Neutron Production by μ Mesons Which Penetrate Lead*†

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The mean product of cross section and multiplicity ($\langle\sigma m\rangle$) for evaporation neutrons produced when fast cosmic-ray μ mesons traverse a Pb producer has been measured. A magnet cloud chamber above the producer and a hodoscope-absorber array below it serve to identify μ mesons; neutron-producing events are selected by the detection of a delayed coincidence of a thermalized neutron with a penetrating particle. $\langle\sigma m\rangle=(22\pm8)\times10^{-29}$ cm^2/nucleon. Theoretical calculations based on experimental photoneutron yields give $\langle\sigma m\rangle=15\times10^{-29}$ cm^2/nucleon for the yield due to knock-on showers, and $\langle\sigma m\rangle=9\times10^{-29}$ cm^2/nucleon for the direct yield from equivalent photons of the μ-meson field. This theory also agrees with the results of underground measurements at higher average momenta. There is no evidence of μ-meson scattering in excess of Coulomb scattering. Protons which suffer nuclear interactions produce more than 50 neutrons, but seldom produce penetrating secondaries.

INTRODUCTION

THE reported cross sections for the interaction of fast μ mesons with nuclei vary considerably, depending on the method of detection used.[1] Two types of experiments have been performed in which low-energy secondary particles are detected. George and Evans[2] and Kaneko *et al.*[3] have observed stars produced by fast particles passing through photographic emulsions exposed underground. George and Evans, who counted only stars with at least three heavy prongs, reported $\sigma=(4.6\pm0.5)\times10^{-30}$ cm^2/nucleon and a mean heavy-prong multiplicity of 6. Kaneko *et al.* found that inclusion of stars with 1 and 2 heavy prongs would raise the cross section to about 7×10^{-30} cm^2/nucleon. On the other hand, the Washington University group[4] and Cocconi and Tongiorgi[5] detected neutrons produced by fast μ mesons in subterranean sites. The work of Annis, Wilkins, and Miller[4] yields only the mean product of cross section and multiplicity, $\langle\sigma m\rangle$; $\langle\sigma m\rangle=(40.3\pm2.1)\times10^{-29}$ cm^2/nucleon for Pb, in essential agreement with the results of Cocconi and Tongiorgi (if their rough corrections for shower processes and nucleonic events in the surrounding water are omitted). For Fe, AWM found $\langle\sigma m\rangle=(16.2\pm0.2)\times10^{-29}$ cm^2/nucleon. In comparison, the mean product of cross section and multiplicity for protons emitted in George's work is 2.8×10^{-29} cm^2/nucleon. The inclusion of one- and two-prong events could not raise this appreciably, because of their low multiplicity.

The identification of μ mesons in these experiments has depended on the fact that more strongly interacting particles should not penetrate to the depths used. George and Cocconi showed that the interaction rates there decreased with depth with a mean length (distance for decrease by factor e) of ~4000 g cm^{-2}. A more direct identification of the incident particles is desirable, in view of the differing results obtained. More detailed information on the characteristics of the nuclear interactions would also be valuable.

EXPERIMENTAL PROCEDURE

In the present work, which was performed at sea level, the momenta and signs of particles entering a lead producer were measured using a cloud chamber in a mean magnetic field of 8.5 kilogauss. The experimental arrangement is shown in Fig. 1. Paraffin neutron moderators and $B^{10}F_3$ neutron proportional counters[6] were placed as close as possible to the producer. Below the lead producer were placed three layers of absorber and four trays of Geiger tubes. These tubes labeled H_2 through H_5 in Fig. 1 and the counters in tray H_1 were individually connected to hodoscope indicating units. Shield counters S_1, S_2, and S_3 were placed at the sides of the absorber, and each group of shield counters was connected to a hodoscope unit. The materials and thicknesses of the two producers and three absorbers, the cumulative equivalent Pb thickness, and the momenta necessary for μ mesons and protons to penetrate to this depth are given in Table I.

A Pb filter of 118 g cm^{-2} was placed between the A' and A Geiger trays above the chamber to reduce the

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1 A review of much of the work is given by E. Amaldi, Suppl. Nuovo cimento **11**, 406 (1954).

2 E. P. George and J. Evans, Proc. Phys. Soc. (London) **A63**, 1248 (1950); E. P. George and J. Evans, Proc. Phys. Soc. (London) **A64**, 193 (1951); E. P. George, *Progress in Cosmic Ray Physics*, edited by J. G. Wilson (Interscience Publishers, Inc., New York, 1952), Vol. I, p. 424; E. P. George and J. Evans, Proc. Phys. Soc. (London) **A68**, 829 (1955).

3 Kaneko, Kubozoe, Okazaki, and Takahata, J. Phys. Soc. Japan **10**, 600 (1955).

4 R. D. Sard, Phys. Rev. **80**, 134(A) (1950); Sard, Crouch, Jones, Conforto, and Stearns, Nuovo cimento **3**, 326 (1951); M. F. Crouch and R. D. Sard, Phys. Rev. **85**, 120 (1952); H. C. Wilkins, thesis, Washington University, September, 1952 (unpublished); Annis, Wilkins, and Miller, Phys. Rev. **94**, 1038 (1954), hereafter referred to as AWM.

5 G. Cocconi and V. C. Tongiorgi, Phys. Rev. **84**, 28 (1951).

6 Made by N. Wood Counter Laboratory, Chicago, Illinois. The enriched $B^{10}F_3$ was provided by the Isotopes Division of the U. S. Atomic Energy Commission.

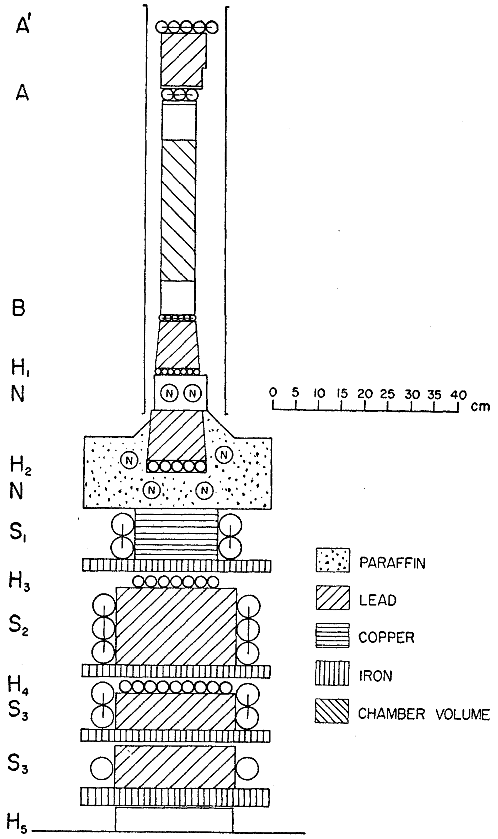

FIG. 1. Schematic diagram of the apparatus. This is a section in the vertical plane containing the axis of the cloud chamber and magnet.

counting rate due to electron showers, and a third tray, B, was placed just below the chamber. The cloud chamber was expanded and the chamber and hodoscope photographed when a coincidence of the A', A, and B trays ("AB" event) was followed by the detection of a thermalized neutron within 255 μsec. This sequence defines an "AB:N" event.

The hodoscope furnished information on the range of the primary particle after it traversed the producer, the occurrence of any large angle scattering, and the production of any penetrating charged secondaries. Because of the delay in detecting thermalized neutrons, each hodoscope unit had to store the information as to whether its Geiger tube fired in coincidence with the AB event until the presence or absence of a neutron count within the 255-μsec gate was determined. The storage unit in each unit was a standard scaler flip-flop; its state was indicated by a neon bulb in the plate circuit of the normally nonconducting triode. Each flip-flop was triggered by the output of a pentode which determined coincidences of the AB master pulse with the individual Geiger tube of the unit. If no neutron was detected within the 255-μsec gate, the master circuit reset all the flip-flops electronically. If a neutron was detected, the reset pulse was delayed until a single-frame 16-mm camera photographed the bulbs.

With the apparatus described, it is possible to separate unaccompanied μ mesons which produce neutrons and penetrate the entire absorber from other cosmic-ray processes which may produce neutrons. The contribution due to protons which penetrate the absorber can be shown to be negligible by the following considerations. Mylroi and Wilson[7] have shown that protons of momenta greater than 2 Bev/c constitute less than 0.5% of the ionizing radiation in this momentum range, that protons have an absorption length of 160 ± 40 g cm^{-2} Pb, and that penetrating secondaries are seldom produced in the nuclear stoppings. From these considerations, the *a priori* probability that a penetrating particle is a proton is 5×10^{-5}. The detection of a neutron resulting from a nuclear interaction further makes it practically certain that the penetrating particle is not a proton, as a proton would have been stopped in the interaction. The likelihood that a penetrating particle is a π meson is even smaller. The natural flux of π mesons at sea level is negligible. Unaccompanied π mesons could be produced only by protons interacting in the filter above the chamber, as neutron primaries would not fire the A' tray. Since protons rarely produce penetrating secondaries when they do interact, and the probability that a π meson would traverse the entire absorber without a nuclear stopping is small, it is clear that the number of penetrating π mesons must be even smaller than the number of penetrating protons. These conclusions are confirmed by the fact that equal numbers of positive and negative penetrating particles were found among the AB:N events, indicating a negligible proton contribution. Many high-momentum positive particles were seen to stop in the producing layers, far short of their ionization range; these were presumably protons which suffered catastrophic interactions in the producer.

In order to evaluate the mean product of cross section and multiplicity, it is necessary to know, in addition to data on the producer, the rate of μ-meson traversals of the entire producer and the efficiency for

TABLE I. Makeup of producer and absorber structure.

Block	Materials and thickness (g cm^{-2})	Equivalent cumulative Pb thickness (g cm^{-2})	Momentum for penetration (Bev/c) μ	Proton
1	Pb 115	115	0.245	0.820
2	Pb 123	238	0.385	1.08
3	Cu 85 Fe 20	369	0.538	1.30
4	Pb 190 Fe 20	584	0.785	1.63
5	Pb 198 Fe 60	857	1.12	1.95

[7] M. G. Mylroi and J. G. Wilson, Proc. Phys. Soc. (London) A64, 404 (1951).

detection of coincident neutrons. The latter was measured by using a 70-microcurie Ra-α-Be source which has been standardized indirectly against Argonne National Laboratory's "Source No. 38." It was assumed that no serious systematic error is caused by the difference in energy between the source neutrons and those produced by fast μ mesons. An average rate for the source in various positions in the producer was used. The correction to the random efficiency for the finite gate length T is $1-\exp(-T/\tau)$, where τ is the neutron mean life. The value of τ could only be estimated on the basis of other similar work. The value 1.5×10^{-4} sec was used; the result is quite insensitive to errors in this factor. The neutron counting rate with the source in a standard position was taken each day, and the average efficiency for the whole period normalized to the average standard position rate. The coherent efficiency for the upper producing layer found in this way was 0.74%; for the lower producer it was 1.48%. The efficiency for neutrons produced in the center of the copper absorber layer was found to be 1.06%.

The fraction of the AB rate due to particles which penetrate the whole absorber was determined by taking a group of hodoscope and chamber pictures with only an AB event required. This same group of pictures was used to estimate the inefficiency of the Geiger tube-hodoscope units by noting the number of failures for particles which penetrated the entire absorber. The average inefficiency was found to be $(18\pm2)\%$, despite the fact that the hodoscope units were checked for operation daily. (It has since been found that the inefficiency resulted from fluctuating delays in the lighting-up of the neon bulbs, in conjunction with the short shutter opening time of the Ciné camera used.) The inefficiency does not complicate the analysis of any significant fraction of the pictures.

DATA AND ANALYSIS

489 technically suitable $AB{:}N$ pictures were taken in an aggregate sensitive time of 3.45×10^{4} minutes. 380 satisfactory AB pictures were taken. The equipment was checked daily during the runs, and its functioning monitored by an Esterline-Angus 20-pen operation recorder. The total number of AB and N counts during the $AB{:}N$ run were $(1.432\pm0.04)\times10^{5}$ and $(1.111\pm0.001)\times10^{6}$, respectively.

The cloud chamber and hodoscope films were scanned first with a simple magnifier, and the events cataloged. The correlation of the chamber and hodoscope pictures was checked with the aid of the operation recorder chart, which also indicated proper operation of the apparatus. Most of the unsatisfactory pictures were culled here. All cloud chamber pictures were then viewed by using a twin-lens stereoscopic projector. The sign, approximate curvature, and geometrical position of each unaccompanied track were determined. The image fell on a large scale drawing of the apparatus projected on the midplane of the chamber, so that the

TABLE II. Types of $AB{:}N$ events found.

	No. in 185 events	No. in 304 events	Total
(1) Protons stopping:			
first Pb producer	14	18	32
second Pb producer	11	17	28
(2) μ^- mesons stopping:			
first Pb producer	3	12	15
second Pb producer	7	15	22
(3) Particles penetrating whole absorber without showers:	(−)3	(−)3	(−) 6
	(+)2	(+)4	(+) 6
With shower development in block shown:	Producer 1: 1(−)		
	Producer 2: 2(+, ?)		
	Absorber 1: 1(+)		
(4) Particles penetrating Pb producer but stopping in absorber:	(−)2	(−)7	(−) 9
	(+)6	(+)5	(+)11

position of the track projection could be checked against the hodoscope record. All of the unaccompanied tracks in the AB pictures were compared with calibrated arcs, in order to check the momenta against the particle ranges. The dip angles of the AB tracks were also estimated by measuring the angular deviation between the two overlapping projected images, in order to determine whether the particle paths stayed in the absorber structure.

All of the first 185 $AB{:}N$ pictures which showed a single penetrating particle traversing the chamber were further analyzed for track position and curvature using a microscope comparator. Measurements on ten "no-field" tracks ($B=325$ gauss) at normal magnet power indicate that the maximum detectable momentum was roughly 10 Bev/c for the average conditions of the experiment. Since higher precision was not needed in this experiment, no further studies of the errors were made.

The majority of these 185 $AB{:}N$ pictures showed showers produced in the magnet. Nearly all those in which a single particle traversed the chamber fell in one of three categories. In order of frequency, these were: (1) positive particles with $pc>1$ Bev stopping in the two Pb producers; (2) negative particles stopping in the producing layers due to ionization loss; (3) particles of both signs penetrating the entire absorber. Events in category (1) have been interpreted as nuclear stoppings of protons, as found by Mylroi and Wilson.[7] Those in (2) are clearly μ^- mesons producing neutrons from Pb subsequent to their capture from rest.[8] The events of category (3) are those of particular interest in this work. Consequently, in the last 304 $AB{:}N$ pictures, all of those cases in which a positive or indeterminate particle of high momentum failed to penetrate

[8] For a summary of the literature on this process, see R. D. Sard and M. F. Crouch, *Progress in Cosmic Ray Physics*, edited by J. G. Wilson (Interscience Publishers, Inc., New York, 1954), Vol. II, p. 1.

TABLE III. Fractions (F_n) of particles in the AB group stopping between the tray shown and the succeeding tray. The row marked *Ratio* gives the ratio of particles stopping to those penetrating the whole absorber. The *Ratio (expected)* row gives the ratios calculated from Rossi's range spectra.[a]

Tray	0	1	2	3	4	5
F_n	0.019±0.006	0.018±0.006	0.018±0.006	0.022±0.007	0.051±0.011	0.191±0.023
Ratio	0.100±0.032	0.094±0.032	0.094±0.032	0.12 ±0.040	0.27 ±0.07	
Ratio (expected)	0.074	0.081	0.094	0.12	0.14	

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

the producers were considered to be stopping protons, and no further measurements were made on them. Similarly, negative particles of sufficiently low momentum which stopped in the producer were counted as μ^- mesons. Only single particles which penetrated the two producing layers were analyzed further.

The over-all results of the cataloging of the $AB:N$ pictures are shown in Table II. The fractions of the AB pictures showing particles stopping at the various absorber levels are given in Table III.

EXPERIMENTAL RESULTS

In order to evaluate the experimental results, it is necessary first to consider the effects due to stopping μ^- mesons and protons.

A. Neutrons from Stopped μ^- Mesons

The numbers of neutron detections expected from μ^- mesons stopping in the various absorbers have been calculated. For the neutron multiplicity in Pb we use the value [8] 1.8, derived from measurements using the same neutron source as in this experiment. For the multiplicity from Cu the value 1.3 was assumed as a rough interpolation between Widgoff's[9] values for Al and Sn. The neutron detection efficiencies used for the last two Pb absorbers were based on the efficiency measured for the Cu, reduced according to an inverse square law for the distance to the bottom neutron counters. The total number of μ^--meson stoppings in each layer was taken as the fraction determined from the AB data times the total number of AB counts in the $AB:N$ sensitive time. The expected and measured numbers of events are shown in Table IV. The agreement for the two Pb producers provides a check on the experimental factors used. It would appear that the multiplicity for Cu is smaller than assumed. The eight cases of μ^- mesons stopping in the Cu and first Pb absorbers account for all but one of the nine cases in category 4 of Table II. The ninth particle has momentum of 860 Mev/c, but did not fire either the third or fourth Geiger tray. It is not clear which of several possible interpretations apply to it; it cannot be, however, an event of the type principally under consideration in this work. Thus all but one of the negative particles stopping in the absorber are simply μ^- mesons which produce neutrons when captured by Pb or Cu.

TABLE IV. Expected and measured numbers of neutron detections from stopped μ^- mesons.

Absorber	Expected[a]	Measured[b]
First Pb producer	16 ± 5	15±4
Second Pb producer	30 ±10	22±5
Cu[c] absorber	16 ± 5	5±2
Pb[c] absorber	2.5± 0.8	3±2
Pb[c] absorber	1.8± 0.4	0

[a] Standard errors quoted are those due to the statistical uncertainties introduced from the AB data. These are the major errors.
[b] Standard statistical errors are quoted.
[c] These values are based on the efficiency of detection for neutrons produced in the center of the Cu. Averaging over the Cu volume should reduce them by about 20%.

[9] M. Widgoff, Phys. Rev. **90**, 891 (1953).

B. Neutrons from Catastrophic Stoppings of Protons

The numbers of catastrophic proton stoppings expected can be calculated using the results of Mylroi and Wilson.[7] The number of $AB:N$ events detected is the number of stoppings multiplied by the mean neutron multiplicity $\langle m_p \rangle$ and the neutron detection efficiency ϵ, if $\epsilon\langle m_p \rangle \ll 1$; if this condition is not satisfied, higher moments of the multiplicity enter into the rate. The multiplicity so calculated is (92_{-18}^{+22}) for protons stopping in the top producer and (106_{-32}^{+39}) for stoppings in the second. These apparent multiplicities are so large that the simple expression used no longer holds, and we can only conclude that they are lower limits on $\langle m_p \rangle$ (e.g., for a Poissonian distribution, $\langle m_p \rangle \approx 180$). On the other hand, our solid angle definition is not precise for particles stopping in the producers, and it may be that the number of catastrophic stoppings has been underestimated. It seems clear that the multiplicity is greater than 50. This large value can be ascribed to nucleonic cascades in the thick producers (238 g cm^{-2} or $8\frac{1}{4}$ inch Pb). Cocconi *et al.*[10] have measured the neutron multiplicities for mountain-altitude cosmic-ray interactions in which charged particles were emitted. They found a multiplicity of 50 for a 4.5-inch Pb producer, but only 10 for a 0.25-inch Pb producer, in fair agreement with an estimate of 6 for the multiplicity in single events made by Ortel.[11] In computing the number of stopping protons it was assumed that the interaction and absorption mean lengths are equal in Pb. Of the 28 protons stopping in the second producer, 4 show double discharges in the first counter group,

[10] Cocconi, Tongiorgi, and Widgoff, Phys. Rev. **79**, 768 (1950).
[11] W. C. G. Ortel, Phys. Rev. **93**, 561 (1954).

indicating that the primary interaction probably occurred in the first producer. In addition, 3 cases were found in which a positive particle penetrated the two Pb producers before stopping, but multiple discharges appeared in one of the first two trays. Thus, contrary to the assumption made, some penetrating secondaries are produced. This is further reason to believe that the assumed nuclear cascade takes place, and that the calculated multiplicity refers to a plural process.

The 11 positive particles which penetrate the two Pb producer blocks but do not pass through the whole absorber (category 4 in Table II) are all of high momentum, and are believed to be stopping protons. Three have been dealt with above; of the remainder four stop in the Cu and four in the following Pb block. Two of the latter scatter noticeably, and so may have interacted in the Cu. The expected numbers calculated from the multiplicity deduced above are 4.3 in the Cu and 0.4 in the Pb. These are not inconsistent with the numbers found, so that it appears that all of the positive particles which do not penetrate the whole absorber in $AB:N$ events are protons.

C. Neutrons Produced by Fast μ Mesons

Fifteen cases have been found in which a particle traversed the entire absorber and a neutron was detected in delayed coincidence, including three in which some shower development is shown. Seven of these are positive, seven negative, and one undeterminable; this supports the arguments given earlier that the particles are μ mesons. The AB pictures show that 0.19 ± 0.02 of the AB rate is due to particles penetrating the whole absorber. The expected number of accidental coincidences is then 3.7. The expression for the mean product of cross section and multiplicity per nucleon is

$$\langle\sigma m\rangle=\frac{n}{(AB)fNz\epsilon},$$

where n=number of $AB:N$ events, (AB)=number of AB counts, f=fraction of AB's which penetrate whole absorber, N=Avogadro's number, z=thickness of producer in g cm^{-2}, and ϵ=coherent neutron efficiency. The product $z\epsilon$ is calculated for each of the two Pb producers and they are added. There may also be production in the Cu; it is assumed that $\langle\sigma m\rangle_{\mathrm{Cu}}=\langle\sigma m\rangle_{\mathrm{Fe}}$. AWM[4] found in their underground experiment that $\langle\sigma m\rangle_{\mathrm{Fe}}=0.40\langle\sigma m\rangle_{\mathrm{Pb}}$, so that the thickness used for Cu is reduced by this factor in calculating $z\epsilon_{\mathrm{Cu}}$. 15% of the total production is then due to Cu. The result is

$$\langle\sigma m\rangle=(22\pm8)\times10^{-29}\ \mathrm{cm^2/nucleon}.$$

It is unlikely that any appreciable number of μ mesons scatter out of the absorber in neutron production events, as no cases have been found in which high-momentum negative particles triggered only the first one or two trays. The minimum projected scattering angle, deduced from comparison of the hodoscope and chamber records, has been measured for both the $AB:N$ and a similar sample of AB pictures. The mean angle was 1.3° for the $AB:N$ events and 1.1° for the AB sample; the greatest scattering angle was 5° in each case. It seems unlikely, therefore, that any sizeable proportion of the "anomalous" scattering reported[12] is due to inelastic processes in which neutrons are produced.

COMPARISON WITH THEORY

There are thought to be two ways in which fast μ mesons may cause neutron production in a thick absorber. The first is by the interaction of the electromagnetic field of the μ meson with the Pb nucleus directly. This effect can be calculated by using the Williams-Weizsäcker approximation and the experimental photoneutron yields. The second mode is through real photons produced in showers started by electrons "knocked on" by the incident μ meson. With the thick absorbers used in this experiment, few of the showers would be detectable in the hodoscope. We have calculated the expected $\langle\sigma m\rangle$ for both of these processes, using the photoneutron yields of Jones and Terwilliger.[13] The giant resonance contribution was expressed as $\langle\sigma m\rangle=5.0\times10^{-24}\delta(W-15)$ Mev cm^2/atom, where W is the photon energy. For $20<W<320$ Mev, $\langle\sigma m\rangle$ may be expressed by $\langle\sigma m\rangle=2\times10^{-27}W$ cm^2/atom. For $W>320$ Mev, the assumption was made that $\langle\sigma m\rangle$ remains constant at 6.4×10^{-25} cm^2/atom. The direct-interaction $\langle\sigma m\rangle_\mu$ is calculated by multiplying the above yields by the equivalent photon spectrum of the μ-meson electromagnetic field,[14]

$$n(E_\gamma)dE_\gamma=\frac{2}{137\pi}\frac{dE_\gamma}{E_\gamma}\ln\left(\frac{2E_\mu}{3E_\gamma}\right),$$

and integrating over the μ-meson spectrum. The integration was performed graphically using the spectrum of Owen and Wilson.[15] The result is $\langle\sigma m\rangle_\mu=9.5\times10^{-29}$ cm^2/nucleon, of which 3.2×10^{-29} cm^2/nucleon is due to equivalent photons of energies above 320 Mev, where an assumed yield was used. For comparison with underground work, the $\langle\sigma m\rangle_\mu$ for a momentum of 10 Bev/c (the approximate average at the depth of 20 m.w.e.) has been calculated. The result is 16.3×10^{-29} cm^2/nucleon, of which 6.6×10^{-29} cm^2/nucleon is due to photons with $E_\gamma>320$ Mev.

The shower photon effect was calculated in two ways.

[12] Appapilai, Mailvaganum, and Wolfendale, Phil. Mag. **45**, 1059 (1954); H. J. J. Braddick and B. Leontic, Phil. Mag. **45**, 1287 (1954). Earlier references are cited by these authors and by E. Amaldi, reference 1.
[13] L. W. Jones and K. M. Terwilliger, Phys. Rev. **91**, 699 (1953).
[14] W. Heitler, *The Quantum Theory of Radiation* (Oxford University Press, New York, 1954), third edition, p. 414.
[15] B. G. Owen and J. G. Wilson, Proc. Phys. Soc. (London) **A68**, 409 (1955).

In both cases the Owen and Wilson μ-meson spectrum[15] and the "Rutherford formula" for the knock-on probability[16] were used. In the first method we applied "Approximation B" shower theory (corrected for departure from the asymptotic cross section) to find the photon track length in the Pb absorber, which was assumed to be infinite. The Jones and Terwilliger photoneutron yields[13] were then used to calculate $\langle\sigma m\rangle_{\rm sh}$. The result was 14.6×10^{-29} cm^2/nucleon. In the second calculation, we estimated the neutron yield per knock-on electron by using the cloud chamber result[17] that the mean neutron multiplicity is 0.4 for electron showers of energies estimated to be between 250 and 600 Mev. If we assume that the multiplicity is proportional to the electron energy, and that the electron spectrum is of the form dE/E^2, the constant of proportionality is found to be 1.05×10^{-3} Mev^{-1}. The result for $\langle\sigma m\rangle_{\rm sh}$ is 16×10^{-29} cm^2/nucleon, in good agreement with the previous calculation.

The first method of calculation gives $\langle\sigma m\rangle_{\rm sh}=27$ 10^{-29} cm^2/nucleon for 10 Bev/c μ mesons.

CONCLUSIONS

The direct and shower contribution to $\langle\sigma m\rangle$ just calculated add up to 25×10^{-29} cm^2/nucleon, which agrees with the measured value of $(22\pm8)\times10^{-29}$ cm^2/nucleon. Because of the large statistical uncertainty of the experimental result and the great importance of shower production, not very much information can be gained on the direct interactions from this experiment alone. From other work (see below) it is unlikely that the direct $\langle\sigma m\rangle$ is a great deal smaller than the value calculated.

A comparison of these results with those at a depth of 20 m.w.e. is enlightening. AWM[4] found $\langle\sigma m\rangle = (40.3\pm2.1)\times10^{-29}$ cm^2/nucleon for Pb. We calculate that the direct interaction should furnish a $\langle\sigma m\rangle_\mu$ of 16×10^{-29} cm^2/nucleon (of which 6.6 is from photons of $E_\gamma>320$ Mev) and the shower production $\langle\sigma m\rangle_{\rm sh}$ should be 27×10^{-29} cm^2/nucleon, so that the calculated values agree well with this experimental value at higher mean energy. The theoretical $\langle\sigma m\rangle_\mu$ for direct production also agrees with Cocconi's corrected value.[5] It thus appears that the two interaction modes assumed are capable of explaining all the experiments in which neutrons are detected, although further experimentation is needed in order to evaluate the relative contributions of the shower and direct interactions. In the present work, the identification of the μ mesons by magnet cloud chamber and hodoscope is more certain than in the underground experiments using counters alone. The agreement of the theory with both the sea-level and underground results indicates that the underground events were correctly assumed to be primarily due to μ mesons. There is no evidence of nucleonic cascades in these events.

The smaller values of the direct $\langle\sigma m\rangle_\mu$ deduced from nuclear emulsion work must indicate that in many of the neutron-producing events no charged particles are produced.

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[16] B. Rossi and K. Greisen, Revs. Modern Phys. **13**, 240 (1941); B. Rossi, *High-Energy Particles* (Prentice-Hall, New York, 1952), p. 17.

[17] E. J. Althaus and R. D. Sard, Phys. Rev. **91**, 373 (1953).