nucleon. In each case it has been found that the result of the a.d. theory differs from that of the retarded field theory by the absence of the terms that correspond to the contribution of the field reaction to the nucleon parameter—be it mass, moment of inertia, or isotopic spin—involved in the scattering. It may be noted that the field reaction terms corresponding to radiation damping (which save the cross section from ultraviolet catastrophe) are the same in both the theories. The details of the calculations show quite clearly that this cancellation of field reaction occurs in virtue of the reactive terms in the equations of motion of the a.d. theory, representing the effect of the future motion of the particle, i.e., terms involving integrals of the type $\int_\tau^\infty \cdots d\tau$, where τ is the proper time of the particle.

I wish to thank Dr. R. C. Majumdar for suggesting the above problem and for helpful discussions. I also wish to thank the Atomic Energy Commission, Government of India, for the award of a research fellowship.

PHYSICAL REVIEW VOLUME 94, NUMBER 4 MAY 15, 1954

Nuclear Interaction of Fast μ Mesons*†

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(Received January 28, 1954)

An experimental study has been made of events in which a fast μ meson interacts with a nucleus to produce at least one evaporation neutron. The experimental results of major importance are $\sigma\bar{m} = (9.1\pm1.2)\times10^{-27}$ cm²/Fe-nucleus; $1.03<\bar{m}<7.7\pm2.2$; and $(1.2\pm0.4)\times10^{-27}$ cm²/Fe-nucleus$<\sigma<(8.8\pm1.1)\times10^{-27}$ cm²/Fe-nucleus, where σ is the cross section for such events and $\bar{m}$ is the mean multiplicity of evaporation neutrons emitted. These results are in good agreement with the results of calculations based on present information on the nuclear interaction of γ rays, which lead to the prediction of a σ of about 2.4×10^{-27} cm²/Fe-nucleus and an $\bar{m}$ of about 3.3. The surprisingly large cross section and small mean multiplicity of neutrons are shown to be reasonable by calculating that about 90 percent of all μ-meson nuclear interactions result in the transfer to the nucleus of less than 300 Mev.

INTRODUCTION

It is now generally known that the μ meson has a weak but nonvanishing interaction with nuclei, both in capture processes and in interactions in flight. Several experiments have been done by other workers in an attempt to determine the cross section for interaction of a fast μ meson with a nucleus. The numbers quoted in the literature[1] differ considerably, due to the fact that the various experimental techniques employed are not equally sensitive to all the processes by which μ mesons interact with nuclei.

Knowledge of the interaction cross section under various conditions makes it possible to draw conclusions as to the nature of the interaction processes involved. Specifically, the fact that the cross section measured in the present experiment is large compared to previous measurements leads, as we show later, to the conclusion that μ mesons of about 11-Bev energy in their interaction with nuclei lose on the average only several hundred Mev.

The data taken by Cocconi and Tongiorgi,[1] in an experiment rather similar to the present one, are, we feel, consistent with the data presented here. The present experiment was designed to detect unambiguously nuclear interactions of μ mesons in which the neutron multiplicity is low; while the Cocconi experiment detected high-multiplicity interactions very efficiently, there was some ambiguity in their assignment of low-multiplicity interactions to mesons.

The present experiment is an outgrowth of the studies at this laboratory[2] of neutron production by fast μ mesons in lead; attention was shifted to iron in order to reduce the neutron yield from γ rays in knock-on showers.

* This article is based on a doctoral dissertation presented to the Graduate Board of Washington University by H. C. Wilkins.
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[1] E. Amaldi and G. Fidecaro, Phys. Rev. **81**, 339 (1951); Castagnoli, Gigli, and Schinto, Nuovo cimento **10**, 893 (1953); Amaldi, Castagnoli, Gigli, and Schinto, Nuovo cimento **9**, 453 (1952); **9**, 969 (1952); Proc. Phys. Soc. (London) **65**, 556 (1952); G. Cocconi and V. C. Tongiorgi, Phys. Rev. **84**, 28 (1951); E. P. George and J. Evans, Proc. Phys. Soc. (London) **A63**, 1248 (1950); E. P. George in *Progress in Cosmic Ray Physics* (North-Holland Publishing Company, Amsterdam, 1952), p. 428.

[2] R. D. Sard, Phys. Rev. **80**, 134 (1950); Sard, Crouch, Jones, Conforto, and Stearns, Nuovo cimento **8**, 326 (1951); M. F. Crouch and R. D. Sard, Phys. Rev. **85**, 120 (1952); H. C. Wilkins, thesis, Washington University, St. Louis, September, 1952 (unpublished). The result of Crouch and Wilkins for the cross-section multiplicity product in 7.6 cm Pb—$(83\pm4)\times10^{-27}$ cm² per nucleus—has been quoted in E. J. Althaus and R. D. Sard, Phys. Rev. **91**, 382 (1953); as pointed out in this paper, it was necessary to assume a large cross section for μ-meson events in which little energy was transferred to the nucleus, in order to explain the large number of cloud chamber pictures containing only a single penetrating particle.

APPARATUS AND DATA

In this experiment nuclear interactions were studied by counting low-energy (less than about 10 Mev) neutrons associated with the passage of μ mesons through a slab of iron. The penetration by the μ meson was indicated by a coincidence of pulses from Geiger counters placed above and below the absorber (Fig. 1). Neutrons were slowed down in the paraffin and were recorded as associated with a penetration if the thermalized neutrons were detected within a 186 μsec time interval starting 7 μsec after the penetration. The equipment was arranged to record those penetrations that were followed by the detection of one or more, two or more, and three or more neutrons within this time interval.

Special features of the experiment included the following:

(1) The number of penetrations was recorded directly.

(2) Penetrations were rejected if in any tray of Geiger counters above the absorber two or more counters were discharged.

(3) In part of the experiment the equipment was arranged so as to discriminate against soft showers initiated by knock-on electrons in the absorber.

The experiment was performed in a limestone cave with a coverage of about 2000-g cm^{-2} (average energy of the μ mesons = 11 Bev). The equipment used was basically the same as that used in the former experiment of Crouch and Sard[3] on the neutron multiplicity associated with the capture of negative μ mesons. A few simple modifications had to be made in order to detect events associated with penetrating particles

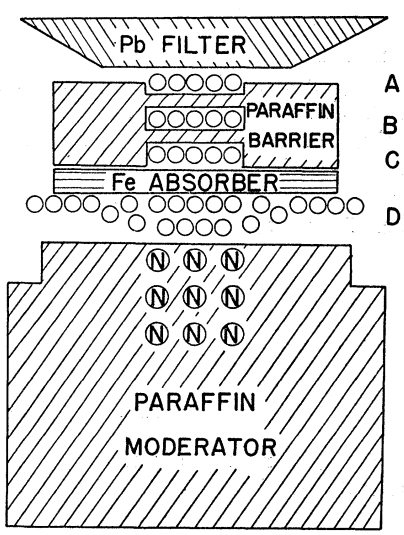

FIG. 1. Schematic of the apparatus—front view. A, B, C, and D refer to the respective trays of Geiger counters. The BF_3 neutron counters are embedded in the paraffin moderator.

[3] M. Crouch and R. D. Sard, Phys. Rev. 85, 120 (1952).

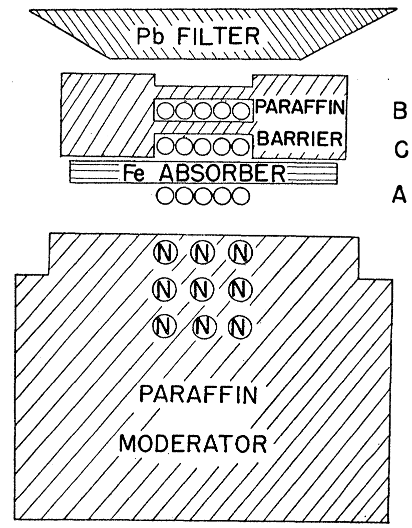

FIG. 2. Schematic of the apparatus for "control" experiment—front view. Note that the D counters have here been replaced by the A counters.

rather than with particles which reach the end of the range in the absorber; otherwise, no major changes in the geometry or circuitry were made. For a detailed description of the site and the equipment the reader is referred to the report of the previous experiment. Only a very brief description will be given here.

The three trays of Geiger counters A, B, and C, the Pb filter, the paraffin barrier, and the absorber were mounted on horizontal tracks to facilitate changes in the geometry. The bank of D counters was made large enough to cover the solid angle included by the A and C trays above the absorber. The boron trifluoride counters were embedded in a 700-kg block of paraffin, which served to thermalize the neutrons and thus render them detectable by the BF_3 counters.

A penetration was indicated by a fourfold coincidence $ABCD$. If this coincidence was accompanied by the simultaneous discharge of at least one other counter in either the A, B, or C trays, then the event was recorded as a "multiple" and the event was discarded in the analysis. Other events were designated as "singles."

The arrangement of the equipment in Fig. 2 deserves comment. As indicated above, the arrangement shown in Fig. 1 permitted single-multiple discrimination only in the trays of Geiger counters placed above the absorber. The counters in the D tray were simply connected in parallel, thus not making it possible to distinguish between events in which one or more than one charged particle emerged from the absorber. It is evident that if the tray below the absorber could be made to distinguish between single and multiple discharges, then the equipment could be made to discriminate against events in which large showers develop in the absorber. This was accomplished by replacing the D tray by the A tray and making the appropriate modifications in the electronic circuits.

The neutron detection efficiency was determined by the use of a $Ra-\alpha-Be$ source of known neutron flux. This source was the same as that used in the experiment of Crouch and Sard and as pointed out in the report of that experiment,[3] the neutron flux of the source is uncertain by about ten percent, corresponding to the uncertainty in the flux from the Bureau of Standards source which was used for calibration. Thus there may be a systematic error of up to 10 percent in our value of the efficiency and any quantities depending on the efficiency. The neutron counting rate was measured with this source in various positions on and in the absorber. The efficiency for each of these positions was determined and weighted according to the relative μ-meson flux through that part of the absorber. The average efficiency thus determined had to be further corrected by taking into consideration the finite time during which the equipment would accept a neutron count. It was found that the probability of detecting a neutron once thermalized decreased exponentially with time with a detection mean life of 162 ± 7 μsec. Thus, the efficiency for detection of neutrons associated with penetrations would be less than that for source neutrons by a factor

$$(1-e^{-T/\tau}),$$

where T is the gate length for counting neutrons and τ is the detection mean life. This factor is 0.68 ± 0.02 for the experiment. The efficiency for the 7.6-cm Fe absorber was 0.0178 and for the 5.1-cm Fe absorber it was 0.0176.

Another source of inefficiency was in the neutron detecting circuits. After a neutron discharged one of the BF_3 counters, the circuit would not accept another neutron pulse for a time d which we call the dead time of the neutron detecting circuit.

Since the energy spectrum for neutrons from nuclear interactions in the absorber is not the same as for the artificial source neutrons, it might be expected that the detection efficiency for artificial source neutrons differs from that for the neutrons from nuclear interactions. If this were true then it would be expected that the top 3 neutron counters would be of different importance in the two cases. By disconnecting the top neutron counters the counting rate for neutrons associated with penetrations decreased by a factor 3.63 ± 0.97. The efficiency for source neutrons decreased by a factor 3.84. Thus, one can think of the detection efficiency as being flat as a function of neutron energy, up to an energy of the order of 10 Mev, then dropping rapidly to zero. *In this experiment, neutrons of energy much greater than 10 Mev cannot be thermalized, and thus are not detected.*

ANALYSIS OF DATA

The quantities that we are interested in evaluating are (1) the cross section (per nucleus) σ for a nuclear interaction in which at least one neutron is released, and (2) the mean number $\bar{m}$ of neutrons released in such interactions. From an experiment of the present type, neither of these quantities can be evaluated separately; rather the product $\sigma\bar{m}$ emerges from an analysis of the data.

Let us define the following quantities:

x = effective thickness of the absorber in g cm^{-2},
N = Avogadro's number,
σ = cross section per nucleus for a nuclear interaction in which at least one neutron is released,
$P(m)$ = probability that in this interaction, m neutrons will be released,
ϵ = efficiency for detection of neutrons associated with penetrations,
R = number of penetrations per unit time,
R_n = number of penetrations recorded per unit time that are accompanied by the detection of n or more neutrons,
R_n' = the value R_n would have if the dead time d of the neutron detecting circuit were zero,
A = atomic weight for the material of the absorber.

In terms of these quantities one can write

$$R_n'=\frac{RNx\sigma}{A}\sum_{m=n}^{\infty}P(m)\left[1-\sum_{i=0}^{n-1}{}^mC_i(1-\epsilon)^{m-i}\epsilon^i\right],\quad (1)$$

where ${}^mC_i=[m(m-1)(m-2)\cdots(m-i+1)]/(i!)$. It can be shown that

$$R_1'+R_2'+R_3'+R_4'+\cdots=\frac{RNx\sigma}{A}\sum_{m=1}^{\infty}P(m)m\epsilon=\frac{RNx\sigma}{A}\epsilon\bar{m},\quad (2)$$

$$R_2'+2R_3'+3R_4'+4R_5'+\cdots=\frac{RNx\sigma}{A}\sum_{m=1}^{\infty}P(m)\epsilon^2\frac{m^2-m}{2}=\frac{RNx\sigma}{2}\epsilon^2(\langle m^2\rangle_{\text{Av}}-\bar{m}).\quad (3)$$

In the actual experiment there are only three channels, but the error introduced in $\sigma\bar{m}$ by neglecting R_n' for $n\geq4$ is negligible.

In our experiment, the dead time d, during which the neutron circuit could not accept another neutron count, was not negligible, so that the observed R_n rates are too low. A straightforward but laborious calculation shows that the corrected rate R_n' is related to the observed rate R_n by the relations

$$R_1'=R_1,\quad R_2'=aR_2,\quad R_3'=bR_3,$$

where a and b are complicated functions of ϵ, d, T, and τ. Thus the previous formulas involving R_2' and R_3' can be used with R_2' and R_3' replaced by aR_2 and bR_3, respectively. For the experiment of Fig. 1, $d=13.3$ μsec, giving approximately $a=1.18$ and $b=1.66$. For the experiment of Fig. 2, $d=48.9$ μsec, giving $a=1.71$. From Eqs. (2) and (3),

$$\sigma\bar{m}=\frac{(R_1+aR_2+bR_3)A}{RNx\epsilon},\quad (4)$$

$$\sigma(\langle m^2\rangle_{\text{Av}}-\bar{m})=\frac{2A(aR_2+2bR_3)}{RNx\epsilon^2}.\quad (5)$$

From (4) and (5) and the fact that $\langle(m-\bar{m})^2\rangle_{\text{Av}}>0$, it follows that $\bar{m}<r$, where

$$r=1+\frac{2(aR_2+2bR_3)}{\epsilon(R_1+aR_2+bR_3)}.\quad (6)$$

Thus, using Eq. (6) an upper bound on $\bar{m}$ can be calculated from the counting rates. Corresponding to

TABLE I. Summary of the data.

Absorber	Arrangement of Fig. 1 7.6 cm Fe	5.1 cm Fe	None	Arrangement of Fig. 2 7.6 cm Fe	None
Penetration rate	39.7/min	42.5/min	40.3/min	35.4/min	36.6/min
Penetrations with N					
raw rate	0.793±0.035/hr	0.724±0.034/hr	0.576±0.036/hr	0.686±0.046/hr	0.446±0.042/hr
corrected rate[a]	0.594±0.035/hr	0.493±0.034/hr	0.328±0.036/hr	0.456±0.046/hr	0.205±0.042/hr
Penetrations with $2N$					
raw rate	0.011±0.004/hr	0.014±0.005/hr	0.002±0.002/hr	0.016±0.007/hr	0.008±0.006/hr
corrected rate[a]	0.011±0.004/hr	0.011±0.005/hr	0.002±0.002/hr	0.016±0.007/hr	0.008±0.006/hr
Penetrations with $3N$					
raw rate	0	0.002±0.002/hr	0	0	0
corrected rate[a]	0	0.002±0.002/hr	0	0	0

[a] The corrections applied to the data were of two types: (1) correction for accidental coincidences and (2) correction for events recorded both in the "single" and the "multiple" channels. The latter kind of event was due to the accidental overlapping of the "single" and the "multiple" long gate pulses used in the recording equipment. These data are not corrected for the finite dead time of the equipment.

this upper bound on $\bar{m}$ there is a lower bound on σ given by Eq. (4).

An upper bound on σ can also be obtained. Another expression for R_1 is $(RNx\eta\sigma)/A$, where η is the efficiency of the system for detecting the nuclear event. η would be equal to ϵ if only one neutron were emitted and would be 1 if an infinite number of neutrons were emitted. Thus, an upper bound on σ is

$$\sigma < (R_1A)/(RNx\epsilon).$$

It can also be shown that if the neutron production is due to a combination of processes, each corresponding to a different σ and a different multiplicity distribution, then the results are additive, i.e.,

$$R_1 + aR_2 + bR_3 = [(RNx\epsilon)/A](\sigma\bar{m})_T,$$

where $(\sigma\bar{m})_T$ is given by

$$(\sigma\bar{m})_T = \sum_{i=1}^{N} \sigma_i\bar{m}_i.$$

The data are summarized in Table I. The neutron coincidence rates R_n are the corrected observed rates reduced by the corresponding rates without absorber. R is the penetration rate given in Table I. The effective thickness is 1.14 times the actual thickness of the absorber. This factor was obtained by taking into consideration all possible angles of incidence on the absorber, each weighted by the $\cos^2\theta$ law of μ-meson intensity.

By using Eq. (4), the values of $\sigma\bar{m}$ are found to be as follows for the experiment of Fig. 1:

$$\sigma\bar{m} = (9.2\pm1.6)\times10^{-27}\ \text{cm}^2/\text{nucleus for 7.6 cm Fe},$$
$$\sigma\bar{m} = (7.5\pm2.4)\times10^{-27}\ \text{cm}^2/\text{nucleus for 5.1 cm Fe},$$

and for the experiment of Fig. 2,

$$\sigma\bar{m} = (9.9\pm2.5)\times10^{-27}\ \text{cm}^2/\text{nucleus for 7.6 cm Fe}.$$

(It is seen that the double and triple neutron rates are too small to permit evaluation of $\sigma\langle m^2\rangle_{\text{Av}}$ and higher moments.)

COMPETING EFFECTS

The results given above are the cross-section multiplicity products for all possible processes by which a charged particle penetrating the absorber can release one or more evaporation neutrons in the absorber. To obtain results for the primary interaction of a μ meson with a nucleus, an estimate must be made of the contribution of other processes. Among these competing processes the following might be considered important.

1. Effect of Shower γ Rays

Evaporation neutrons could possibly arise by the following process (see Fig. 3): a μ meson imparts energy to a knock-on electron in the absorber; the knock-on electron then initiates a soft shower, the γ rays of which interact with nuclei of the absorber to produce evaporation neutrons. This event would be accepted by the apparatus shown in Fig. 1. A lengthy calculation

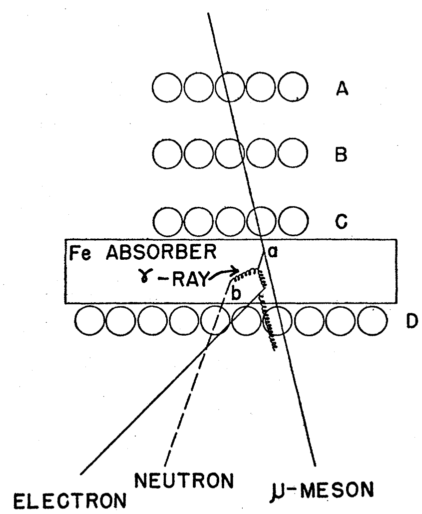

FIG. 3. Effect of shower γ rays in absorber. A μ meson knocks on an electron in the Fe absorber at a. This electron initiates a soft shower, and one of the γ rays in the shower causes a nuclear interaction at b.

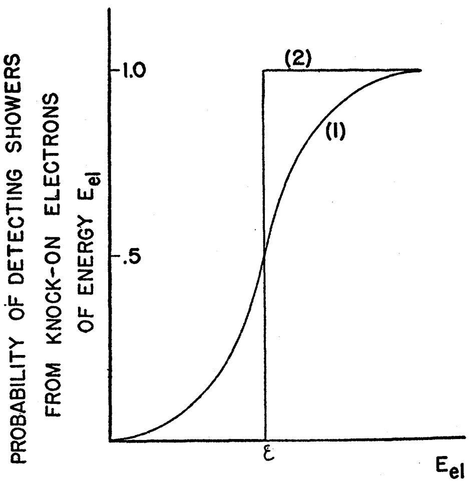

FIG. 4. Curve 1 represents the probability that a knock-on electron of energy E_{el} initiate a shower that is detectable as a "multiple" event. Curve 2 is a simplified version of 1 for the purpose of calculations.

based on Snyder's solution[4] of the approximation "B" shower theory diffusion equations and on the observed neutron yield from the "giant resonance" interaction of 20-Mev γ rays leads to the prediction that shower γ rays could contribute to $\sigma\bar{m}$ as much as 10×10^{-27} cm^2/nucleus for the experiment with 7.6-cm Fe absorber. This is approximately the observed value. Of course, one would not expect approximation "B" to give very good results for γ-ray energies as low as 20 Mev. The "control" experiment, illustrated in Fig. 2 and discussed earlier, was designed to test the effect of shower γ rays in producing neutrons. Since in the "control" experiment events were discarded if more than one charged particle emerged from the absorber, events associated with large showers in the absorber are discriminated against. Thus, if the observed $\sigma\bar{m}$ for the original experiment were partly due to the effect of shower γ rays, then the "control" experiment should yield a smaller $\sigma\bar{m}$ than the original experiment.

To evaluate the effect of the "control" experiment we reason first that high-energy knock-on electrons will produce showers so large that the probability of their being detected as "multiples" in the control experiment is very close to one. For very low-energy knocksons this probability is zero. The exact shape of the curve of probability of a "multiple" count *versus* knock-on electron energy is not known but it might be as indicated by curve (1) in Fig. 4. In order to simplify the calculations, we assume that the curve has the shape of (2) in Fig. 4 (i.e., knock-on electrons of energy less than $\mathcal{E}$ will not register as "multiples") and proceed to find the $\mathcal{E}$ that fits the data.

To relate $\mathcal{E}$ to the counting rates, we calculate the probability, $P(E_{el}>\mathcal{E})$, that a μ meson in passing through the absorber will give to a knock-on electron an energy greater than $\mathcal{E}$:

$$P(E_{el}>\mathcal{E})=\frac{Nx}{A}\int_{E\mu=0}^{\infty}\int_{E_{el}=\mathcal{E}}^{E_{el\max}} N(E_\mu)dE_\mu\frac{\partial\sigma}{\partial E_{el}}dE_{el}, \quad (7)$$

where[5]

$$N(E_\mu)dE_\mu=\frac{(4.27)10^6dE_\mu}{(E_\mu+7700)^{2.65}}$$

is the number of μ mesons 2000 g cm^{-2} underground with energy between E_μ and $E_\mu+dE_\mu$,

$$E_{el\max}=\frac{2m_{el}c^2E_\mu^2}{m_\mu^2c^4+2m_{el}c^2E_\mu}$$

is the maximum transferable energy, and

$$\frac{\partial\sigma}{\partial E_{el}}dE_{el}=(25.1)(Z)(10^{-26})\frac{dE_{el}}{E_{el}^2}$$

is the differential cross section per atom for a μ meson to give to a knock-on electron an energy between E_{el} and $E_{el}+dE_{el}$.[6]

In all of these equations, energies are measured in Mev. Figure 5 is a plot of $P(E_{el}>\mathcal{E})$ *vs* $\mathcal{E}$.

To obtain the rate at which tray A of Fig. 2 counts "multiples" produced in the absorber, the experiment illustrated in Fig. 6 was performed. The Pb was used to insure that the particles triggering the array of counters were penetrating particles. Only those "multiples" occurring in tray A were counted and the difference between the multiple rates "with" and "without" the Fe absorber was taken as the rate of

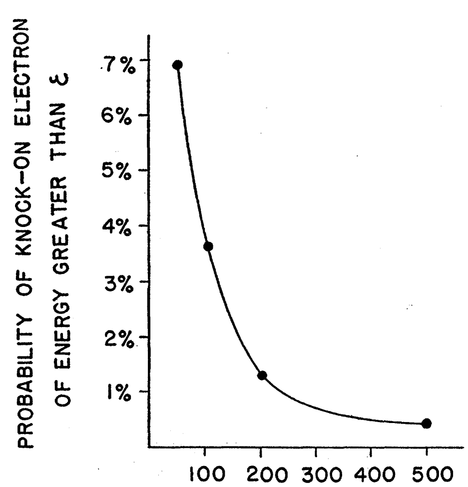

FIG. 5. Plot of the probability that a μ meson knock on an electron of energy greater than ε *vs* ε.

[4] H. Snyder, Phys. Rev. **76**, 1563 (1949).

[5] D. C. Peaslee, Nuovo cimento **9**, 61 (1952); Barrett, Bollinger, Cocconi, Eisenberg, and Greisen, Revs. Modern Phys. **24**, 133 (1952).

[6] B. Rossi, *High Energy Particles* (Prentice-Hall, Inc., New York 1952).

detection of multiple events produced in the absorber. To make sure that the μ-meson spectrum did not change, the run "without" absorber was made with the Fe still in the telescope, but now over the B tray [Fig. 6(b)]. The results are given below:

	Absorber above	Absorber below
AB rate	(49.6 ± 0.2)/min	(48.9 ± 0.2)/min
A_mB rate	(2.79 ± 0.05)/min	(1.90 ± 0.04)/min.

Thus, 1.8 percent of the μ mesons produce knock-on electron showers that are detected.

Referring to Fig. 5, we see that this probability corresponds to $\mathcal{E}=170$ Mev. This means that, on the average, showers initiated by knock-on electrons of energy greater than 170 Mev are detected, whereas those of smaller energy are not detected as "multiples."

In the calculation (approximation B) of an equivalent μ-meson cross section for evaporation neutron production through the intermediary of shower γ rays, it was found that showers resulting from knock-on electrons of energy greater than 170 Mev contribute roughly half the total calculated cross section. Since conventional shower theory overestimates the number of 20-Mev photons near the beginning of a shower,[7] the contribution of shower γ rays to $\sigma\bar{m}$ in the "control" experiment must be less than half the contribution in the other experiment with 7.6-cm Fe. If, for example, all of the measured $\sigma\bar{m}$ observed in the experiment of Fig. 1 had been due to shower γ rays as predicted by shower theory, then the expected value for the "control" experiment of Fig. 2 would have been less than

$$0.5(9.2\pm1.6)10^{-27}=(4.6\pm0.8)10^{-27}\ \text{cm}^2/\text{nucleus}.$$

But the observed value is $(9.9\pm2.5)10^{-27}$ cm^2/nucleus; in the same time the standard deviation would have been about 1.7 if the value of $\sigma\bar{m}$ had been 4.6, and the difference between the expected value and the observed value is 5.3×10^{-27}. If one assumes that the true value of this difference is zero (i.e., 0 ± 1.9) the probability of a fluctuation as large as 5.3×10^{-27} is about 0.004. Therefore, the $\sigma\bar{m}$ value for 7.6-cm Fe cannot all be ascribed to the effect of shower γ rays. On the contrary, the experimental results suggest that the effect of shower γ rays is negligible.

2. Effect of Nuclear Cascades Beginning in the Absorber

The neutrons detected in the experiment are those due to the original event plus any that are produced in nuclear cascades developing in the absorber and in the paraffin surrounding the neutron counters. Therefore, in order to give a $\sigma\bar{m}$ value that can be ascribed to the primary nuclear interaction of a μ meson, the effect of nuclear cascades must be considered.

The experiment gives evidence that nuclear cascades have at most a small effect. This evidence consists of the following considerations:

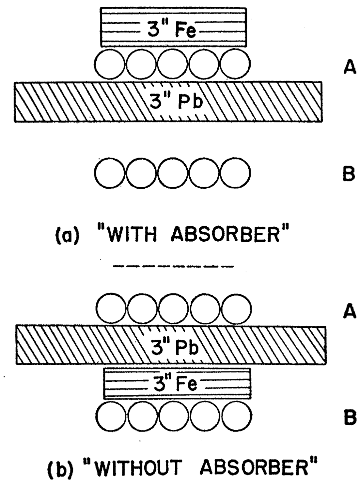

FIG. 6. Schematic of the apparatus used to test the efficiency of the "control" experiment for shower detection.

(a) If a nuclear cascade continued to develop in the paraffin surrounding the neutron counters, the lower counters would be more important for the detection of neutrons from the cascade than for the detection of neutrons from the original event. Thus, by disconnecting the top three neutron counters, the neutrons from the cascade in the paraffin would be favored. The results given earlier indicate that the efficiency for detecting neutrons from the absorber (and cascade, if any) is not significantly different from the efficiency for detection of neutrons from the artificial source. This result suggests that there is very little, if any, effect of nuclear cascade in the paraffin.

(b) It is reasonable to assume that if nucleons from nuclear interactions of μ mesons are energetic enough to cause a large nuclear cascade, then protons and π mesons would often be able to get out of the absorber. Such events would register as "multiples" in the "control" experiment and hence would not contribute to the neutron counting rate. The fact that $\sigma\bar{m}$ for the control experiment did not differ significantly from the corresponding quantity for the other experiment suggests that neither shower γ rays nor nuclear cascades are important in 7.6-cm Fe.

3. Effect of Neutrons, Protons, and π Mesons Arising from Nuclear Interactions Outside the Absorber

For a fast neutron to give rise to a spurious count, it would have to accompany a penetrating charged particle through the Geiger-counter telescope and initiate a nuclear event in the absorber (Fig. 7). Neutrons from nuclear interactions in the Pb filter above the telescope might thus give rise to spurious counts. This process is unlikely because protons that might accompany the neutron out of the Pb filter would trigger another counter in the Geiger-counter telescope and thus the event would not register.

[7] R. R. Wilson, Phys. Rev. 86, 261 (1952).

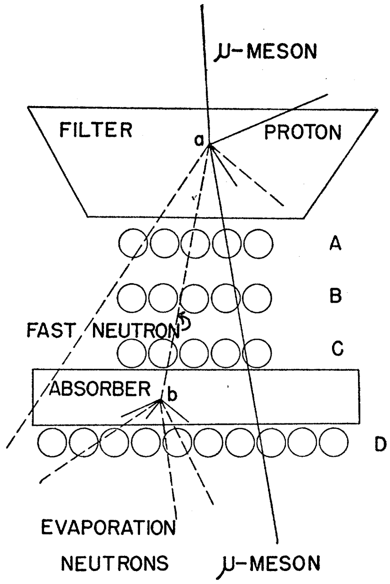

FIG. 7. A possible sequence of events resulting in a "single" accompanied by a spurious neutron count. A μ meson interacts at a, and continues on through trays $ABCD$. One of the secondary fast neutrons interacts at b.

Protons and π mesons originating in the filter can be neglected since in most cases a proton from an interaction in the filter will be accompanied by the original μ meson, thus triggering a multiple count. Protons and π mesons originating in the roof of the cave have a relatively small chance of penetrating the filter.

The most powerful evidence for believing that few high-energy secondary nucleons are produced per μ meson-nucleus interaction is the fact that the "control" experiment gives the same $\sigma\bar{m}$ as does the experiment of Fig. 1. Secondary protons or mesons would register as "multiples" in the "control" experiment, so that if they were produced with any frequency, the "control" experiment would have resulted in a far smaller $\sigma\bar{m}$.

These considerations indicate that neutrons, protons, and π mesons produced outside the absorber have no important effect on the neutron counting rates in the experiment.

SUMMARY OF RESULTS

The experimental data indicate that competing effects are unimportant in the experiment. Therefore, it is justifiable to lump the results of the three experiments—that with 7.6-cm Fe absorber, with 5.1-cm Fe absorber, and the control experiment. The results of major importance are

$$\sigma\bar{m}=(9.1\pm1.2)\times10^{-27}\ \text{cm}^2/\text{Fe-nucleus},$$

$$1.03<\bar{m}<7.7\pm2.2,$$

$$(1.2\pm0.4)\times10^{-27}\ \text{cm}^2/\text{Fe-nucleus}<\sigma<(8.8\pm1.1)\times10^{-27}\ \text{cm}^2/\text{Fe-nucleus}.$$

DISCUSSION OF RESULTS

The work of George and Evans[8] gave 4.4×10^{-30} cm²/nucleon for the cross section for production of stars of at least one minimum ionizing track in the lower hemisphere and at least 3 "heavy" prongs (presumably protons). (The minimum excitation energy of these stars was of the order of 150 Mev.) The mean number of ionizing prongs for these stars was about 6, so that the mean number of neutrons must have been about 7;[9] so that $\sigma\bar{m}=1.7\times10^{-27}$ cm²/Fe-nucleus, a value much smaller than the $\sigma\bar{m}$ measured in the present experiment. As we shall show below, this apparent discrepancy can be explained, when the low-energy interactions of μ mesons with the nucleus are taken into account.

In an experiment rather similar to the present one, in that nuclear interactions were detected by observing evaporation neutrons, Cocconi and Tongiorgi[1] evaluated $\sigma\bar{m}$ for Pb and for Al. However, as mentioned previously, the low-multiplicity events could not unambiguously be assigned to μ-meson interactions. From measurements on the nuclear interactions of γ rays, it is possible, as we show below, to calculate a partial $\sigma\bar{m}$ for interactions in which μ mesons transfer less than about 300 Mev to the nucleus. This corresponds, on the average, to a neutron multiplicity of about 6. Hence we shall use the Cocconi and Tongiorgi data to calculate a partial $\sigma\bar{m}$ for events in which more than 300 Mev is transferred to the nucleus. If one ignores the data in their first six channels, one can calculate a $\sigma\bar{m}$ for events in which 7 or more neutrons are emitted. Making a very crude interpolation between the Cocconi results for Pb and Al, one finds that $\sigma\bar{m}$ is between 2×10^{-27} [10] and 4×10^{-27} cm²/Fe-nucleus and that $\bar{m}\approx11$. The two limits on $\sigma\bar{m}$ correspond to extreme assumptions concerning the effect of the secondary particles capable of producing nuclear interactions.[11]

A photoplate experiment on star production is biased against low-energy interactions. The present experiment requires only that at least one evaporation neutron be released. That such low-energy events occur is evident if one represents the electromagnetic field of the μ meson as a spectrum of "equivalent" γ rays.

In order to analyze this model further, it is assumed that μ mesons interact with nuclei by way of these equivalent photons. The spectrum of photons is given by the Williams-Weizsäcker formula

$$R(E_\gamma)dE_\gamma=\frac{2}{137\pi}\frac{dE_\gamma}{E_\gamma}\ln\left[\frac{2}{3}\frac{E_\mu}{E_\gamma}\right].$$

[8] E. P. George in *Progress in Cosmic Ray Physics* (North-Holland Publishing Company, New York, 1952), p. 428.

[9] K. J. LeCoutenur, Proc. Phys. Soc. (London) **A63**, 259, 498 (1950).

[10] This value of $\sigma\bar{m}$ is about twice as large as the corresponding quantity for the George data.

[11] This effect was probably larger in the Cocconi experiment than in the present one.

In this equation, $R(E_\gamma)dE_\gamma$ is the number of photons with energy between E_γ and $E_\gamma+dE_\gamma$ associated with a μ meson of energy E_μ. It is further assumed that these equivalent photons interact with matter by the same processes as do real γ rays. The processes by which real γ rays are known to interact with nuclei are the following.

(1) Star Production

The process by which high-energy γ rays (E_γ greater than about 100 Mev) produce high-energy stars is thought to be one in which a π meson is first produced in and then absorbed by the (same) nucleus. The cross section for this process is about 2×10^{-28} cm^2/nucleon per effective quantum at low energies.[12] Assuming that this value is applicable for all E_γ, and making use of the Williams-Weizsäcker formula and the μ-meson energy spectrum, one obtains a value of cross section

$$\sigma_{\text{theor}}\approx0.15\times10^{-27}\text{ cm}^2/\text{Fe-nucleus}$$

for events in which more than 300 Mev is transferred to the nucleus. Thus, it is not unreasonable to assume that this process can account for a $\sigma\bar{m}$ of between 2×10^{-27} and 4×10^{-27} cm^2/Fe-nucleus in the present experiment (e.g., take $\sigma=0.2\times10^{-27}$ cm^2/Fe-nucleus and $10<\bar{m}<20$ for events in which 7 or more neutrons are emitted).

(2) "Giant Resonance" Interactions

The interaction cross section of γ rays with Fe has a "giant resonance" in the vicinity of 20-Mev γ-ray energy. This interaction leads to the production of one or possibly two neutrons. Let us assume that the cross section for such low-energy γ rays can be expressed as a δ function:

$$\bar{m}\sigma(E_\gamma)dE_\gamma=\Pi\delta(E-E_{GR})dE_\gamma,$$

in which Π is the integrated cross-section multiplicity product around $E_\gamma=E_{GR}$, and E_{GR} is the energy at the peak.

Then, for a given μ meson, the cross section for an interaction by the giant resonance effect is

$$\sigma=\int_0^\infty \Pi R(E_\gamma)\delta(E_\gamma-E_{GR})dE_\gamma$$
$$=\Pi R(E_{GR}),$$

in which $R(E_\gamma)dE_\gamma$ is the virtual photon spectrum. Such a cross section must be integrated over the energy spectrum of μ mesons, $N(E_\mu)dE_\mu$. Using $\Pi=0.735\times10^{-24}$ cm^2 Mev per nucleus,[13] one obtains $(\sigma\bar{m})_{GR}\approx0.8\times10^{-27}$ cm^2/Fe-nucleus. This would be the contribution of this process to the result of the present experiment.

(3) Low-Energy Interaction of Higher-Energy γ Rays

In recent months more information has been obtained on the energy dependence of the interaction cross section of γ rays of energies up to about 300 Mev. It is found, for example by Terwilliger and Jones,[13] that the cross section for production of evaporation neutrons increases as energy increases (beyond ≈80 Mev) above the giant resonance region. Taking into consideration this rise in cross section with energy up to 300 Mev, the corresponding equivalent photons could contribute about 3.9×10^{-27} cm^2/Fe-nucleus to the $\sigma\bar{m}$ value for the present experiment. These events probably have a neutron multiplicity less than 7, so this number can be combined with our previous results. We will assume a mean multiplicity of 3 for these events.

These three processes thus account for roughly 8×10^{-27} cm^2/nucleus, in reasonably good agreement with our result. Using the numbers in (1), (2), and (3), one finds $\sigma\approx2.4\times10^{-27}$ cm^2/Fe-nucleus for events in which one or more neutrons is emitted, and $\bar{m}\approx3.3$. The "star" producing events, (1), contribute only about 10 percent to the cross section.

ACKNOWLEDGMENTS

The authors wish to express their thanks to Professor H. Primakoff and Professor R. D. Sard for many helpful discussions.

Our thanks also go to the International Shoe Company for permitting us to use the Lemp Cave site, and Mr. J. D. Campbell and his staff for their cooperation and help in making the experiment possible.

[12] Panofsky, Steinberger, and Stellar, Phys. Rev. **86**, 180 (1952); R. D. Miller, Phys. Rev. **82**, 260 (1951).

[13] L. W. Jones and K. M. Terwilliger, Phys. Rev. **91**, 699 (1953).