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# A Cloud-Chamber Study of Neutron Production by Sea-Level Cosmic Rays with Particular Reference to μ-Mesons Stopped in Lead*†

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A multiple-plate cloud chamber has been used at sea level to test the conclusion drawn from counter experiments that neutrons of several-Mev energy are liberated when negative μ-mesons are stopped in lead. The stopped mesons are recognized by comparison of visually estimated ionization and range. With the plate thicknesses used, mesons can be distinguished from electrons and protons. To discriminate against π-mesons, which would have to be produced locally, there is a minimum of condensed material above the chamber, and mesons accompanied by any other particle in the top compartment are excluded from the statistics. Alternate plates of Pb and C of equal stopping power are used, evaporation neutrons being expected from mesons stopped in the Pb but not from mesons stopped in the C. The chamber is surrounded by paraffin and $BF_3$ counters, for the detection of neutrons originating in the plates; a G-M tube telescope above the chamber selects charged particles directed through the chamber. The chamber is expanded when a telescope coincidence is associated with at least one detected neutron. In 1207 accepted pictures, there are 14 definite cases of mesons stopping in the Pb, none of mesons stopping in the C. Including probable as well as definite identifications, the corresponding numbers are 19 and 1. These results confirm the production of evaporation neutrons in μ-meson capture in Pb. The large Pb:C ratio shows that π-meson contamination is negligible when our selection criteria are used.

The neutron coincidence pictures reveal the various processes giving rise to these events. Electronic showers account for a large fraction; the "giant resonance" of 15-Mev photons in Pb is probably responsible. About 20 percent of the events are energetic nuclear interactions. There is a significant yield of single penetrating particles, some of which must be fast μ-mesons interacting in Pb with small energy loss. The rate is consistent with underground measurements of the neutron yield. A $V^0$ decay has been found with both branches heavily ionizing; it appears to be a $V_1^0$ with $Q$ in the range 30–55 Mev.

## I. INTRODUCTION

PREVIOUS counter experiments[1,2] have demonstrated the production of neutrons of several-Mev energy in the capture of μ-mesons stopped in lead, and they have also shown[1] that other processes contribute appreciably to the measured counting rates. Particularly clear evidence of the variety and complexity of these other processes is provided by the cloud-chamber pictures obtained at mountain altitude by Fowler and his collaborators.[3] The present experiment was designed to separate unambiguously, by means of cloud-chamber technique, the μ-meson capture process. It was carried out at the same time as two other experiments bearing on the same problem, that of Conforto,[4] in which use was made of a magnetized iron lens, and that of Crouch,[5] carried out underground. All three experiments have confirmed the conclusion of the earlier research.[6] The present experiment also provides data on the other processes giving rise to neutron-charged particle coincidences at sea level.

In the absence of a magnetic field, it is still possible with a cloud chamber to distinguish between electrons, π- or μ-mesons, and protons, by the use of plates of appropriate thickness. In this experiment, the thicknesses—5.8 g $cm^{-2}$ Pb and 3.2 g $cm^{-2}$ C—are such that a stopped meson makes a noticeably dense track only in the last and possibly the next to last compartment, while a stopped proton makes a dense track through at least six. An electron does not ionize heavily in any compartment; its association with other particles to form a shower facilitates recognition. The difference in behavior as regards scattering in the plates is also of help in discriminating between mesons and protons, though, because of its statistical character, it is not conclusive in individual cases.

It is impossible with this technique to distinguish between π- and μ-mesons. But decay in flight and interaction with nuclei of the air render negligible the admixture of π-mesons coming from higher altitude, so that only production in condensed matter just above the chamber needs to be considered. The material was kept to a minimum—only the roof (4 g $cm^{-2}$) and the paraffin moderator (30 g $cm^{-2}$)—and as a further precaution only mesons entering the chamber unaccompanied were

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† A brief account of the part of this work dealing with stopped mesons was given at the Meeting of the American Physical Society at Los Angeles, California, December 28, 1950 [Phys. Rev. **81**, 647 (1951)]. Two of the cases of meson stoppings in Pb reported in the abstract were deemed less than "definite" at later reviews and the one case in C was later reclassified as a proton. This did not change the nature of the conclusions.

Sections I through IV of this article are a condensation of a dissertation presented to the Graduate Board of Washington University in September, 1950 by one of the authors (E.J.A.) in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

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[1] Sard, Ittner, Conforto, and Crouch, Phys. Rev. **74**, 97 (1948); Sard, Conforto, and Crouch, Phys. Rev. **76**, 1134 (1949); W. B. Fowler, Phys. Rev. **79**, 178 (1950); Sard, Crouch, Jones, Conforto, and Stearns, Nuovo cimento **8**, 326 (1951).

[2] G. Groetzinger and G. W. McClure, Phys. Rev. **74**, 341 (1948); **75**, 340 (1949).

[3] Fowler, Sard, Fowler, and Street, Phys. Rev. **78**, 323 (1950); Fowler, Street, Fowler, and Sard, Phys. Rev. **78**, 323 (1950); W. B. Fowler, thesis, Washington University, May, 1951 (unpublished).

[4] A. M. Conforto, thesis, Washington University, October, 1950 (unpublished); A. M. Conforto and R. D. Sard, Phys. Rev. **86**, 465 (1952).

[5] M. F. Crouch, thesis, Washington University, September, 1950 (unpublished); M. F. Crouch and R. D. Sard, Phys. Rev. **85**, 120 (1952).

[6] Independent confirmation has meanwhile also been obtained by Groetzinger, Berger, and McClure, Phys. Rev. **81**, 969 (1951).

accepted in the statistics. It will appear from the analysis of the data that the $\pi$-meson contamination was negligible.

A G-M tube telescope above the chamber selected incoming charged particles directed so as to pass through all the plates. A C-shaped mass of paraffin enclosing the top, side, and bottom of the cloud chamber contained boron-ten counters with an over-all efficiency of about 1.2 percent for detecting coherent neutrons of several-Mev energy originating in the chamber. The circuit gave an output pulse whenever at least one neutron was detected in association with a telescope coincidence. This type of event, designated $(AB:N)$, was the trigger used for expanding the cloud chamber. For reasons explained below, pictures were also taken with plain telescope $(AB)$ triggering.

As a further test of the view that $\mu$-meson capture in Pb leads to neutron emission, the plates in the chamber were, following a suggestion by Primakoff, made alternately of Pb and C, of equal stopping power for $\mu$-mesons. Mesons should stop with equal frequency in the Pb and C plates. In the first case, practically all of the negatively charged ones interact, each giving rise to about 1.8 evaporation neutrons.[7] In the second case only about 11 percent of the negative $\mu$-mesons interact,[8] and of these only a negligible fraction would be expected to produce an evaporation neutron.[4] The pictures obtained when detection of an evaporation neutron is required for triggering—"$(AB:N)$"—should therefore show many more mesons stopping in the Pb than in the C. With "$(AB)$" triggering, on the other hand, there should be approximately equal numbers of meson stoppings in the two kinds of plates.

A large Pb:C ratio with $(AB:N)$ triggering would also show that the contribution of stopped $\pi$-mesons is negligible. In effect, any stopping $\pi$-mesons must have been produced in the paraffin and metal just above the chamber, in nuclear interactions which have a relatively high probability of being detected. The $\pi$-mesons will stop with equal probability in the Pb and C. The greater average multiplicity of detectable neutrons[9] from $\pi$-meson capture in Pb than in C—$9.3\pm0.5$ as against $1.6\pm0.2$—will, it is true, favor detection of $\pi$-meson stoppings in Pb, but the detecting efficiency for neutrons from the paraffin and metal on top of the chamber is estimated to be about four times that for neutrons from the plates, and the average neutron multiplicity in the $\pi$-meson producing events ought to be at least 4. Thus the Pb:C ratio for stopping $\pi$-mesons is at most 1.4.

The previous experiments[1] had yielded evidence for the production of evaporation neutrons by penetrating $\mu$-mesons. The $(AB:N)$ pictures were expected also to throw light on this phenomenon, as the bulk of the telescope particles are fast $\mu$-mesons.

The pictures taken with ordinary telescope triggering, $(AB)$, gave a sample of the type of pictures resulting from accidental coincidences of $(AB)$ and $(N)$ in the $(AB:N)$ run. They also gave a few cases in which a stopping meson could be definitely identified by the presence of a decay electron, so permitting a test of our technique for recognizing stopped mesons by their ionization and range. It was not considered necessary to take enough $(AB)$ pictures to confirm statistically the equality of stopping power of the Pb and C plates, as the theory of nonradiative collision loss on which the choice of plate thickness was based, can be considered as established experimentally to sufficient accuracy for the purpose of this experiment.

## II. APPARATUS

The cloud chamber shown in Fig. 1 was rectangular, with illuminated gas volume $50.8\times50.8\times15.2$ cm. Except for the windows, and the brass rear piston stop, the chamber was made almost entirely of Duralumin. The piston was a $\frac{5}{32}$-inch Duralumin plate 53.2 cm square sandwiched between two Neoprene sheets; a black velvet covering furnished the photographic background. The expansion ratio was determined by the forward position of the piston, controlled by four rods with micrometer dials, two of which can be seen in the figure. With 1.5 atmospheres of argon and ethyl alcohol vapor (95 percent), the expansion ratio was around 1.10. The expansion valve, of the type described by Fussell,[10] had a triggering coil at the airgap,[11] in addition to the main holding coil. The single $\frac{3}{8}\times21$ inch xenon flash tube used for illumination was mounted in a cylindrical lens;[12] a stack of spherical condensing lenses produced a parallel beam defined by the side-window of $15.2\times50.8$ cm. A mirror mounted outside the opposite side-window, reflected the beam back on itself. The same flash tube was used for viewing, switched to a low energy supply and pulsed about 30 times per second. Two automatic cameras were used, a stereoscopic one on the axis, and one at 15° to the right, with tilted lens.

The absorbers were six Pb plates of 0.51 cm (5.8 g cm$^{-2}$) and five graphite plates of 1.9 cm (3.2 g cm$^{-2}$), mounted alternately on two vertical slabs of "Allite",[13] a transparent plastic less susceptible than Lucite to attack by alcohol. The plates were covered with 0.005-inch Al foil to improve the illumination, and 0.003-inch W wires were stretched vertically 12.7 cm apart at the front and back of the plate structure to serve as spatial references (these wires are visible in the photographs shown below).

The "geometry" of the experiment is shown in Fig. 2.

[7] R. D. Sard and M. F. Crouch, in *Progress in Cosmic Ray Physics, Vol. II* (North Holland Publishing Company, Amsterdam, to be published), where the experimental results are reviewed.

[8] W. E. Bell and E. P. Hincks, Phys. Rev. **88**, 1424 (1952).

[9] V. C. Tongiorgi and D. A. Edwards, Phys. Rev. **88**, 145 (1952).

[10] L. Fussell, Jr., Rev. Sci. Instr. **10**, 321 (1939).

[11] F. H. Chu and G. E. Valley, Rev. Sci. Instr. **19**, 496 (1948).

[12] Patterned after a system described by Lofgren, Ney, and Oppenheimer, Rev. Sci. Instr. **19**, 271 (1948).

[13] Manufactured by the Homalite Corporation, Wilmington, Delaware.

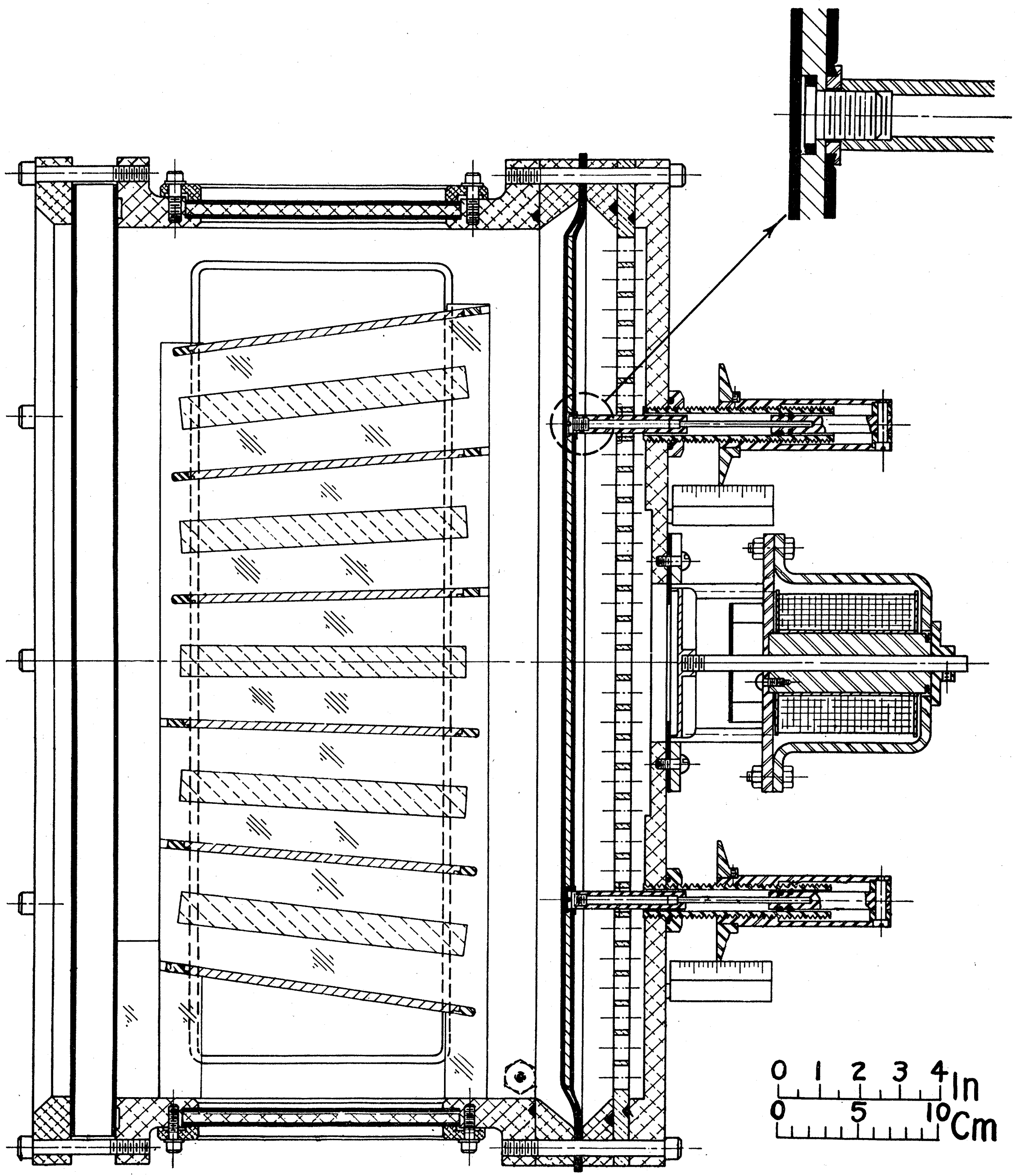



FIG. 1. Right side view of the cloud chamber showing the lead and graphite structure in place. Usual sectioning symbols for material are used.

The Geiger tubes were connected in parallel to form sixteen groups, $A_i$ and $A_i'$ parallel to the chamber axis and $B_i$ and $B_i'$ transverse to it ($i=1, 2, 3, 4$). The telescope coincidence circuit, taken over from an earlier experiment,[3,14] responded whenever there was a coincidence between any pair $A_iA_i'$ and any pair $B_jB_j'$. In this way, one had effectively 16 telescopes; the counters were so placed that the cone of each telescope fitted the part of the bottom plate that lay within the illuminated region. The fifteen $B^{10}$ proportional counters[15] were

[14] Cool, Fowler, Street, Fowler, and Sard, Phys. Rev. **75**, 1275 (1949).

[15] The neutron counters were made and filled by the N. Wood Counter Laboratory, Chicago, Illinois, using enriched $BF_3$ pur-

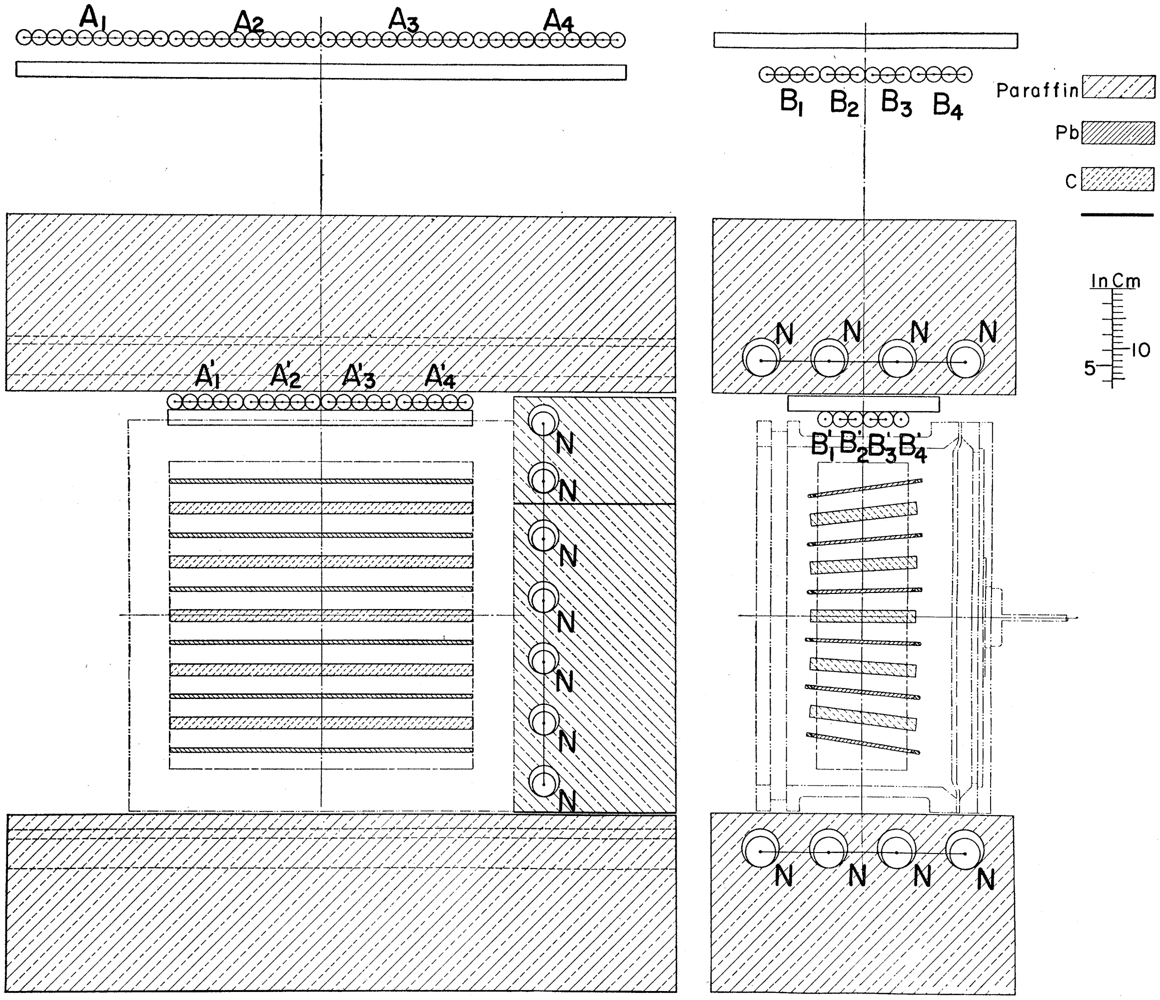



FIG. 2. Front and right side views of the geometrical arrangement. $A$, $A'$, $B$, and $B'$ designate groups of Geiger counters, while $N$ designates neutron counters.

embedded in a C-shaped mass of paraffin embracing the chamber as closely as possible. They were connected in parallel to an amplifier, whose output, designated ($N$), was placed in coincidence with a 139-$\mu$sec gate triggered, with a delay of 2.5 $\mu$sec, by the telescope pulse, ($AB$). A delayed coincidence, ($AB$:$N$), signified detection of at least one disintegration neutron produced by the telescope event.[16]

The neutron-detecting efficiency was measured for a small Ra-$\alpha$-Be source placed at various positions in the chamber; the strength of the source was known to within about 10 percent. The average efficiency was 2.1 percent; it should be about the same for the evaporation neutrons produced in cosmic-ray interactions. The requirement that they be detected in a finite coincidence gate, however, reduces the actual efficiency, as some of the neutrons are captured by the boron after the gate is closed. With a neutron mean life of 162 $\mu$sec,[5] our 139-$\mu$sec gate reduced the efficiency for coherent neutrons to 1.2 percent.

The efficiency for neutrons from outside the C must have been very much smaller. The apparatus was separated from the sky by a slate and wood roof estimated to be equivalent to 4.0 g cm$^{-2}$ air.

### III. EXPERIMENTAL PROCEDURE

The experiment was conducted at St. Louis, Missouri, at 160 meters above sea level. Periods of ($AB$:$N$) and ($AB$) triggering were alternated so that about equal numbers of pictures of each type were obtained which were distributed over the whole time of the experiment. In 673.1 hours of ($AB$:$N$) sensitive time there were 1666 expansions, yielding 1207 acceptable sets of pictures; 1453 ($AB$) expansions gave 1283 acceptable sets of pictures. Pictures were rejected when they were ob-

chased from the Isotopes Division of the U. S. Atomic Energy Commission.

[16] For a more detailed discussion of neutron coincidence technique see reference 1.

jectively of poor quality, or when faulty operation of the apparatus was known or suspected. The selection was made before analysis.

The counting rates are shown in Table I. The $(AB)$ rate, which because of imperfect counters is 15 percent below that expected, is comparable with that obtained in typical counter experiments, a consequence of the large size of the cloud chamber and the use of a multiple telescope. From the measured $(AB)$ and $(N)$ rates and the coincidence gate length of 139 $\mu$sec, the accidental $(AB:N)$ rate is calculated to be 0.29 $hr^{-1}$, or 11.7 percent of the observed rate. There is of course no way of telling whether a particular $(AB:N)$ picture is genuine or accidental, but classification of the $(AB)$ pictures according to the same categories as the $(AB:N)$ ones permitted calculation of the expected number of casual $(AB:N)$ pictures of each type. The short run with Cd sheaths on the $BF_3$ counters sufficed to verify that the $(AB:N)$ rate does not contain a significant admixture of non-neutronic events.

TABLE I. Average counting rates.[a]

| Type of count | Time, hr | Rate |
|---|---|---|
| $(AB)$ | 1080.1 | $18.41\pm0.02$ min$^{-1}$ |
| $(N)$ | 959.0 | $113.8\ \pm0.05$ min$^{-1}$ |
| $(AB:N)$ | 673.1 | $2.48\pm0.06$ hr$^{-1}$ |
| $(N)$ with Cd | 20.3 | $20.4\ \pm0.1$ min$^{-1}$ |
| $(AB:N)$ with Cd | 20.3 | $0.15\pm0.09$ hr$^{-1}$ |

[a] The indicated errors are only estimated statistical standard deviations.

## IV. ANALYSIS OF THE PICTURES WITH REGARD TO MESON STOPPINGS

For the analysis of the pictures with regard to neutron production by stopped $\mu$-mesons, the following criteria were applied: 1. The track must be so directed when it enters the chamber as to lie in the cone defined by the counter telescope. It must, of course, be of counter-control age. 2. It must not be accompanied by any contemporary track in the top compartment, nor be contemporary with any event anywhere in the chamber in which a neutron could be produced (shower or nuclear interaction). 3. The track must pass through the top plate before stopping, so as to be observed in at least two compartments. 4. The track must stop well within the illuminated region, so as to prevent scattering from simulating stopping. 5. It must appear heavily ionizing in the last and only slightly heavy, at the most, in the next-to-last compartment.

These requirements eliminated some bona fide $\mu$-meson stoppings, but they served to discriminate against $\pi$-mesons and other particles.

The fifth criterion, with proper choice of plate thickness, permitted discrimination between electrons, $\pi$- or $\mu$-mesons, and protons.[17] The plates were made thin enough so that a stopped meson would ionize heavily in its last compartment (as distinguished from an electron), and thick enough so that the visibly increased ionization would occur only in the last, and possibly the next to last, compartment (as distinguished from a proton, heavy in many compartments). The thickness of 5.8 g cm$^{-2}$ Pb and 3.2 g cm$^{-2}$ C corresponds to an ionization of at least 2.4 times minimum for a vertical stopped $\mu$-meson. Table II shows the ionizations, relative to minimum, that are to be expected for vertical $\mu$-mesons, $\pi$-mesons, and protons in the various compartments of the cloud chamber.[18] The figures given are the smallest values for each compartment. The greatest value for a given compartment is equal to the smallest value for the next lower one; e.g., for a $\mu$-meson, the ionization in the next to last compartment lies between 1.8 and 2.4 times minimum.

Figure 3(a), an accepted picture from the $(AB:N)$ series, shows a meson stopping in the second Pb plate. The track is very dense in the last compartment, moderately dense in the next to last compartment, and "minimum" in the top compartment. We infer that tracks become noticeably heavy at somewhere between 1.8 and 2.4 times minimum ionization. This is confirmed by Fig. 3(b), showing a particle stopped in the second carbon plate, definitely identified as a meson by the presence of the decay electron emerging upward from the plate.[19] The track is decidedly dense in the last compartment, and just barely dense in the next to last. A proton would leave a decidedly dense track in all three compartments. Figure 3(c) shows a proton stopping in the fourth Pb plate. Its track is dense in all seven compartments.

Visual estimates of ionization are, of course, very uncertain, particularly for short segments of track. To distinguish between mesons and protons in our case, it was only necessary, however, to discriminate between densities of 2×minimum and 5×minimum in the next-to-last compartment. The requirement that the track be noticeably dense in the last compartment did of course exclude some meson stoppings (oblique incidence or scattering inside the plate), but it did not detract from the purity of the accepted data.

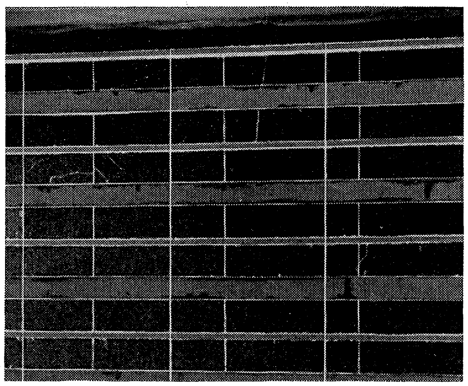
TABLE II. Ionization in argon of $\mu$-mesons, $\pi$-mesons, and protons, in passing normally through successive absorbers, each of thickness equal to the range of a 69-Mev/$c$ $\mu$-meson. The table gives the smallest ionization density above the indicated plate, relative to minimum ionization.

| Particle \ Plate | 1 (stops) | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $\mu$-meson | 2.4 | 1.8 | 1.5 | 1.4 | 1.3 | 1.3 | 1.2 | 1.2 | 1.2 | 1.1 | 1.1 |
| $\pi$-meson | 2.7 | 2.0 | 1.7 | 1.6 | 1.5 | 1.4 | 1.3 | 1.3 | 1.2 | 1.2 | 1.2 |
| proton | 5.7 | 4.5 | 3.8 | 3.4 | 3.0 | 2.8 | 2.6 | 2.5 | 2.4 | 2.3 | 2.2 |

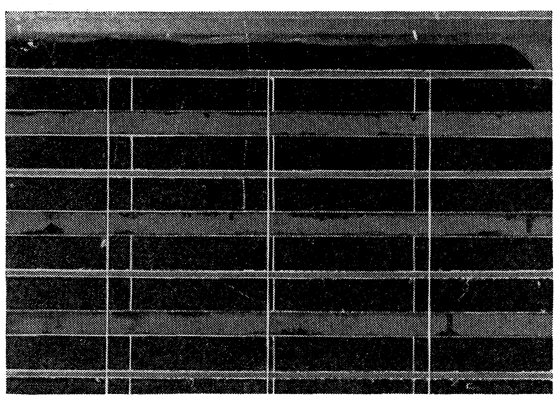
[17] As regards the change of ionization with range, particles of mass $\sim1000m_e$ are indistinguishable from protons in our chamber.

[18] Calculated from the well-known formula for energy loss in weak collisions and the range curve, given by B. Rossi and K. Greisen, Revs. Modern Phys. 13, 240 (1941).

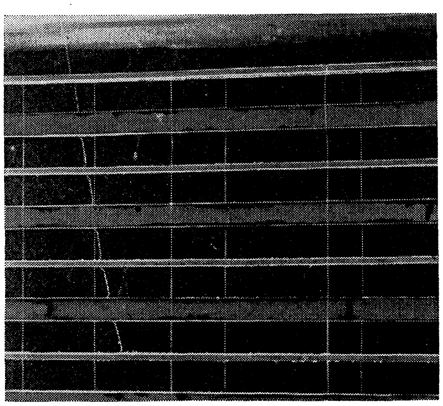
[19] This picture was obtained in the $(AB)$ run. It was excluded from our unaccompanied $\mu$-meson statistics because of the presence of counter-age tracks in the top compartment.



(a)



(b)



(c)

FIG. 3. (a) Event 1811, triggered by neutron coincidence. A $\mu$-meson stopping in the second Pb plate (right side view). (b) Event 2344, triggered by G-M counters alone. A $\mu$-meson stopping in the second C plate emits a decay electron that goes out to the right. Presence of other contemporary tracks in the top compartment renders it "accompanied" (a center view). (c) Event 2049, triggered by neutron coincidence. A proton stopping in the fourth Pb plate (right side view).

Each of the authors examined all the pictures independently, from both the $(AB:N)$ and $(AB)$ runs, and selected the cases appearing to meet the five requirements stated above. He classified these as definite or possible, depending on the sureness with which the recognition was made. The two authors then compared their results. Pictures which both considered definite were classified "definite" (first row of Table III). Those which one considered definite and the other possible were classified "probable" (second row); those which both considered possible were classified "doubtful" (third row).

The 14 definite stoppings in Pb in the $(AB:N)$ series constitute proof that evaporation neutrons are produced by mesons stopped in lead. The Pb:C ratio of 14:0, or 19:1 if the probable cases are included, proves that most of these mesons are $\mu$-mesons.

The number of meson stoppings observed is of the order of magnitude expected from the known $\mu$-meson intensity at sea level.[20] The fraction of telescope coincidences giving a negative $\mu$-meson stopping in one of the five Pb plates (of 16 g cm$^{-2}$ air equivalent) is expected to be

$$0.45\times\frac{5.0\times10^{-6}\text{ g}^{-1}\text{ sec}^{-1}\text{ sterad}^{-1}}{1.02\times10^{-2}\text{ cm}^{-2}\text{ sec}^{-1}\text{ sterad}^{-1}}\times16\text{ g cm}^{-2}=3.5\times10^{-3},$$

and in the sensitive time yielding 1207 $(AB:N)$ pictures there were $(1207/2.48)\times18.4\times60=5.36\times10^{5}$ telescope coincidences. With the coherent neutron detection efficiency of 1.2 percent and an average neutron multiplicity[7] of 1.8, the expected number of $(AB:N)$ events resulting from negative $\mu$-meson stoppings in the Pb is

$$3.5\times10^{-3}\times5.36\times10^{5}\times1.2\times10^{-2}\times1.8=41.$$

In view of the losses due to scattering in the chamber and to our very rigid selection criteria, the figure can be considered in excellent agreement with the observed numbers given in the first column of Table III. This conclusion is confirmed by the results for $(AB)$ triggering. A calculation similar to that just given leads one to expect 20 stoppings in 1283 pictures. Only 5 definite plus probable were observed.

The contribution of accidental $(AB:N)$ coincidences to the observed meson stoppings is negligible. In effect, the $(AB)$ statistics of Table III show that "definite" and "probable" meson stoppings constituted 5/1283 of the telescope coincidences. Thus there were $2.1\times10^{3}$ in the $(AB:N)$ run. The probability of a random neutron being detected in coincidence is $(114/60)\times139\times10^{-6}=2.6\times10^{-4}$, so that the expected number of accidentals in the $(AB:N)$ "definite" and "probable" stoppings is about 0.55, as compared with the 20 cases observed.

Table III also gives the numbers of accompanied mesons, i.e., tracks satisfying all but the second criterion. Some of these obtained with $(AB:N)$ trig-

[20] B. Rossi, Revs. Modern Phys. **20**, 537 (1948).

gering are undoubtedly $\mu$-mesons, but the Pb:C ratio of 18:7 suggests an appreciable admixture of $\pi$-mesons.

The next row lists the slow protons, i.e., tracks satisfying criteria 1, 3, 4 and having the characteristic appearance (Table II) of a proton slowed down by atomic collisions. It is very unlikely that a slow proton will produce a neutron in the plates, and the seven slow protons observed with $(AB{:}N)$ triggering result no doubt from nuclear interactions in the paraffin and metal just above the chamber. Four of the seven are accompanied. The approximate equality of the numbers stopping in the C and Pb plates confirms, within the very poor statistics, the equality of the stopping powers. The number of protons observed gives some indication of the number of $\pi$-meson stoppings to be expected, as both the protons and $\pi$-mesons result from nuclear interactions just above the chamber. The results obtained at Bristol[21] indicate that for ranges of the order of magnitude involved here ($\sim$30 g $\text{cm}^{-2}$ air) the number of $\pi$-mesons is about 0.1 of the number of protons. Neutron production on capture in Pb will at most double the yield of pictures of $\pi$-meson stoppings, so that, again, we conclude that the $\pi$-meson contribution to our meson-stopping figures is small.

The last row lists the tracks satisfying criteria 1, 3, and 4, but failing to show noticeably increased ionization in the last compartment. These are mainly electrons, also presumably resulting from interactions above the chamber.

None of the meson stoppings seen with $(AB{:}N)$ triggering shows a decay electron. The plate thicknesses are fairly small compared with the mean range of a decay electron, and, in fact, the $(AB)$ pictures show 4 observed decay electrons in 13 meson stoppings. The absence of decay electrons in the $(AB{:}N)$ pictures confirms, within rather poor statistics, that the stopped mesons that produce neutrons are negative.

TABLE III. Particles stopping in the five Pb and five C plates.

| | $(AB{:}N)$ trigger (1207 pictures) | | $(AB)$ trigger (1283 pictures) | | | |
|---|---|---|---|---|---|---|
| | | | Stoppings in Pb | | Stoppings in C | |
| | Stoppings in Pb | Stoppings in C | without decay electron | with decay electron | without decay electron | with decay electron |
| *$\mu$-mesons* | | | | | | |
| definite | 14 | 0 | 1 | 0 | 2 | 0 |
| probable | 5 | 1 | 1 | 0 | 1 | 0 |
| doubtful | 8 | 3 | 0 | 2 | 0 | 0 |
| *Accompanied mesons* | | | | | | |
| definite plus probable | 18 | 7 | 2 | 0 | 2 | 2 |
| *Protons* | 4 | 3 | 0 | | 1 | |
| *Electrons* | 3 | 3 | 0 | | 0 | |

[21] Camerini, Fowler, Lock, and Muirhead, Phil. Mag. **41**, 413 (1950).

TABLE IV. Types of pictures obtained, other than stoppings (for which see Table III). The yields with neutron triggering, $(AB{:}N)$ have been corrected for casuals, as explained in the text, when the correction amounted to more than 10 percent. Corrected values are noted by an asterisk. Numbers in parentheses are those of recognized slow mesons coming from interactions in the chamber.

| | $(AB{:}N)$ (1066* pictures) | | $(AB)$ (1283 pictures) | |
|---|---|---|---|---|
| 1. Low energy events | 333* | | 432 | |
| 2. Electromagnetic-cascades | | | | |
| small | | | | |
| originating in chamber | 32 | | 16 | |
| originating above chamber | 56 | | 30 | |
| medium | 143 | | 28 | |
| large | 100 | | 8 | |
| 3. Energetic nuclear interactions | | | | |
| A. Penetrating showers | | | | |
| originating in chamber | | | | |
| with heavy prongs | 12 | | 1 | |
| without heavy prongs | 4 | | 0 | |
| originating above chamber | | | | |
| with stars in chamber | 10(2) | | 0 | |
| without stars in chamber | 21 | | 6 | |
| B. Mixed showers | | | | |
| originating in chamber | 1(1) | | 0 | |
| originating above chamber | | | | |
| with stars or penetrating showers starting in chamber | 12(1) | | 0 | |
| without stars or penetrating showers starting in chamber | 33 | | 1 | |
| C. Stars | Pb | C | Pb | C |
| with ionizing primary | 74(10) | 12(3) | 2(1) | 0 |
| non-ionizing primary | 14(2) | 4(1) | 5 | 2 |
| D. Nuclear cascades | 14 | | 2 | |
| 4. Penetrating particles | | | | |
| unaccompanied | | | | |
| undeflected | 30* | | 365 | |
| scattered | 27* | | 52 | |
| | Pb | C | Pb | C |
| large-angle scatter | 6 | 4 | 1 | 0 |
| accompanied | 33* | | 227 | |

## V. THE NATURE AND RELATIVE FREQUENCIES OF THE PROCESSES GIVING NEUTRON COINCIDENCES

As was expected, the pictures showed that many other processes besides $\mu$-meson capture give rise to $(AB{:}N)$ coincidences. Thus, the total of definite and probable unaccompanied meson stoppings (20) is only about 2 percent of 1066 genuine $(AB{:}N)$ pictures. (Caution needs to be exercised in carrying this proportion over to counter experiments on neutron coincidences because of the large effect of scattering on the cloud-chamber results. More important, the present cloud-chamber study shows an appreciable contribution to the $(AB{:}N)$ rate by very absorbable showers, so that the fractional contribution of $\mu$-meson capture to the total rate will be very dependent upon absorber and filter thicknesses. There was but little filtering of the atmospheric soft component in the present experiment.)

Table IV shows the number of pictures corresponding to each category chosen for the analysis, other than stopping particles, which have already been enumerated in Table III. The two major columns correspond, respectively, to $(AB{:}N)$ and $(AB)$ triggering. The entries in the $(AB{:}N)$ column are corrected for accidental coincidences by means of the observed $(AB)$ frequencies. For example, 365 of the 1283 $(AB)$ pictures show undeflected unaccompanied penetrating particles, so that this fraction of the 141 accidental $(AB:N)$ pictures, or 40, are of this type. For the corresponding category under $(AB:N)$ the observed 70 cases have been diminished by 40, leaving approximately 30 cases really associated with neutron production. This correction has only been made where it amounts to more than 10 percent of the observed number of $(AB:N)$ pictures. An asterisk indicates a corrected yield.

In comparing the yields of various types of pictures with $(AB)$ and $(AB:N)$ triggering, one must bear in mind that the rate at which $(AB)$ expansions were made ($0.25\ \text{min}^{-1}$, as determined by the resetting time) was six times the rate at which $(AB:N)$ expansions were made ($2.5\ \text{hr}^{-1}$). If the resetting time had been shorter, the $(AB)$ rate of photography would have been even greater. Only those categories for which the $(AB:N)$ fractional yield was more than six times the $(AB)$ fractional yield were actually photographed more frequently by the use of neutron coincidence triggering. These categories are: $\mu$-meson stoppings in Pb (Table III), proton stoppings (Table III), large electromagnetic cascades (defined below), and energetic nuclear interactions (defined below).

The categories used in Table IV are mutually exclusive. The *low energy events* comprise technically acceptable pictures with no telescope track penetrating the top plate and no tracks further down in the chamber indicative of cascade development or nuclear interaction. Most of these pictures probably represent electron-photon cascades of low energy.

The next category is *electromagnetic cascades*—electron-photon showers in which no particles other than electrons can be identified. Some heavier particles may of course be present, especially in the large showers. The showers are sorted according to the largest size they attain in the chamber. The maximum development of the shower does not, of course, necessarily occur in the chamber. The showers are called small if they show 3 to 6 tracks, medium if they show 7 to 19, and large if they show 20 or more. These sizes, when they are shower maxima, correspond to energies of the initiating electron of approximately 250–600, 600–1900, and more than 1900 Mev.[22] The result for small showers agrees with R. R. Wilson's "Monte Carlo" calculations [Phys. Rev. **86**, 261 (1952)].

The *energetic nuclear interactions* are divided into a number of mutually exclusive categories. For defining *penetrating showers*, a particle is classed as penetrating if it goes through at least two Pb plates (each of 0.9 radiation length) without multiplying. A penetrating shower is then defined as an event with at least two related penetrating particles, either originating at a common point in the chamber or appearing to diverge from a small region above the chamber. A *mixed shower* is defined as one showing both penetrating particles and electronic cascades. According to present views, it is merely a penetrating shower in which photons resulting from $\pi^0 \rightarrow 2\gamma$ decay initiate showers. *Stars* are events in which at least three tracks meet at a point and at least one of them is heavily ionizing. Any stars in which two or more penetrating particles are produced are, however, listed instead as penetrating showers. The stars are divided into those initiated by charged particles and those initiated by neutral ones. *Nuclear cascades* are events in which two or more recognizable nuclear interactions (giving rise to stars, penetrating or mixed showers, or large deflections) occur in the chamber. We limit ourselves here to cascades starting in the chamber by requiring one and only one primary. Where there is no ionizing-link, the second interaction could, however, be due to an accompanying neutral particle.

It was sometimes possible to identify mesons (mass $200\text{–}300m_e$) among the particles coming from interactions, by the characteristic change of ionization with range. These identified slow mesons are noted in parentheses.

*Penetrating particles* are events in which one particle goes through *all* the plates without producing a charged secondary other than a knock-on electron. The few cases showing two or even three penetrating particles are not tabulated—their frequency is negligible in the $(AB:N)$ series and only about 6 percent (double: single) in the $(AB)$ run. The penetrating particles are divided into those with or without accompanying tracks elsewhere in the chamber. A rough classification of the unaccompanied tracks according to scattering is also made; in this the first Pb plate is not counted because of the distortion in the top compartment. If there is no projected deflection greater than 2° in any of the other plates, the particle is classed as undeflected. If there is only one deflection greater than 2° and it is greater than 10°, the particle is classed as single-scattered. Otherwise it is listed as scattered.

We discuss now some of the conspicuous features of Table IV.

### (a) Electromagnetic Cascades

The large number (331) of electron-photon showers in which there is no indication of heavier particles is striking. Furthermore, most of the 333 low energy events are low energy showers of this type, so that roughly half of the $(AB:N)$ events are simply electronic showers. In the large cascades penetrating particles would, of course, be hidden, and nuclear interactions would usually not be noticed, but this is not the case for the more numerous low energy showers. Tongiorgi has previously demonstrated neutron production in Pb by extensive showers, and has concluded[23] from her counter experiments that mesons and nucleons are the particles responsible. Our pictures show, on the other hand, that

[22] B. Rossi, *High-Energy Particles* (Prentice-Hall, Inc., New York, 1952), Fig. 5.22.2, after Belenky.

[23] V. C. Tongiorgi, Phys. Rev. **74**, 226 (1948).

in low energy electromagnetic cascades in Pb there is appreciable neutron production, without benefit of mesons and nucleons.

Rough values of the neutron multiplicities can be found by comparing the yields of corresponding types of pictures with $(AB:N)$ and $(AB)$ triggering. Thus, for small showers originating in the chamber the yields are, respectively, 32 and 16. It follows that (16/1283) of the $(AB)$ events were of this type. In the $(AB:N)$ sensitive time there were $5.36\times10^5$ $(AB)$ events, giving $6.7\times10^3$ showers of the type considered. With a neutron detecting efficiency of $1.2\times10^{-2}$ and a mean neutron multiplicity $\bar{m}$, we have

$$32=\bar{m}\times1.2\times10^{-2}\times6.7\times10^3$$

or $\bar{m}=0.4$. Similarly, the average numbers of neutrons per "medium" and "large" shower are 1.0 and 2.5, respectively. The smallness of these figures fits in with the cloud-chamber observation[24] that electronic showers are effectively eliminated by requiring more than one detected neutron in a neutron coincidence arrangement.

The most likely mechanism for the neutron production in electronic showers is the "giant resonance" photonuclear reaction in Pb at 15 Mev.

We calculate the expected yield of neutrons. It is given, aside from trivial factors, by the product of the integrated (cross section times average neutron multiplicity) and the track length of 15-Mev photons in the 35 g $cm^{-2}$ of Pb in the chamber. The former is[25] about 5 Mev$\times10^{-24}$ $cm^2$. Approximate formulas are available[22] for the track length in an entire shower. The error involved in applying them to our finite Pb thickness is least for small showers originating in the chamber. We limit our consideration to this type of event. Using the "corrected approximation $B$" expression [reference 22, Eq. (5.19.9)], we find that the average multiplicity of disintegration neutrons in a shower initiated by an electron of energy $E_0$ Mev is $4\times10^{-4}E_0$. With an inverse-square differential energy spectrum ranging from 250 to 600 Mev, the average value of $E_0$ is 380 Mev, giving $\bar{m}=0.15$. The discrepancy with the quasi-experimental value, $\bar{m}=0.4$, may not be significant—neutron production in the material above the chamber makes the latter figure too high, and the fact that the photon energy is only twice the critical makes the track length formula quite uncertain. In fact, the agreement in order of magnitude is impressive.

### (b) Energetic Nuclear Interactions

Approximately 20 percent of the $(AB:N)$ pictures show energetic nuclear interactions. The qualification as energetic is relative—very few of the events photographed involve energy transfers of more than 1 Bev—and merely distinguishes the interactions from those involving energies of the order of magnitude of nuclear level spacings.

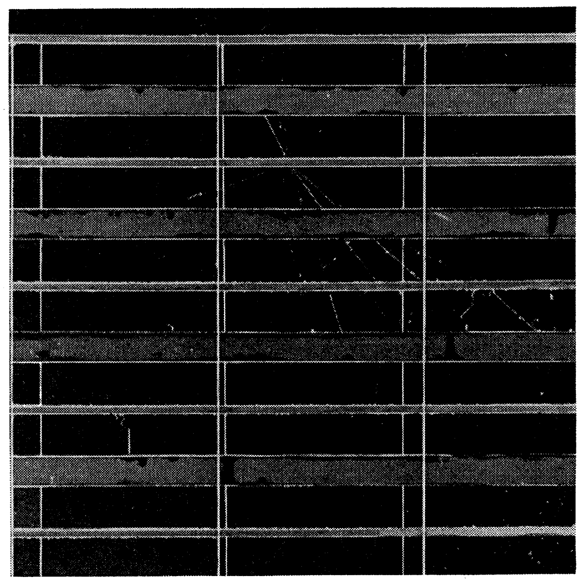


FIG. 4. Event 1131, neutron coincidence, showing an ionizing-produced star in the second Pb plate, with production of two mesons that stop in the third C plate. The primary, a minimum-ionization telescope particle, is faint in the print (right view).

About 10 percent of the interactions—thus 2 percent of the $(AB:N)$ pictures—show recognizable slow mesons emerging. Figure 4 is a case in which two slow mesons can be identified, penetrating two plates and stopping in the third.

There are many more stars in the Pb than in the C plates. The stars with ionizing primaries are most significant in this respect, as those produced by neutral particles are usually associated with neutron-producing interactions elsewhere in the chamber or in the material above it. The observed ratio, 74:12, is $6.2\pm1.9$. The amounts of Pb and C in the chamber (35 and 16 g $cm^{-2}$, respectively) are in the ratio 2.15:1 on a nucleon basis and 0.83:1 on a nuclear area basis. The interaction probability lies no doubt between these limits. The higher Pb:C ratio observed for stars, while it could be a chance fluctuation, is very probably significant. It can be easily explained. In a large nucleus a greater fraction of the nucleon recoil energy goes into thermal excitation. In addition, the high Coulomb barrier in Pb favors neutron evaporation.

### (c) Penetrating Particles

In the $(AB)$ series, the penetrating particles constitute about 50 percent of the events photographed. The overwhelming majority of these particles are undoubtedly $\mu$-mesons. In the $(AB:N)$ run a greatly reduced but still nonvanishing yield of this type of picture is obtained. The total observed is 172; the expected number of accidental pictures of this type is 71, leaving $101\pm13$ genuine $(AB:N)$ events. In these

[24] Barker, Sard, and Sowerby, Phil. Mag. 44, 46 (1953).
[25] K. M. Terwilliger, thesis, University of California (Berkeley), 1952 (unpublished).

events no secondary charged particles other than obvious knock-on electrons are seen to emerge from the plates, and in almost all of them there is no large-angle scattering, yet at least one neutron in the energy range up to about 10 Mev is produced. This observation supports the argument[26] that invisible nuclear interactions in a plate can lead to large apparent mean free paths for nuclear interactions of particles in penetrating showers.

It is now known[5,27] that fast $\mu$-mesons will occasionally produce nuclear disintegrations. The absolute neutron yield from 86 g $cm^{-2}$ Pb, at a depth of 2000 g $cm^{-2}$ of limestone below sea level, has been determined;[5,28] expressed as a cross section times average neutron multiplicity, it is $40\times10^{-29}$ $cm^2$ per nucleon. Let us apply this figure to the fast $\mu$-mesons traversing our chamber, neglecting the change of the meson spectrum with depth and the dependence of multiplicity on thickness of producer. The errors so incurred will tend to make our estimated rate for the cloud chamber too high. The neglect of interactions in the carbon and aluminum causes an error in the other direction, which is, however, negligible (Cocconi and Tongiorgi, reference 27). To make the comparison with the counter experiment more rigorous, we confine our attention to the unaccompanied penetrating particles that do not experience large-angle scattering. Proceeding as in (a), the number of p.p.'s of this type traversing the chamber in the accepted $(AB:N)$ sensitive time is

$$(417/1283)\times5.36\times10^5=1.74\times10^5,$$

so that the expected number of $(AB:N)$ pictures of this type is $1.74\times10^5\times(40\times10^{-29}\times6.02\times10^{23}\times35)\times1.2\times10^{-2}=17$ which is to be compared with the observation of 57.

There is another mechanism which must be considered. There are a few protons in the cosmic radiation at sea level. Their intensity is only about 1 percent of that of the $\mu$-mesons but their interaction cross section in Pb is roughly geometrical, i.e., about $10^{-26}$ $cm^2$ per nucleon.[29]

Following the analysis in Fowler's thesis,[3] we use the Bristol emulsion data[30] to estimate the fraction of proton-produced interactions that would appear as penetrating particles in our experiment. These are "$1p$" stars with no gray or black tracks getting out of the plate. We find that the fraction of ionizing-produced interactions which are of this type is 9 percent, with a mean number of "black" neutrons estimated as 9. The expected number of pictures is therefore

$$17\times0.01\times(9\times10^{-26}/40\times10^{-29})\times0.09=3.4.$$

The Bristol tabulation omits stars with less than three heavy prongs. Making a generous allowance for these on the basis of Page's results,[31] we get a total of 8.1 expected pictures instead of 3.4 (the increase in number of events is partially compensated by the decrease in neutron multiplicity). It appears difficult to explain all of our penetrating particle pictures as $1p$ stars in the lead plates. The $1p$ stars in the C and Al may be neglected in comparison, because of the low neutron multiplicity from light nuclei.

An argument[3] against interpreting the bulk of the pictures as $1p$ events is the absence of noticeable deflection in the plates. In the $1p$ stars (reference 30, Fig. 6), only 14 out of 208 events show projected deflections of less than 10°. Of course the $1p$ events omitted from the Bristol tabulation because of having too few heavy prongs would be expected to show smaller deflections. But their number is far too small to account for all of the $57\pm10$ unaccompanied penetrating particles.* *Note added in proof:*—Another possible mechanism is neutron production by $\mu$-mesons stopped in the paraffin under the chamber. This might account for most of the 27 scattered p.p.'s but could not account for the 30 undeflected p.p.'s. The conclusion of the next paragraph stands.

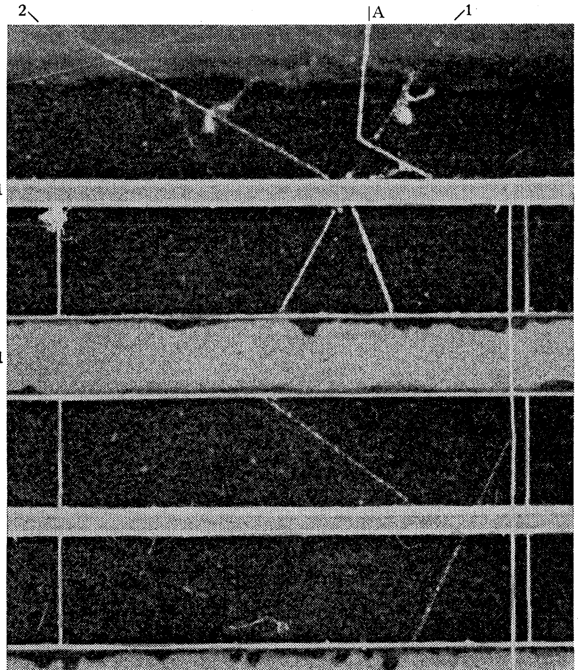



FIG. 5. Event 2903, a $V^0$ decay in the top compartment, the tracks designated by $A$ and $B$. The $V^0$ presumably comes from the star produced by (1) in the first Pb plate. From the same star there issues (3) which meets (3′) in the first C plate; (3) is probably a meson, (3′) its decay electron (center view).

[26] K. H. Barker and C. C. Butler, Proc. Phys. Soc. (London) **A64**, 4 (1951).
[27] E. P. George and J. Evans, Proc. Phys. Soc. (London) **A63**, 1248 (1950); R. D. Sard, Phys. Rev. **80**, 134 (1950); Sard, Crouch, Jones, Conforto, and Stearns, Nuovo cimento **8**, 326 (1951); G. Cocconi and V. C. Tongiorgi, Phys. Rev. **84**, 29 (1951).
[28] H. C. Wilkins, thesis, Washington University (St. Louis), June, 1952 (unpublished).
[29] M. G. Mylroi and J. G. Wilson, Proc. Phys. Soc. (London) **A64**, 404 (1951).
[30] Brown, Camerini, Fowler, Heitler, King, and Powell, Phil. Mag. **40**, 862 (1949).
[31] N. Page, Proc. Phys. Soc. (London) **A63**, 250 (1950).

We conclude that an appreciable fraction of the penetrating particle pictures represent nuclear interactions of fast $\mu$-mesons with small energy transfer, the yield being compatible with the underground counter measurements.[5,28]

W. B. Fowler (reference 3, thesis) has found a significant number of pictures of the same type in his $(AB:N)$ series with a multiple-plate chamber at mountain altitude. His analysis indicates that both of the mechanisms considered above need to be invoked, in addition, perhaps, to others.

### VI. *V* PARTICLES

In the 1207 $(AB:N)$ pictures, there has been found one probable $V^0$ decay.[32] It is shown in Fig. 5. Table V gives the relevant information. The ionization was estimated by comparison with identified stopping mesons and protons on the same roll of film. The angles and ranges were calculated from the side view and one of the center views. The most likely interpretation of this picture is that a fast particle, (1), interacts with a nucleus of Pb-1, producing a star. The visible products of the star are (2), of ionization 3–5$\times$minimum, (3) of ionization 4–6$\times$minimum, and (4) of ionization at least 6$\times$minimum. A neutral $V$ particle is also produced, moving upward with small velocity. After going about 1.1 cm it decays into $(A)$ and $(B)$; the plane of $(A)$ and $(B)$ passes near the star. $(B)$ stops in Pb-1 (27.4 g cm$^{-2}$ slant thickness). It is foreshortened in the view shown, and appears more heavily ionizing than when seen stereoscopically. According to the present interpretation, this picture shows the birth and death of a $V^0$ of unusually low energy, both decay particles being heavily ionizing.

Alternative interpretations need to be considered. One possibility is that (1) happens to have associated with it a particle $(A)$ that is scattered through 52° in a collision with a gas nucleus. The estimated limits on the ionization of $(A)$ permit us to set limits on the recoil energy of an argon nucleus so struck (for C, H, or O the recoil energy is greater in inverse proportion to the mass). If $(A)$ is a proton, the recoil energy is at least 1 Mev, and a blob would be visible. If $(A)$ is a $\pi$-meson, however, the recoil energy could be as low as 20 kev, which might not give a visible blob. This possibility cannot be ruled out, but it is, of course, very unlikely that (1) be accompanied by a slow meson which undergoes Rutherford scattering through 52° in the gas.

Another possibility is that (1) is accompanied by a $\pi$-meson $(A)$ which decays in flight into a $\mu$-meson $(B)$. The relativistic dynamics of this two-body decay rules out a deviation as large as 52° unless $\beta_A < 0.34$, corresponding to an ionization greater than 5.4$\times$minimum. From the structure visible in the track it is unlikely that the ionization is this high, but again the possibility cannot be completely ruled out.

[32] E. J. Althaus, Phys. Rev. **83**, 896 (1951). The charged $V$ decay also reported in this abstract appears doubtful on re-examination.

TABLE V. Information about the $V^0$ decay found in the $(AB:N)$ events. Tracks labeled as in Fig. 5. $\theta$ is the smallest angle between the branches of the fork.

| Particle | $\theta$ | Branch | Estimated ion density | Path length g cm$^{-2}$ Pb |
|---|---|---|---|---|
| $V^0$ (Fig. 5) | 128° | $A$ | 4–6$\times$minimum | — |
| | | $B$ | 3–5$\times$minimum | 0–27.4 |

It is impossible that a $\mu\rightarrow e$ decay is involved, as an electron would be strongly scattered in the gas before reaching the ionization density of track $(B)$ or $(A)$. The $\delta$-ray on $(B)$ provides additional evidence. It is 9 mm long, corresponding[33] to a 35-kev electron. The ionization limits on $(B)$ given in Table V correspond to maximum knock-on energies ranging from 150 to 320 kev, so the $\delta$-ray must have come off at an angle near 90°. As $(B)$ is not noticeably deflected, its mass must be at least several electron masses.

A fourth possibility considered is that a neutral particle from the star in Pb-1 produces a two-prong star in the gas. The absence of a blob argues against this. As a star of this type would not be seen if it occurred in a plate, we have no experimental basis for calculating its probability of occurrence in the gas. But making generous assumptions about the number of upward neutrons (5) and their interaction cross section (one-half geometric), we find that the probability of an interaction in the gas, given the star in Pb-1, is $3\times10^{-4}$. This is smaller than the yield of $V^0$'s is expected to be, but, again, this alternative explanation cannot be definitely excluded.

Assuming that the interpretation as a $V^0$ is correct, we can set limits on its mass by using our ionization estimates and the measured angular opening. For a decay into two particles,

$$M^2 = m_A^2 + m_B^2 - 2p_Ap_B[\cos\theta - \{1+(m_A/p_A)^2\}^{\frac{1}{2}}\{1+(m_B/p_B)^2\}^{\frac{1}{2}}].$$

The ionization determines $(m/p)$ and $\theta$ is known. Hence we can directly set limits on the value of the expression in brackets; these are 5.5 and 9.8. Assuming that one of the particles is a proton and the other a $\pi$-meson ($V_1^0$ scheme[34]) we find that our ionization estimates require $Q$ to be in the range 30–55 Mev. This result is in excellent agreement with more precise measurements,[35] and confirms the consistency of our interpretation. If we assume both particles to be $\pi$-mesons, $Q$ ranges between 10 and 30 Mev, which is considerably lower than the best values for the $V_2^0$ scheme.[34,35]

Track (3) stops in the first carbon plate, and the thin track (3′) which emerges underneath projects back to

[33] Rutherford, Chadwick, and Ellis, *Radiations from Radioactive Substances* (Cambridge University Press, Cambridge, 1930), p. 443.

[34] Armenteros, Barker, Butler, Cachon, and Chapman, Nature **167**, 501 (1951); Armenteros, Barker, Butler, and Cachon, Phil. Mag. **42**, 1113 (1951).

[35] K. H. Barker (private communication); Thompson, Rossi, and Leighton at Rochester conference, December, 1952 (unpublished).

the extended path of (3). Apparently (3) is a slow meson which gives rise to the decay electron (3′). The latter goes out of the illuminated region.

It is remarkable that in one relatively low energy interaction (classified as a star) there are produced both a slow $V^0$ and a slow $\pi^+$-particle.

It is a pleasure to acknowledge the continued encouragement of Professor A. L. Hughes during the construction of the apparatus. We wish to thank Mr. O. Retzloff for his invaluable assistance in the design and his excellent direction of the construction of the cloud chamber, Mr. J. D. Miller for assistance in the design and construction of some of the sequencing circuits, Mr. Jen Pu Cheng for his work in constructing most of the Geiger counters, and Mr. N. Harmon for the measurement of the neutron-detecting efficiency.

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# The Production of Mesons above 10 Bev

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12 000 local penetrating showers from carbon and paraffin have been compared using a 31-channel hodoscope in order to study nucleon-hydrogen collisions above 10 Bev. The average multiplicity of penetrating charged particles from the detected showers from carbon is found to be $4.42\pm0.20$ and the multiplicity from hydrogen considerably less. An upper limit of 2.4 is given. It is concluded that the multiple production of mesons is infrequent at this energy.

## I. INTRODUCTION

It is well known that when a nucleus is struck by a high energy nucleon one or more mesons are often produced. Several theories have been proposed to account for their production.[1–5] Since their predictions differ considerably, it is of obvious importance to decide between them. However, these theories deal in the first place with the results of a collision of only two nucleons. But from the known collision mean free paths of the particles and the density of matter within the nucleus, it seems likely that there will be more than one interaction generally when a complex nucleus is struck. This view is supported by considerable experimental evidence.[6–8] Thus the results of a collision between a nucleon and a compound nucleus (which is easy to observe) is complicated by cascading and, as yet, no theory of the cascade within a nucleus has been demonstrated to be correct for the energies with which we are concerned. There is thus an obvious incentive for trying to observe the collisions of energetic nucleons with hydrogen. A number of experiments have been made with this object.[9–12] The experimental difficulties are considerable.

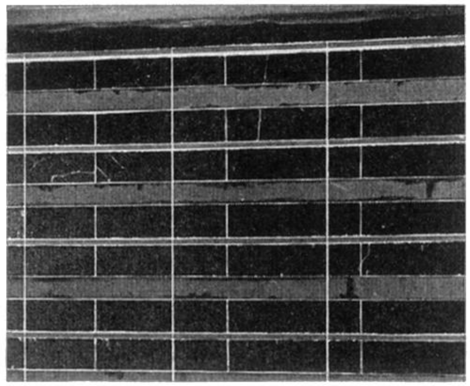
In the present experiment the method used was to observe, with a hodoscoped G-M counter system, the local penetrating showers from a thin layer of paraffin and later from a layer of carbon equivalent to that in the paraffin. Thus the method is similar to the well-known subtraction technique often used in the study of the low energy interactions of particles from accelerators. In our experiment the average primary energy was about 30 Bev.[13]

## II. EXPERIMENTAL ARRANGEMENT

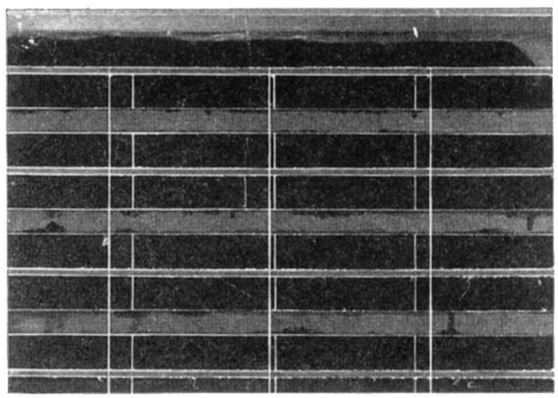
A sketch of the apparatus which was operated at sea level is given in Fig. 1. There were five trays of G-M counters, $A$, $B$, $C$, $D$, and $E$. Each of these trays contained 12 counters. All the counters were 50 cm long and 3.8 cm in diameter. The counters of trays $A$ and $B$ were in contact, and those of tray $A$ had their axes at 90° to those of tray $B$. Tray $C$ was separated from tray $B$ by 60 cm of carbon and 7.5 cm of lead and there was a further 5 cm of lead between trays $C$ and $D$. These last two trays were shielded at their sides and ends by 15 cm of Pb. Each of the counters in trays $A$ and $B$ could operate a neon lamp.

The condition for a master pulse was the discharge of at least two counters in each of trays $B$, $C$, and $D$.

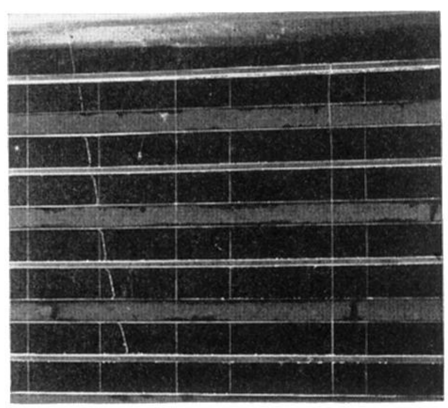
[1] E. Fermi, Progr. Theoret. Phys. (Japan) **5**, 570 (1951); Phys. Rev. **81**, 863 (1951).
[2] W. Heisenberg, Z. Physik **133**, 65 (1952); Nature **164**, 65 (1949).
[3] Lewis, Oppenheimer, and Wouthuysen, Phys. Rev. **73**, 127 (1948).
[4] W. Heitler, Revs. Modern Phys. **21**, 113 (1949).
[5] J. McConnell, Proc. Roy. Irish Acad. **A55**, 101 (1951).
[6] Salant, Hornbostel, Fisk, and Smith, Phys. Rev. **79**, 184 (1950).
[7] Lovati, Mura, Salvini, and Tagliaferri, Nuovo cimento **VII**, 943 (1950).
[8] Camerini, Davies, Fowler, Franzinetti, Muirhead, Lock, Perkins, and Yekutieli, Phil. Mag. **42**, 1241 (1951).
[9] M. L. Vidale and M. Schein, Nuovo cimento **VIII**, 774 (1951).
[10] Weaver, Long, and Schein, Phys. Rev. **87**, 531 (1952).
[11] Walker, Duller, and Sorrels, Phys. Rev. **86**, 865 (1952).
[12] G. W. Rollosson, Phys. Rev. **87**, 71 (1952).
[13] McCusker, Messel, Millar, and Porter, Phys. Rev. **89**, 1172 (1953).



(a)



(b)



(c)

FIG. 3. (a) Event 1811, triggered by neutron coincidence. A $\mu$-meson stopping in the second Pb plate (right side view). (b) Event 2344, triggered by G-M counters alone. A $\mu$-meson stopping in the second C plate emits a decay electron that goes out to the right. Presence of other contemporary tracks in the top compartment renders it "accompanied" (a center view). (c) Event 2049, triggered by neutron coincidence. A proton stopping in the fourth Pb plate (right side view).

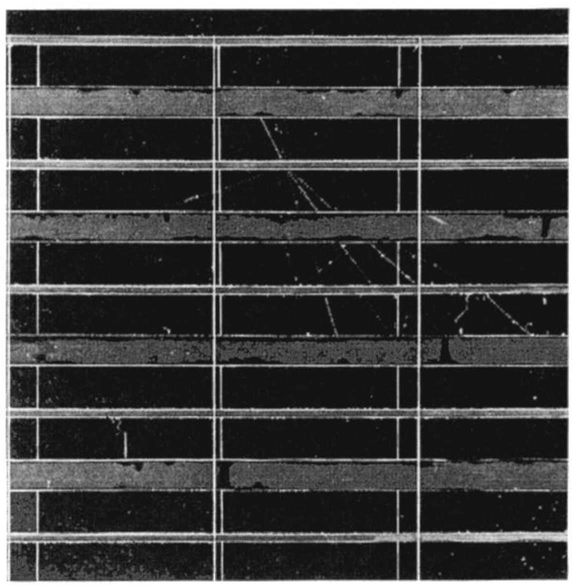


FIG. 4. Event 1131, neutron coincidence, showing an ionizing-produced star in the second Pb plate, with production of two mesons that stop in the third C plate. The primary, a minimum-ionization telescope particle, is faint in the print (right view).

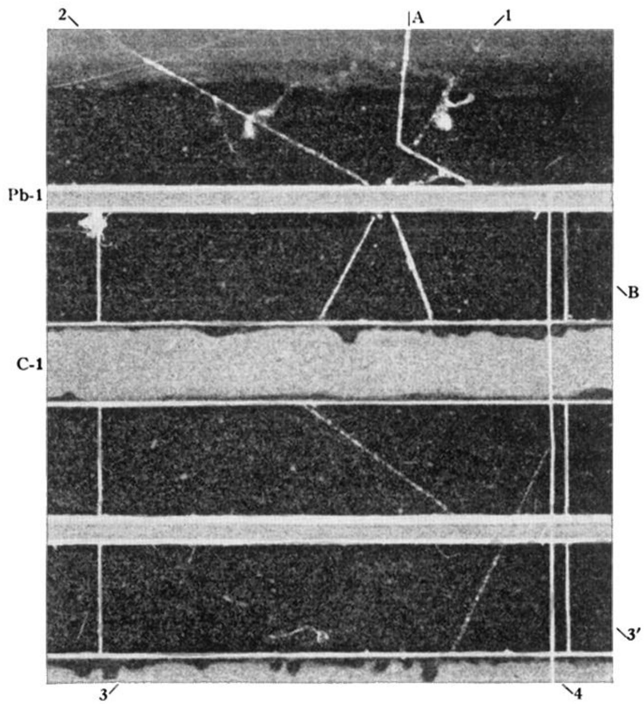



FIG. 5. Event 2903, a $V^0$ decay in the top compartment, the tracks designated by $A$ and $B$. The $V^0$ presumably comes from the star produced by (1) in the first Pb plate. From the same star there issues (3) which meets (3′) in the first C plate; (3) is probably a meson, (3′) its decay electron (center view).