g/cm$^2$ indicate.

It is not possible to deduce from the present measurements any quantitative information regarding the low energy portion of the heavy primary spectrum because a substantial fraction of the particles of atomic number $Z>8$ in the band of energies admitted between $\lambda=52°$

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[23] T. Coor, Phys. Rev. **82**, 478 (1951).
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[25] J. J. Lord, Phys. Rev. **81**, 901 (1951).
[26] Camerini, Fowler, Lock, and Muirhead, Phil. Mag. **41**, 413 (1950).

and $\lambda = 69°$ (where the vertical cut-off energies are 0.57 Bev per nucleon and 0.025 Bev per nucleon, respectively) are absorbed as a result of energy loss by ionization in the 10 g/cm² residual atmosphere above the apparatus.

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# The Emission of $L$ X-Rays of Lead in $Po^{210}$ Decay*

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By use of a proportional counter x-ray spectrometer, it is established that $Po^{210}$ sources emit characteristic $L$ photons of Pb, in yield $2.93\times10^{-4}$($\pm$15 percent) per alpha-particle. The excitation of these photons is ascribed to the ejection of $L$ electrons from the electronic cortege of the nucleus in the act of alpha-decay, in a manner treated by Migdal's theory. The probability of $L$ electron ejection is about $8.8\times10^{-4}$ per alpha-particle, as computed from the observed photon yield and Kinsey's fluorescence yields. The theory in its present state accounts for only 13 percent of the photons observed.

## I. INTRODUCTION

THE emission of low energy photons of low intensity from $Po^{210}$ sources was observed and studied experimentally by Curie and Joliot[1] and has been noticed by others.[2,3] Curie and Joliot detected the photons by means of an ionization chamber connected to an electroscope, and identified photon energies by absorption coefficients. They found, within the limitations of this technique, that the photon energies were those expected for the $L$ and $M$ x-radiations of Po. Further, they thought that the intensities of the radiations increased with the thickness of the $Po^{210}$ source (they used sources of roughly constant area and of strengths up to about 50 mC), and hence, were inclined to believe that the radiations were Po x-rays excited by alpha-particle bombardment of the undecayed Po atoms in the source.

We study these radiations by means of a proportional counter x-ray spectrometer, and establish that the $L$ x-rays, at least, are the characteristic $L$ radiations of Pb. We ascribe their production to the ejection of $L$ electrons from the electronic cortege of the nucleus in the act of alpha-decay, a process which has been the subject of a theoretical study by Migdal.[4]

## II. THE APPARATUS

The proportional counter x-ray spectrometer is an improved version of the one which has been described elsewhere.[5] The counter tube is a cylinder of brass, or brass with an inner cylindrical liner of aluminum (to eliminate fluorescence radiations from the brass wall), about four inches in diameter and twelve inches long, with an axial center-wire of stainless steel 0.004 inch in diameter. The window is a hole, one inch in diameter, drilled through a flat surface built up at the center of the cylindrical counter wall, and covered with a beryllium disk 0.005 inch thick. The counter gas is a 9:1 mixture of noble gas (A or Kr) and methane or ethane, at a total pressure of one atmosphere. With the argon-methane filling, pulses of convenient height are obtained with the center wire at about +2600 volts. The counter wall is grounded.

The stability requirements on the high voltage supply are quite stringent; if one demands that the pulse height be stable to better than 0.5 percent during the course of a run, the high voltage supply must be stable to

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