Gugelot for preparation of a C^{11} sample. Kind interest in these experiments by Drs. J. A. Wheeler, M. G. White, and M. ten Bosch is gratefully acknowledged. The loan of Navy project equipment (Contract N6ori-105, Task Order I) and of equipment by Drs. R. Sherr and H. W. Fulbright is also appreciated. The author is further indebted to Mr. T. A. King for a sample of anthracene and to Dr. H. Poss for study of this specimen. Thanks are due the Office of Naval Research, the University of Rochester, and conference members, for the exchange of ideas at the recent Rochester conference on high speed counters. Finally, the author wishes to thank the Brookhaven National Laboratory for an opportunity to continue part of this work on counters.

PHYSICAL REVIEW VOLUME 75, NUMBER 5 MARCH 1, 1949

Further Experiments on Cosmic-Ray Bursts*

H. S. Bridge and B. Rossi
Physics Department and Laboratory for Nuclear Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts

(Received November 29, 1948)

The paper describes further results obtained by the observation of coincidences between pulses of a Geiger-Mueller counter tray and of an ionization chamber. The experiments were carried out partly aboard a B-29 aircraft and partly on the top of Mt. Evans in Colorado. The main purpose of the experiments at Mt. Evans was an investigation of the "transition curve" in lead. The experimental data are consistent with the assumption that the coincident bursts observed with a lead shield between the Geiger-Mueller tubes and the ionization chamber are mainly produced by cascade showers initiated by electrons and photons either incident upon the lead from the atmosphere or produced in the lead by nuclear interactions. The experiments aboard the B-29 furnish information on the variation with altitude of the radiation responsible for the nuclear interactions.

I. INTRODUCTION

EXPERIMENTS made by means of a tray of Geiger-Mueller counters and an ionization chamber, arranged one above the other and separated by several inches of lead, revealed the existence of time coincident pulses, whose rate of occurrence increases rapidly with altitude.[1] This phenomenon was interpreted by postulating the existence of ionizing particles different from electrons or ordinary mesons, which are much more abundant at high altitude than at sea level and are capable of producing secondary electrons or photons of high energy after traversing moderate thicknesses of lead. The electrons or photons undergo cascade multiplication in the lead, and the resulting showers are responsible for the ionization bursts in the chamber.

In order to test this interpretation, an experiment was carried out[2] in which part of the solid lead absorber between the Geiger-Mueller tray and the ionization chamber was replaced with a cloud chamber containing a number of lead plates; the expansion was triggered by the coincident pulses of the Geiger-Mueller tray and the ionization chamber. The cloud-chamber pictures thus obtained showed that shower production by penetrating particles was indeed responsible for a large fraction of the coincidences. Furthermore, they showed that the showers usually contained electrons as well as penetrating or heavily ionizing particles. This was taken as evidence that the showers originated in nuclear, rather than in electromagnetic, interactions. The

* The work described in this paper was assisted by the joint program of the Office of Naval Research and the Atomic Energy Commission. The B-29 aircraft was provided by the U. S. Air Forces. The facilities for the work at Mt. Evans were supplied by the Inter-University High Altitude Laboratory.

[1] H. Bridge, B. Rossi, and R. W. Williams, Phys. Rev. **72**, 257 (1947).

[2] H. S. Bridge, W. E. Hazen, and B. Rossi, Phys. Rev. **73**, 179 (1948); H. S. Bridge and W. E. Hazen, Phys. Rev. **74**, 579 (1948).

same experiments indicated, however, that air showers were probably responsible for part of the coincidences between the Geiger-Mueller counters and the ionization chamber. Also, the possibility was not ruled out that some of the coincidences might be caused by nuclear interactions resulting in the production of heavily ionizing particles, rather than in the production of electron showers.

This paper describes some further results on burst production under lead which were obtained by observation of coincidences between pulses of ionization chambers and of Geiger-Mueller counters. The chambers and the associated circuits used in this experiment were described in a recent paper by Bridge, Hazen, Rossi, and Williams,[3] to which the reader is referred for technical details. Measurements were made partly on the ground (Mt. Evans, Colorado, altitude 14,300 feet; Lexington, Massachusetts, altitude 255 feet) and partly aboard a B-29 aircraft flying at altitudes of 20,000, 25,000, and 30,000 feet.

II. EXPERIMENTS ABOARD THE B-29

1. The Experimental Arrangement

The arrangement used in the experiments aboard the B-29 is shown schematically in Fig. 1. The ionization chamber (I) had a diameter of 7.5 cm and an effective length of 52 cm. It was filled with pure argon at 7.3-atmospheres of pressure (at 25°C) and contained a polonium source of α-particles placed near the inner surface of the cylindrical wall. The pulses produced by the polonium α-particles, whose maximum size we denote by P_α, served as a standard for the measurement of the ionization bursts observed in the chamber. A pulse of size P_α corresponded to the amount of ionization produced by the passage through the chamber of 53 electrons of 10 Mev traveling perpendicularly to the chamber axis.[4]

Each of the Geiger-Mueller counters in trays A and B had a diameter of 2.5 cm and an effective length of 51 cm. The total effective area of tray C was 320 cm² in some of the experiments and 465 cm² in the others. The total effective area of tray D was 465 cm².

The lead block between tray A and the ionization chamber was 15 cm thick, 15 cm wide, and 60 cm long. The lead covering tray D was 10 cm thick.

An electronic circuit recorded events in which a pulse of the ionization chamber greater than 0.6 P_α was accompanied by one or more pulses in tray A and by two or more pulses in tray B (coincidences AIB_2). The output pulse of the electronic circuit operated a message register and, in addition, triggered a circuit which provided an intensifier pulse and a fast linear sweep for a cathode-ray oscilloscope. The pulses of the

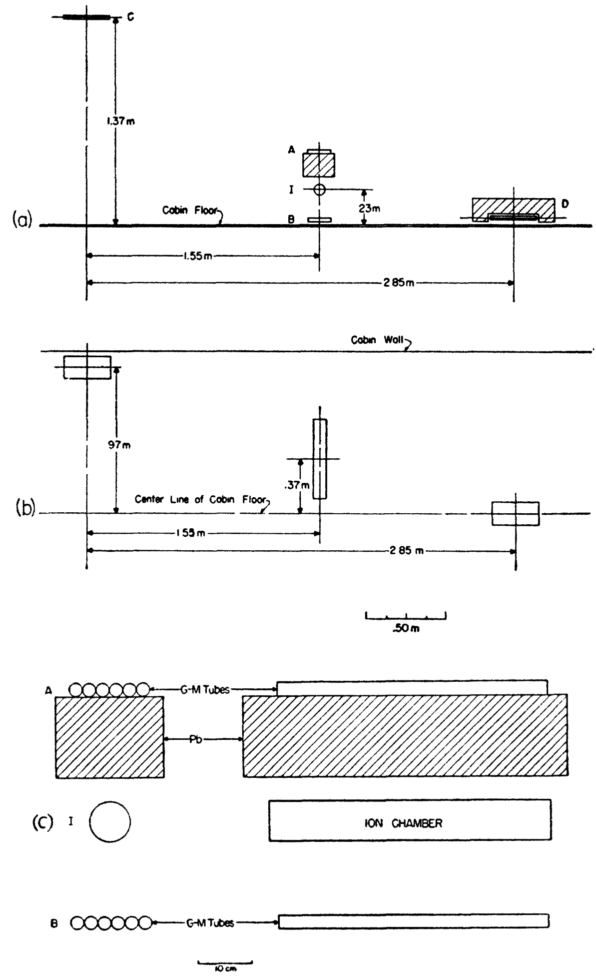

FIG. 1. Experimental arrangement used in the measurements aboard the B-29. (a) Side view; (b) top view; (c) details of the coincidence set $A\ I\ B$.

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[3] Bridge, Hazen, Rossi, and Williams, Phys. Rev. **74**, 1083 (1948).

[4] See B. Rossi and K. I. Greisen, Rev. Mod. Phys. **13**, 240 (1941).

(a)
(b)
(c)

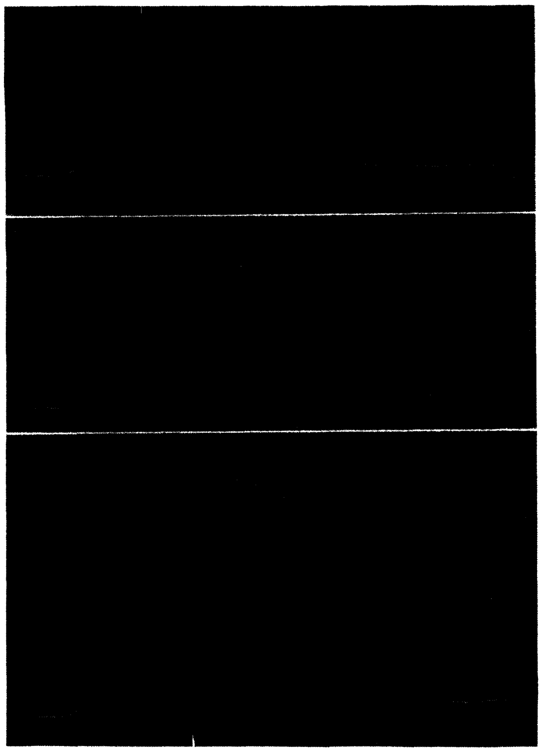


FIG. 2. Samples of pulse records. (a) α-pulse; (b) σ-pulse; (c) ν-pulse.

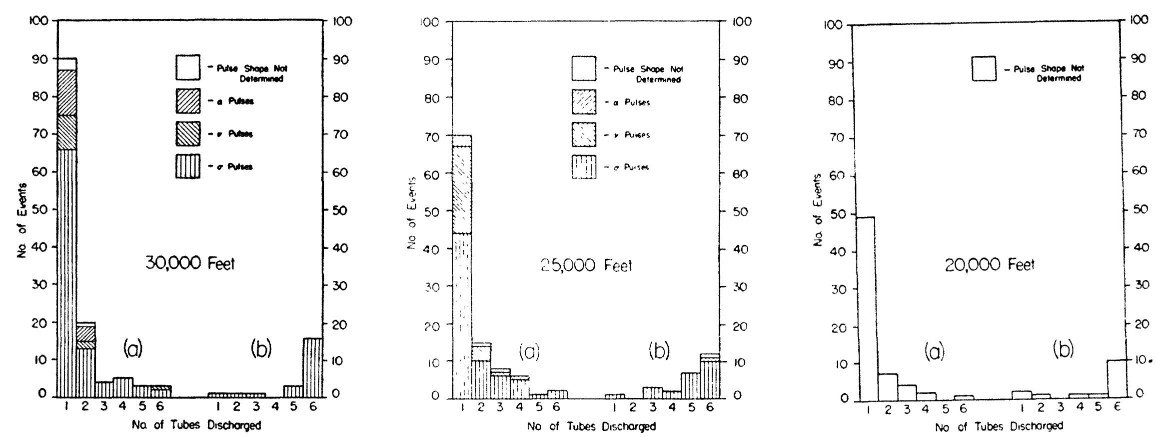
ionization chamber, suitably amplified and delayed, were applied to the deflecting plates of this oscilloscope. Coincidences between the (IB_2) event and pulses of the six individual tubes in tray A were recorded separately by neon bulbs which were photographed on the same film and simultaneously with the oscilloscope trace.

Two additional neon bulbs recorded discharges of the lateral trays C and D occurring simultaneously with the coincidence (AIB_2). Samples of the records obtained are shown in Fig. 2.

2. The Experimental Results

The experimental results are summarized in Figs. 3 and 4 and in Table I. Figure 3 shows a breakdown of the data obtained at the three elevations (20,000, 25,000, and 30,000 feet) according to the shape of the ionization pulse and according to the number of counters discharged in tray A, as indicated by the corresponding neon bulbs. Events in which the coincidence (AIB_2) was or was not accompanied by pulses in tray C or D are considered separately. The shapes of the ionization pulses are classified into three categories, as suggested by Bridge, Hazen, Rossi, and Williams,[3] namely: α-pulses (see Fig. 2a), σ-pulses (see Fig. 2b), and ν-pulses (see Fig. 2c). Pulses of the α- and the ν-type mark the passage through the chamber of heavily ionizing particles. Pulses of the σ-type are characteristic of showers of lightly ionizing particles, even though occasionally groups of heavily ionizing particles may give a pulse of this type.

Table I shows the total numbers of cases in which coincidences (AIB_2) were accompanied



(a) (b) (c)

FIG. 3. Distribution of the records obtained with the instruments shown in Fig. 1, according to pulse shape and to number of tubes discharged in tray A. The area of tray C was 465 cm² for the 30,000-foot flight and for half of the 25,000-foot flight. It was 320 cm² for the rest of the flights. Histograms (a) refer to coincidences (AIB_2) unaccompanied by pulses in either C or D; histograms (b) refer to coincidences (AIB_2) accompanied by pulses in either C or D or both.

by pulses in tray C but not D (event AIB_2C-D), tray D but not C (event AIB_2D-C), both tray C and D (event AIB_2CD), and in neither tray C nor D (event AIB_2-CD).

Figure 4 summarizes the results on the variation with altitude of the rate of occurrence of coincidences AIB_2. The sea level point was obtained at Lexington, under a roof of about 12 g cm^{-2}, with the same equipment used in the B-29 flights. Figure 4 also shows the coincidence rates corrected for air showers in the manner to be discussed below.

3. Discussion

The diagrams in Fig. 3 clearly indicate that two different phenomena are responsible for the coincidences between the pulses of the ionization chamber and of the Geiger-Mueller trays A and B. We believe that these two phenomena are: (a) nuclear interactions produced in the lead block or in the chamber wall by penetrating ionizing particles. In most of these events only one Geiger-Mueller counter in tray A and none in tray C or D is discharged (see Fig. 5a). (b) Air showers incident at a large zenith angle which discharge the counter trays A and B and the ionization chamber I without traversing the entire lead block between A and I. In most of these events all of the counters in tray A are discharged, and pulses are recorded also in the lateral trays (see Fig. 5b).

In the present experiments it is not possible to establish a completely unambiguous criterion for separating events caused by nuclear interactions and by air showers, respectively. At a large zenith angle, an air shower of small density, but containing some high energy electrons or photons, could miss the lateral trays, discharge only a small number of counters in tray A, and produce a burst in the ionization chamber after undergoing some multiplication in the lead (see Fig. 5c). On the other hand, it is possible that some of the penetrating particles capable of producing nuclear interactions arrive upon the instrument accompanied by air showers which discharge several counters in tray A, as well as one or both of the lateral trays (see Fig. 5d).

Finally, we may recall that often, when a nuclear interaction of the type shown schematically in Fig. 5a occurs, penetrating particles are

TABLE I. Total number of events observed during the airplane experiments (the data obtained at the various elevations are considered all together).

Event	(AIB–CD)	($AIBC$–D)	($AIBD$–C)	($AIBCD$)
Number of records	291	27	8	27

projected at wide angles with respect to the incident ray and even in the backward direction.[2,5–7] These particles may produce multiple discharges in the upper tray and, more seldom, strike the lateral trays. It is our belief that phenomena of this kind are responsible for most of the events in which multiple discharges in tray A are not accompanied by discharges in the lateral trays.

Provisionally we shall assume that the (AIB_2) coincidences accompanied by a discharge in tray

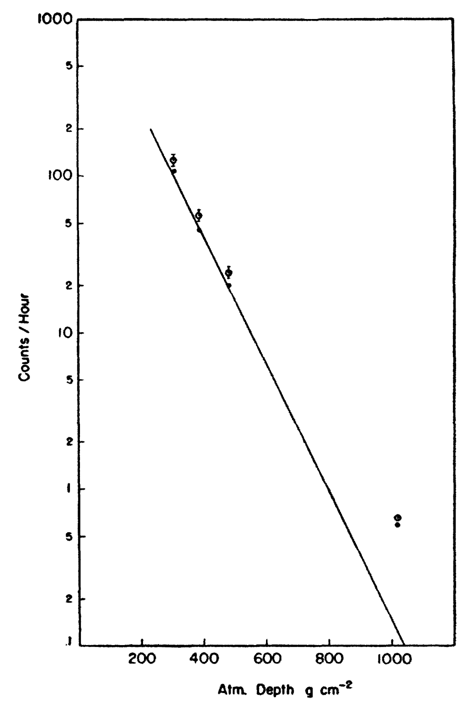


FIG. 4. Hourly rates of threefold coincidences (AIB_2) at various altitudes, as obtained with the experimental arrangement shown in Fig. 1. Minimum pulse required from the ionization chamber: 0.6 P_α. Open dots: observed rates, with corresponding statistical errors; solid dots: rates corrected for air showers. The solid line represents an exponential variation with an absorption thickness of 107 g cm^{-2}.

[5] J. G. Wilson, as quoted by D. Broadbent and L. Janossy, Proc. Roy. Soc. **A190**, 497 (1947).
[6] W. B. Fretter, Phys. Rev. **73**, 41 (1948).
[7] C. Y. Chao, Phys. Rev. **74**, 492 (1948).

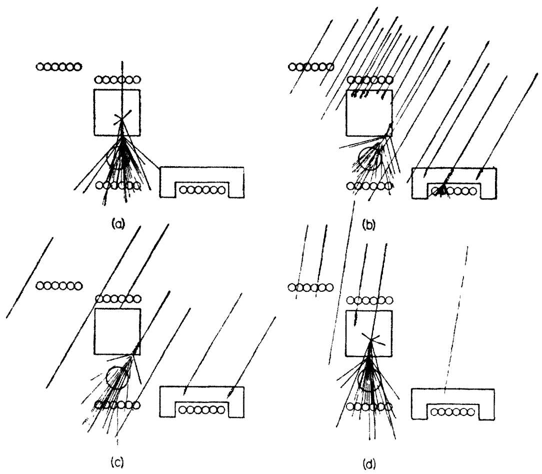


FIG. 5. Schematic representation of various cosmic-ray processes capable of producing (AIB_2) coincidences.

C or D are produced by air showers, and those unaccompanied by discharges in tray C or D are caused by nuclear interactions. The air shower correction to the observed coincidence rates made in Fig. 4 was computed according to this assumption. Since the correction is small, the uncertainty which still exists as to its accurate value does not represent a serious source of error in the determination of the altitude dependence of burst production by nuclear interactions.

The pulse shape analysis of the records obtained at 25,000 and 30,000 feet (see Fig. 3) shows that practically all of the events in which tray C or D is discharged (coincidences AIB_2C-D, AIB_2D-C, and AIB_2CD) and a substantial majority of the events in which trays C and D are not discharged (coincidences AIB_2-CD) are accompanied by ionization pulses of the σ-type. These results are in agreement with our assumption that events in which the lateral trays are discharged are caused by air showers. They also show that among the bursts caused by nuclear interactions some are produced by the passage through the chamber of a few heavily ionizing particles, but most are produced by the passage through the chamber of showers of many lightly ionizing particles. The cloud-chamber experiments mentioned previously (see references 2, 6, 7) show that these showers result from cascade multiplication of high energy electrons or photons produced in the nuclear interactions. The fact that in our experiments more pulses of the σ-type than of the α- and ν-type are observed does not mean that the production of high energy electrons or photons in nuclear interactions is a more common event than the production of heavily ionizing particles. For both types of events one can define an "effective layer" in the material above the ionization chamber where the interaction must take place in order that an observable ionization burst be produced. The thickness of this effective layer depends on the nature and on the energy distribution of the particles arising from the interaction, and is certainly greater for events leading to the production of high energy electrons or photons than for events leading to the production of heavily ionizing particles.

The very rapid increase of the coincidence rate with altitude (see Fig. 4) confirms previous results,[1] as well as the conclusion that most of the bursts observed at high altitudes are produced by particles different from ordinary mesons. It is believed that these particles are high energy protons and possibly "heavy" mesons. It is also likely that some of the coincidences (AIB_2) are produced by nuclear interactions caused by high energy neutrons and in which ionizing particles are projected backwards through the counter tray A.

In Fig. 4 the points at 30,000, 25,000, and 20,000 feet fall approximately on a straight line, but the point near sea level lies above it. This fact may be taken as an indication that radiation and collision processes of ordinary mesons, although unimportant at high altitude, contribute a large fraction of the bursts observed near sea level. It should be noted that these conclusions apply at present only to the relatively small bursts observed in our experiments.

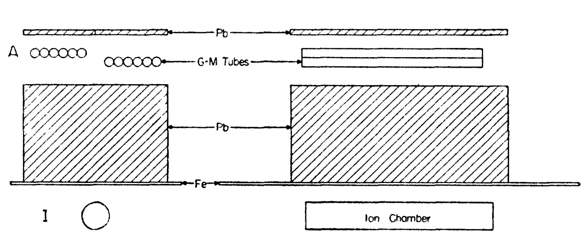


FIG. 6. Experimental arrangement used in the measurements at Mt. Evans.

TABLE II. Summary of the observations made at 14,300 feet by means of the experimental arrangement shown in Fig. 6, with different absorbers between the counter tray A and the ionization chamber I. P represents the chamber bias. $(A\ I)$ is the hourly coincidence rate between pulses of A and I. (A_2I) is the hourly rate of events in which two or more counters in A are discharged simultaneously with I. The permanent 1.27-cm lead absorber above A is *not* included in the tabulated values of absorber thickness.

Absorber	None	2.54 cm Pb	5.08 cm Pb	12.7 cm Pb	27.9 cm Pb	2.54 cm Pb 12.7 cm Fe	2.54 cm Pb 17.8 cm Fe	12.7 cm Pb 17.8 cm Fe
$P>0.6\ P_\alpha$								
$(A\ I)$ obs.	32.3±0.7	57.8±1.1	31.0±0.9	13.7±0.3	9.4±0.3	19.9±0.7	12.9±0.8	8.3±0.4
$(A\ I)$ accid.	3.2	3.3	3.5	3.6	2.4	2.6	2.4	2.4
$(A\ I)$ corr.	29.1	54.5	27.5	10.1	7.0	17.3	10.5	5.9
$P>1.1\ P_\alpha$								
$(A\ I)$ obs.	9.3±0.4	21.1±0.6	12.4±0.6	4.2±0.2	2.85±0.16	7.6±0.4	7.9±0.6	2.69±0.22
$(A\ I)$ accid.	0.4	0.7	0.6	0.25	0.20	0.2	1.8*	0.15
$(A\ I)$ corr.	8.9	20.4	11.8	3.95	2.65	7.4	6.1	2.54
(A_2I)	6.2±0.4	15.8±0.7	7.0±0.6	1.0±0.1	1.1±0.1	3.7±0.3	2.9±0.4	
$P>2\ P_\alpha$								
$(A\ I)$ obs.	3.28±0.23	8.5±0.4	5.7±0.4	1.85±0.11	1.1±0.1	3.3±0.3	2.1±0.3	1.7±0.2
$P>3\ P_\alpha$								
$(A\ I)$ obs.	1.47±0.15	4.7±0.3	3.3±0.3	0.85±0.07	0.64±0.08	1.9±0.2	1.0±0.2	

* The large accidental correction is caused by electric disturbance from a neighboring cloud chamber which affected the ionization chamber circuit, but not the Geiger-Mueller counter circuit.

III. EXPERIMENTS AT MT. EVANS

1. The Experimental Arrangement

The arrangement used in the experiments at Mt. Evans is shown schematically in Fig. 6. The ionization chamber I was the same instrument described in Part II. Each of the Geiger-Mueller counters in tray A was 51 cm long and 2.5 cm in diameter. An iron plate 0.6 cm thick was always present above the ionization chamber, and a lead plate 1.27 cm thick was always present above the counter tray. Additional absorbers of lead and iron could be placed between the ionization chamber and the Geiger-Mueller tray. When an absorber consisting partly of lead and partly of iron was used, the lead was always placed below the iron. An electronic pulse height discriminator selected pulses of the ionization chamber greater than 0.6 P_α, 1.1 P_α, 2 P_α, and 3 P_α, respectively, where P_α indicates, as before, the maximum size of pulses produced by polonium alpha-particles. Recorded were: (a) ionization pulses greater than 0.6 P_α, 1.1 P_α, 2 P_α, and 3 P_α occurring simultaneously with the discharge of at least one Geiger-Mueller tube in tray A (coincidences AI); (b) ionization pulses greater than 0.6 P_α and 1.1 P_α irrespective of whether or not simultaneous pulses occurred in the Geiger-Mueller tray; (c) ionization pulses greater than 1.1 P_α occurring simultaneously with the discharges of at least two Gieger-Mueller tubes in tray A (event A_2I); (d) all pulses of the Geiger-Mueller counter tray A.

2. The Experimental Results

The most significant results obtained with the arrangement described are summarized in Table II. The corrections for accidental coincidences indicated in the table were computed from the resolving time of the coincidence circuit (which by direct observation of the pulses was found to be approximately 50 microseconds) and from the observed rates of single pulses in the Geiger-Mueller tray and in the ionization chamber. (It may be noted that for the 0.6 P_α bias the counting rate of the ionization chamber includes a large contribution from the polonium source.)

Figure 7 shows double logarithmic plots of counting rate against chamber bias for the coincidences (AI) obtained with different lead thicknesses above the ionization chamber. In Fig. 8 the round points represent the (AI) coincidence rates obtained with a chamber bias of 1.1 P_α and with different lead thicknesses. The square dots in the same figure represent differences between (AI) and (A_2I) coincidence rates and thus refer to events in which only one Geiger-Mueller counter is discharged.

The coincidence rates plotted in Figs. 7 and 8 are corrected for accidentals. The lead thicknesses indicated include the thickness of the lead plate above the Geiger-Mueller counters (1.27 cm). Note that the data at 1.27 cm of lead are not directly comparable with the others because they were obtained with a much greater separation between the lead shield and the ionization chamber.

3. Discussion

From an examination of Fig. 7 it appears that power laws of the type $N(P)=\text{const.}\times P^{-\gamma}$ with $\gamma=1.5$ represent satisfactorily the integral pulse height distributions at 3.8, 14.0, and 29.2 cm of lead. The pulse height distribution at 6.35 cm seems to be somewhat flatter, and that at 1.27 cm is definitely steeper than the pulse height distributions at the other thicknesses.

The dependence of counting rate on lead thickness shown by the round dots in Fig. 8 clearly indicates that two different phenomena are responsible for the observed coincidences. It is natural to identify these two phenomena as shower production by high energy electrons and photons and nuclear interactions. The first phenomenon predominates at small thicknesses and explains the sharp maximum of the transition curve indicated by the experiment. The second phenomenon predominates at large thicknesses and explains the "tail" of the transition curve. From the slope of this tail one obtains the following value for the absorption thickness in lead, L_{Pb}, of the radiation responsible for nuclear interactions:

$$L_{Pb}=430\pm 90 \text{ g cm}^{-2}.[8]$$

The corresponding value for iron, as obtained by comparing the counting rates measured with 12.7 cm of lead and with 12.7 cm of lead plus 17.8 cm of iron between A and I (see Table II) is

$$L_{Fe}=320\pm 70 \text{ g cm}^{-2}.$$

The above computation of L_{Pb} and L_{Fe} neglects the effect of air showers. This effect should be smaller in the experiments at Mt. Evans than in the airplane experiments because the chamber was more effectively shielded by the lead (compare Figs. 1 and 6). Also neglected is the background from radiation and collision of ordinary mesons.

The square dots in Fig. 8 show that multiple discharges of the Geiger-Mueller counters occur in a very large fraction of the coincidences observed with small lead thicknesses, most of which are due to shower production by electrons and photons from the atmosphere. This, of course, was to be expected, especially because of the 1.27-cm thick lead shield above the Geiger-Mueller counters. However, even at large thicknesses, where most of the coincidences should be caused by nuclear interactions, multiple discharges of the counter tray are found to occur in one-quarter to one-third of the cases. We believe (see Section II-3) that these multiple discharges are mainly caused by the passage through the Geiger-Mueller counters of secondary particles arising from the nuclear interactions which are also responsible for the bursts

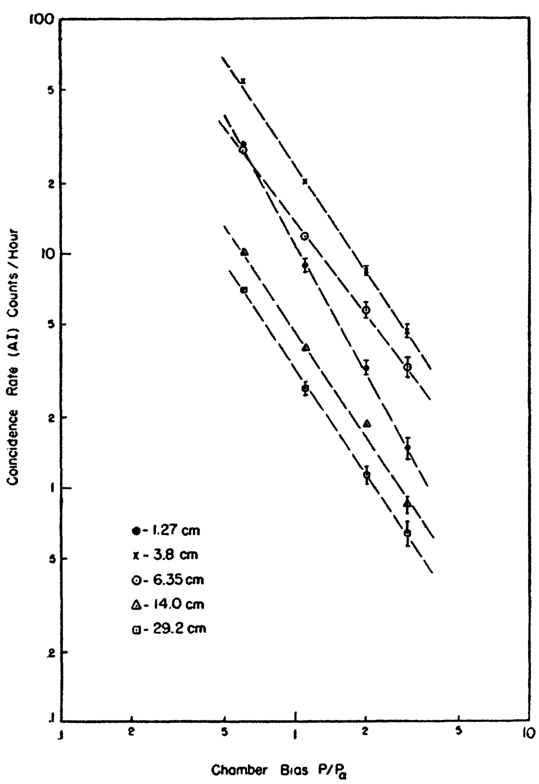


FIG. 7. Counting rate N against chamber bias P/P_α for different thicknesses of the lead absorber in centimeters. The figures include the thickness (1.27 cm) of the permanent lead absorber above the Geiger-Mueller counters.

[8] The value of L_{Pb} derived from these experiments was quoted erroneously as 280±50 in Section 20 of the review article by B. Rossi in Rev. Mod. Phys. 20, 537 (1948). This was due to a mistake in the evaluation of the accidental coincidences.

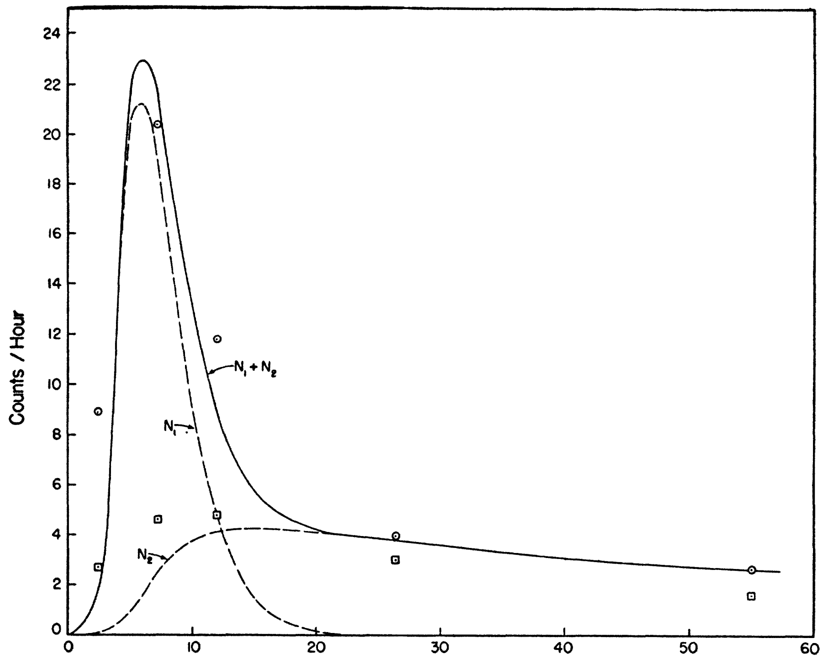


FIG. 8. The curve labeled N_1 is the theoretical transition curve for bursts produced by electrons and photons; the curve labeled N_2 is the theoretical transition curve for bursts produced by nuclear interactions. The round points represent the observed (A I) coincidence rates, and the square points represent the difference of the coincidence rates (A I) and (A_2 I). The abscissa represents the total thickness of lead shield above the ionization chamber in radiation lengths.

in the ionization chamber. This hypothesis may lead one to expect a decrease in the relative number of multiple discharges as the lead thickness between A and I is increased from 12.7 to 27.9 cm; such a prediction is not borne out by the observations—a fact which has not yet received a satisfactory explanation. The existence of correlated nuclear interactions indicated by various experiments may possibly furnish a clue.

We made an attempt to interpret quantitatively the observed transition curve by assuming that nuclear interactions produce bursts exclusively through the intermediary of electron showers (i.e., that the contribution of heavily ionizing particles to the ionization bursts observed under lead is negligible). We further assumed that the energy spectrum of the electrons or photons produced in the lead shield by nuclear interactions is identical to that of the electrons and photons incident upon the lead from the atmosphere and is represented by a power law. Incomplete experimental information and mathematical difficulties of the shower theory made it necessary to adopt the following additional simplifying hypotheses, all of which are very questionable: (a) the production of more than one high energy electron or photon in a nuclear interaction is a rare event; (b) the simultaneous arrival upon the instrument of more than one high energy electron or photon from the atmosphere is a rare event; (c) in the computation of cascade showers, fluctuations can be neglected, and the approximation described as approximation "B" in the review article by Rossi and Greisen can be used.[4]

Under the above assumptions, the number of showers with more than Π-electrons coming out of the lead shield and initiated by electrons or photons incident upon the shield is given by the expression

$$N_1(t) = A[E(\Pi, t)]^{-\alpha}, \qquad (1)$$

where t is the thickness of the lead in radiation lengths, $E(\Pi, t)$ is the energy of an electron or photon which produces a shower of Π-particles after traversing the thickness t, and $AE^{-\alpha}$ is the number of electrons and photons of energy greater than E incident upon the lead (the difference between showers produced by electrons or photons of the same energy in a given lead thickness is here neglected).

Similarly, the number of showers with more than Π-electrons coming out of the lead shield and initiated by electrons or photons arising from nuclear interactions in the lead is given by

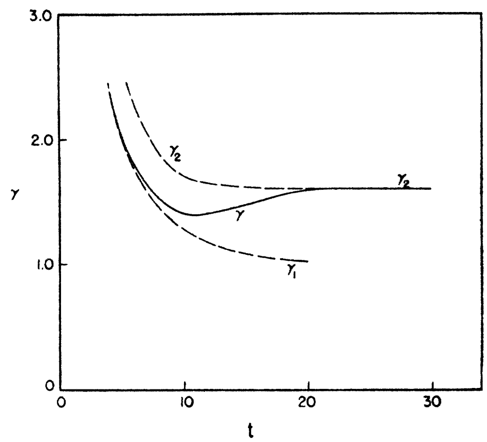


FIG. 9. Theoretical value of $\gamma_1 = -d(\ln N_1)/d(\ln \Pi)$, $\gamma_2 = -d(\ln N_2)/d(\ln \Pi)$, and

$$\gamma = -d(\ln N)/d(\ln \Pi) = (N_1\gamma_1 + N_2\gamma_2)/(N_1+N_2)$$

at $\Pi = 100$ and for various values of t.

the expression

$$N_2(t) = B\int_0^t \exp(-t'/l)[E(\Pi, t-t')]^{-\alpha}dt'/l, \quad (2)$$

where l is the absorption thickness (in radiation lengths) of the radiation producing nuclear interaction and $BE^{-\alpha}$ represents the total number of electrons or photons of energy larger than E produced by this radiation before complete absorption in lead.

The curves in Fig. 8 represent $N_1(t)$, $N_2(t)$, and $N(t) = N_1(t) + N_2(t)$ computed from Eqs. (1) and (2) with $\alpha = 1.6$, $l = 72$, $\Pi = 100$, and such values for A and B as to obtain agreement between the theoretical and experimental values of $N(t)$ near the maximum and at the tail end of the transition curve. The ratio between the values of A and B thus determined is $A/B = 0.4$. The value of Π chosen for the computation is greater than the number of electrons required to produce a pulse equal to 1.1 P_α in the ionization chamber (see Section II-1). However, many of the electrons coming out of the lead are absorbed by the iron plate placed above the chamber. Also, the shape of the theoretical transition curve does not depend critically on the value of Π.

The curves in Fig. 9 represent the quantities:

$$\gamma_1 = -(d(\ln N_1)/d(\ln \Pi)), \quad \gamma_2 = -d(\ln N_2)/d(\ln \Pi),$$

and

$$\gamma = -d(\ln N)/d(\ln \Pi) = (\gamma_1 N_1 + \gamma_2 N_2)/(N_1 + N_2)$$

as functions of t.

Examination of Figs. 8 and 9 shows that the agreement between theoretical predictions and experimental data is as good as one can expect considering the crude approximations made. In particular, it is interesting to note that both experiment and theory indicate a minimum in the value for γ at a thickness where N_1 and N_2 have comparable values. The physical reason for this minimum is that at this thickness the relative contribution of "old showers" (i.e., of showers beyond the maximum) is greater than at either larger or smaller thicknesses.

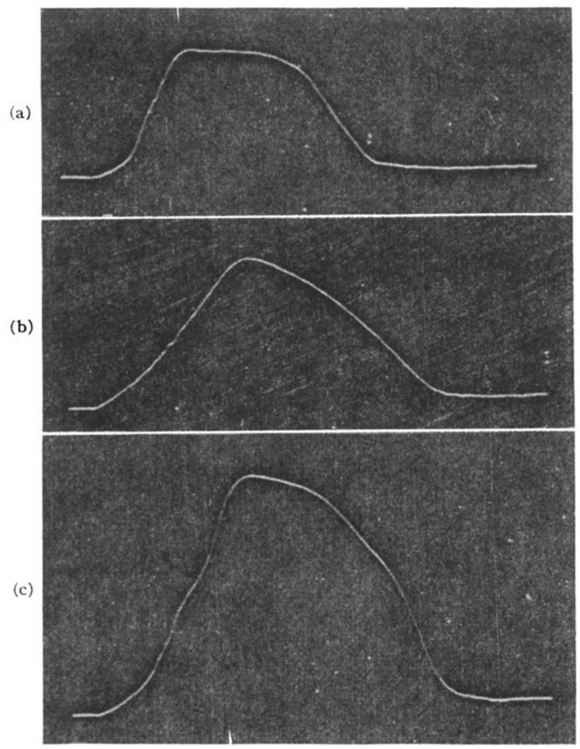


FIG. 2. Samples of pulse records. (a) α-pulse; (b) σ-pulse; (c) ν-pulse.