Nuclear Disintegrations Induced by μ-Mesons

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The absorption curve in water of the cosmic radiation producing nuclear disintegrations was obtained by recording the neutron showers occurring in an absorber surrounded by BF_3 counters. It was found that, while the N-component of the cosmic radiation is responsible for most of the disintegrations observed under the first few meters of water, μ-mesons are the particles causing either directly or indirectly most of the events recorded at depths greater than $\sim$10 m water. The cross section of μ-mesons for nuclear interactions is found to be $\sim 1\times 10^{-29}$ cm^2/nucleon at a depth of 20 m water. Estimates of the absolute intensity of the N-component and of the relative contribution to nuclear disintegrations by μ-mesons and N-component at sea level are given.

I. INTRODUCTION

THE problem of the interaction of μ-mesons with nucleons has been faced experimentally by looking either for anomalous scattering of the μ-mesons of the cosmic radiation or for the products of the nuclear disintegrations induced by them.

Using the first method, Amaldi and Fidecaro[1] were able to show that for the μ-mesons at sea level (average energy $\sim 1\times 10^9$ ev) the upper limit of the cross section for meson-nucleon interaction is 2.3×10^{-30} cm^2/nucleon. With the second method, several authors have obtained in recent years some indication of the occurrence of nuclear disintegrations underground, at depths large enough for the nucleonic component to be practically eliminated: the events detected were showers of penetrating particles[2] and groups of moderate energy neutrons.[3]

Recently George and Evans[4] reported the observation of stars in photographic plates exposed at 60 m water equiv. Most of these events could be interpreted as direct evidence of nuclear disintegrations induced by μ-mesons, and their frequency indicated a cross section of the order of 10^{-29} cm^2/nucleon (average energy of the mesons $\sim 1.5\times 10^{10}$ ev).

Here an experiment is described, in which the absorption curve in water of the radiation producing nuclear disintegrations was obtained. The events were detected by recording the neutron showers produced in an absorber. As has been discussed in several previous papers,[5] whenever a nuclear disintegration occurs, neutrons with energies from $\sim$1 Mev up are released, and if a nucleon cascade develops, each of its steps causes further production of neutrons.

In comparison with the photographic plate technique, this method has the advantage of allowing the detection of the events occurring in thick absorbers, hence of providing data with a comparatively good statistical accuracy.

II. EXPERIMENTAL AND RESULTS

The experiment was performed during the summer of 1950, in Cayuga Lake, Ithaca, New York (altitude of

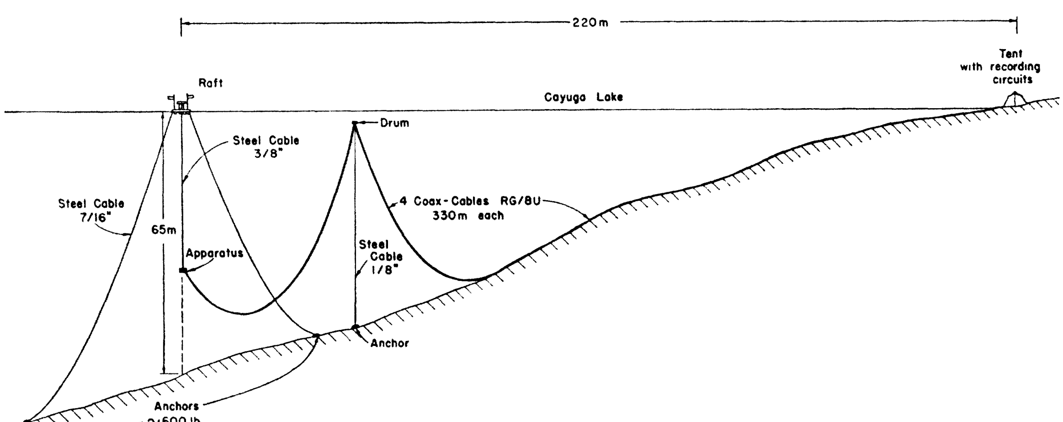

FIG. 1. Layout of the experiment.

[1] E. Amaldi and G. Fidecaro, Phys. Rev. **81**, 339 (1951).
[2] H. J. J. Braddick and G. S. Hensby, Nature **144**, 1012 (1939); E. P. George and P. T. Trent, Nature **164**, 838 (1949).
[3] V. Cocconi Tongiorgi, Phys. Rev. **76**, 517 (1949).
[4] E. P. George and J. Evans, Proc. Phys. Soc. (London) **A, 63**, 1248 (1950).
[5] See, e.g., Cocconi, Cocconi Tongiorgi, and Widgoff, Phys. Rev. **79**, 768 (1950).

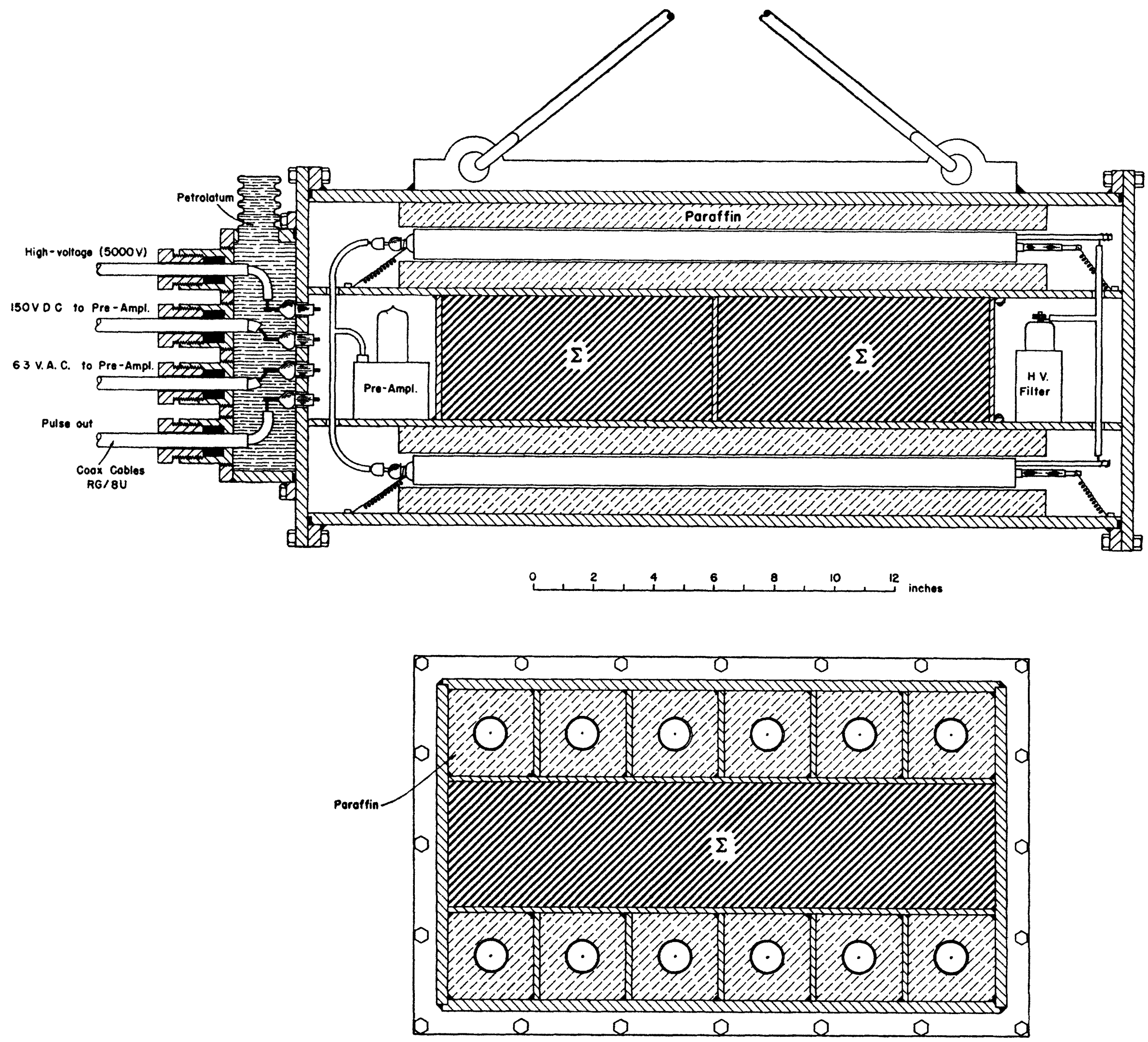

FIG. 2. Side and front views of the water-tight Al box containing the detector. The BF_3 proportional counters had an effective surface of 1″×18″. They were all connected in parallel and operated at the same voltage (∼4500 volts).

the water level 117 m). Valuable help in performing the experiment was given us by Dr. J. Heidmann, to whom we wish to express our appreciation and gratitude.

The general layout of the experiment is sketched in Fig. 1. A raft was anchored 220 m offshore, in a location where the lake is 65 m deep. A winch mounted on it allowed the hoisting of the detector, which was housed in a water-tight aluminum box. Except for a preamplifier, all the recording apparatus was located on shore.[6] Four coax cables *RG/8U*, each 330 m long, were used to carry the high voltage (∼5000 v) to the neutron counters, to supply the preamplifier, and to bring to shore its pulses. These cables stayed in the water without any protection for four months, and showed no sign of leak or deterioration.

[6] We are very grateful to the Pennsylvania Dixie Cement Corporation for the kind hospitality on its ground.

The aluminum box containing the detector is shown in Fig. 2. The detector consisted of 12 BF_3 proportional counters (1″×18″), filled to 101 cm Hg of enriched BF_3, plus 20 cm Hg of Argon, each surrounded by $1\frac{1}{2}$″ of paraffin. Additional slowing down material for the neutrons was provided by the water surrounding the box. The counters, constructed and operated as described in previous papers[3] were all connected in parallel. Their pulses were fed into a preamplifier (Atomic Instrument Company, Model 205-B) then through a matched coax cable, into a linear amplifier (Atomic Instrument Company, Model 204-B) located on shore.

The nuclear disintegrations we intended to study were those occurring inside the absorber Σ placed between the counters; its area was always 18″×18″; data were taken with absorbers of different thicknesses and materials, as listed in Table I.

TABLE I. Rates recorded in the different channels, at various depths and with various absorbers. A count in channel "$m=3$," e.g., means that an event has occurred, in which at least 3 neutrons gave pulses in our counters and were recorded by our circuit. Whenever the absorber was thinner than 4″, it was made of sheets evenly spread in the 4-in. hole. The errors given are standard errors. No errors are given for most of the rates recorded in channel "$m=1$," as the uncertainties due to barometric effect, variations in the amplifier gain, etc., are, in these cases, probably larger than the calculated statistical errors. The figures given in the last column are the over-all efficiencies to record a neutron, as they resulted from measurements taken with a (Ra+Be) source.

Depth	Nature and thickness of absorber (area 18″×18″)	Number of neutrons recorded $m=1$	$m=2$	$m=3$	$m=4$	$m=5$	$m=6$	$m=7$	$m=8$	$m=9$	Efficiency E* (percent)
0 m H_2O	$\Sigma=0$	1370	8.9±0.3	0.34±0.06	0.05±0.02	0					4.8
	$\Sigma=4''$ Pb	8000	937±7	312±4	119±3	49.7±1.7	25.2±1.2	15.2±0.9	8.0±0.7	5.4±0.6	6.3
	$\Sigma=1''$ Pb	3120	188±2	38.8±0.7	8.9±0.4	2.5±0.2	0.87±0.1	0.4±0.07	0.2±0.05	0	5.1
	$\Sigma=\frac{1}{4}''$ Pb	1805	52±0.6	7.6±0.23	1.28±0.1	0.2±0.04	0				4.9
1 m H_2O	$\Sigma=0$	475	4.15±1	0							
	$\Sigma=4''$ Pb	3500	494±9	158±4.8	62.8±3.0	30.6±2.1	14.6±1.5	8.5±1.1	5.6±0.9	3.3±0.7	
2.5 m H_2O	$\Sigma=0$	286±6	3.4±0.7	0.25±0.2	0						4.8
	$\Sigma=4''$ Pb	1650	196±3	68±1.7	25±1.2	11.6±0.6	5.1±0.5	2.95±0.4	1.26±0.26	0.61±0.16	6.3
	$\Sigma=4''$ Al	374	4.88±0.3	0.32±0.09	0.07±0.05	0					
5.5 m H_2O	$\Sigma=0$	169±4	0.3±0.15	0							
	$\Sigma=4''$ Pb	499	39.1±0.4	12.2±0.7	4.7±0.5	2.4±0.3	1.6±0.3	1.03±0.21	0.45±0.14	0.18±0.09	
10.5 m H_2O	$\Sigma=4''$ Pb	321	18.7±0.7	5.0±0.34	2.2±0.23	1.0±0.15	0.6±0.12	0.3±0.08	0.19±0.07	0.07±0.04	
20.5 m H_2O	$\Sigma=0$	100±2	0.04±0.04	0							
	$\Sigma=4''$ Pb	202±2.1	10.6±0.3	3.58±0.19	1.68±0.13	0.83±0.09	0.39±0.06	0.24±0.05	0.15±0.04	0.05±0.02	
	$\Sigma=4''$ Al	112±1.2	0.37±0.03	0.022±0.008	0						
60.5 m H_2O	$\Sigma=0$	90±3	0.03±0.03	0							
	$\Sigma=4''$ Pb	109±1.1	3.36±0.15	1.25±0.09	0.64±0.07	0.35±0.05	0.2±0.04	0.13±0.03	0.08±0.02	0.05±0.02	

* The remarkable increase in the efficiency due to presence of the thick Pb-absorber is to be mainly accounted for by the following reasons: (a) the inelastic collisions with absorber-nuclei cause the neutrons to have smaller average energy when they reach the counters; (b) the diffusion in the absorber causes the neutron source to act not as a point source, but rather as an extended source smeared out in the whole volume of the absorber. When, as in our case, the counters are rather close to the surface of the moderating material, both these effects increase the probability of recording the neutrons.

The over-all efficiency E of the system for recording a neutron produced in $\sum$ was experimentally determined by locating a calibrated (Ra+Be) source in different positions inside the absorbers used. It was found to vary from $E=0.048$ to $E=0.063$ depending on the nature and thickness of the absorber. The values determined for E are given in the last column of Table I. It has been proved in a previous work[5] that the spectrum of the neutrons produced in nuclear evaporations is similar enough to the spectrum of the neutrons emitted by a (Ra+Be) source, to make these determinations accurate within less than 20 percent.

As pointed out before, whenever a nuclear disintegration occurs, a shower of neutrons of moderate energies is generated. These neutrons, slowed down in the paraffin and in the water, will produce in the counters a succession of pulses distributed in time according to the neutron lifetime τ in the detector ($\tau\approx 160$ μsec), the event being practically exhausted in a time of the order of 2 or 3τ. If the pulses emerging from the amplifier were observed on a scope, they would appear as single pulses due to incoherent neutrons crossing the counters and to the counter-background, mixed with occasional groups of pulses caused by the neutron showers generated in the nuclear disintegrations, the latter events being the ones we intended to select.

The selection was made as follows. Whenever a pulse occurred in the counters, a gate of duration $T=160$ $\mu\text{sec}\approx\tau$ was opened, and a count registered in channel "$m=1$." If a second pulse was produced while this gate was on, a coincidence would be recorded, a count registered in channel "$m=2$," and a new gate of duration T opened. If a third pulse occured within this gate, a coincidence would be formed, a count registered in channel "$m=3$" and a fourth gate opened; and so forth up to channel "$m=9$." The readings of the nine registers directly give the integral pulse distribution due to the neutrons produced in the nuclear disintegrations, and recorded by our detector.

The rate of chance coincidences was always negligible. In fact, in the least favorable case, namely, in channel "$m=2$" at the depth of 1 m water, the ratio of the chance coincidences to the total coincidences recorded, was of the order of 10^{-3}.

The data taken without absorber, i.e., with $\sum=0$, were used as a background correction, and subtracted from the results obtained with the different absorbers. This correction takes care of the spurious events leading to the production in the counters of a number of ions comparable with that produced by the $B^{10}(n,\alpha)Li^7$ reaction (α-contamination of the counter walls, stars of heavily ionizing particles, electron bursts, etc.), which will affect only the number of counts recorded in channel "$m=1$"; furthermore it takes care of most of the neutrons generated in the nuclear disintegrations occurring in the surroundings of the absorber $\sum$ (paraffin, counters, aluminum box, water, etc.).

As shown in Table I, 99.9 percent of the counts recorded under water with $\sum=0$ occurred in channel "$m=1$," 0.1 percent in channel "$m=2$," none in the following channels.

Data were taken at depths of 1, 2.5, 5.5, 10.5, 20.5, and 60.5 m water. "Ground points," called hereafter points at depth "0," have been obtained by running the

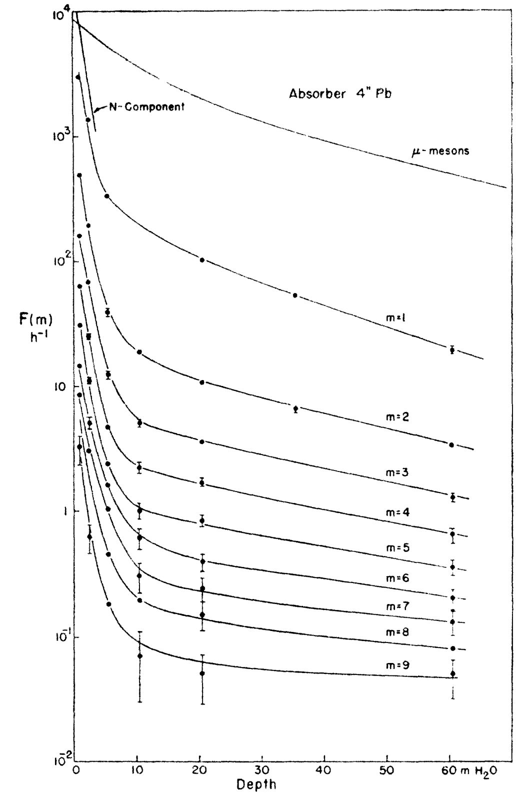

FIG. 3. Rates $F(m)$ recorded in the various channels, *vs* depth in m water, for the absorber $\Sigma=4''$ Pb. The absorption curves of the N-component (MFP=160 g/cm²) and of the μ-mesons are given for comparison.

experiment in the laboratory (260 m above sea level) with the aluminum box used in the lake surrounded on all sides by 6″ of paraffin. It was verified, by using the (Ra+Be) source, that the efficiency of the detector in this condition was the same as that measured in the lake.

All the experimental results are collected in Table I with their standard errors.

III. ABSORPTION CURVE OF THE RADIATION PRODUCING NUCLEAR DISINTEGRATIONS

The frequencies $F(m)$ recorded with $\sum=4''$ Pb, corrected for background, are plotted *versus* depth in Fig. 3.

The depth dependence being approximately the same for the rates recorded in all the channels, we shall discuss all the curves together.

In the first few meters of water, the slope of the curves indicates an absorption length of about 160 g/cm². At greater depths, say from ~10 m water on, the events are produced by a radiation whose absorption length is of the order of 4000 g/cm².

This shows that while the N-component is the radiation producing the great majority of the events observed at the level of the water and under the first few meters of water, at large depths most of the nuclear disintegrations observed are produced by the penetrating component of the cosmic radiation, namely by μ-mesons.

The absorption curves of μ-mesons and N-component are given in the figure for comparison.

By extrapolating to depth "0" the absorption curve obtained at depths greater than 20 m water, one can deduce that at sea level the μ-mesons contribute only ~2 percent of the disintegrations observed, the remaining 98 percent being caused by the N-component.

In reaching the conclusions contained in this section it is implicitly assumed that the probability of recording the nuclear disintegrations is the same at all depths. There is no *a priori* reason for this to be so; however, the procedure is justified by the experimental result that the neutron distribution in the different channels was found to be practically the same everywhere.

IV. QUANTITATIVE INTERPRETATION OF THE RESULTS AT DEPTHS GREATER THAN 10 M WATER

We shall base our discussion on the results obtained at 20 m water, where the frequency of the events still provides good statistics and the intensity of the N-component is already negligible. Curves A and B in Fig. 4 are the results for $\sum=4''$ Pb and for $\sum=4''$ Al, corrected for background. We shall call each of these curves the "recorded multiplicity spectrum" of the neutrons produced in the events occurring in the absorber considered.

Let us consider first the data with $\sum=4''$ Pb. The processes that can give rise to production of neutrons in $\sum$, are:

(a) capture of negative μ-mesons:

using the differential range spectrum given by Rossi[7] and assuming for the slow mesons a $\cos^3\theta$ law of zenith angle dependence, the number of negative μ-mesons expected to stop in Σ (whose mass is 2.37×10^5 g) is 395 hr⁻¹. Assuming that the probability of emitting a neutron is exponential,[8] with average multiplicity 2,[9,10] and using the method described later in this section, one finds that the expected number of counts in the various channels, due to this process, are:

$m=1$	$m=2$	$m=3$
58 hr⁻¹	3 hr⁻¹	0.25 hr⁻¹.

One can see that the contribution of the μ-capture, owing to the low value of the neutron multiplicity, is essentially confined to the first couple of channels.

(b) (γ, n) reactions induced by the photons in equilibrium with the μ-mesons:

this process is discussed in the following paper by Hayakawa, from where one deduces that at 20 m water the equivalent cross

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

[8] Probably a poisson distribution is nearer to the truth than an exponential one. However, the choice of the exponential spectrum, which was made for sake of simplicity, will not affect the final results.

[9] Groetzinger, Berger, and McClure, Phys. Rev. **81**, 969 (1951); Sard, Crouch, Jones, Conforto, and Stearns, Nuovo cimento **8**, 326 (1951).

[10] M. Widgoff (private communication).

section of the μ-mesons for producing neutrons is $\sigma_{\mu,\gamma,n}=1.0\times10^{-28}$ cm²/nucleon, and the average number of neutrons per meson is $\bar{\nu}=1$ to 2. The expected number of neutrons is, therefore:

$$\mathcal{G}_{\gamma,n}=A_{\mathrm{Pb}}\times\sigma_{\mu,\gamma,n}\times\bar{\nu}\ (\mathrm{hr}^{-1})$$

where

$$A_{\mathrm{Pb}}=3600\times2\pi MNI_{\mu v}\int_0^{\pi/2}\cos^n\theta\sin\theta d\theta.$$

With N = Avogadro's number, M = mass of the absorber, I_{Nv} = vertical intensity of the μ-mesons at 20 m water $=2\times10^{-3}$ cm^{-2} sec^{-1} ster^{-1}, $n=2$ and $\bar{\nu}=1.5$, one has

$$A_{\mathrm{Pb}}=2.15\times10^{30}\ \mathrm{cm}^{-2}\ \mathrm{hr}^{-1}$$

and

$$\mathcal{G}_{\gamma,n}=320\ \mathrm{hr}^{-1}.$$

These neutrons contribute about $320\times E=320\times0.063=20$ counts per hour in channel "$m=1$," and 0.8 hr^{-1} in channel "$m=2$."

(c) Nuclear disintegrations induced either directly by the μ-mesons or by their secondaries (photons, π-mesons, nucleons). These events will, in general, give rise to many neutrons, both in the primary interaction and in the subsequent nucleon cascade, hence, they will contribute to the counts recorded in all channels.

To discuss these processes, the rates recorded in the various channels have been corrected by subtracting the contributions of the events (a) and (b) (open circles in Fig. 4).

From the recorded neutron multiplicity spectrum thus obtained, one can deduce the true neutron multiplicity spectrum, by taking into account the probability $f(m)$ of recording the counts in the various channels.

Let

$I(\nu)$ = probability that in an event ν neutrons are released in $\sum$, both in the primary interaction and in the subsequent cascade,

$G(\nu,n)=\binom{\nu}{n}E^n(1-E)^{\nu-n}$ = probability that the ν neutrons give n ($n\leqslant\nu$) pulses in the counters,

$P(n,m)=(1-\kappa^{n-1})(1-\kappa^{n-2})\cdots(1-\kappa^{n-m+1})$, with

$$\kappa=\int_T^{\infty}e^{-t/\tau}dt/\tau,$$

(T is the coincidence gate, and τ is the neutron lifetime) = probability that m out of the n pulses arrive with the right timing to be recorded by channel "m." One has:

$$f(m)=\sum_{\nu=m}^{\infty}\sum_{n=m}^{\infty}I(\nu)G(\nu,n)P(n,m).$$

An appropriate function $I(\nu)$ has to be chosen to make the function $f(m)$ fit the experimental data. With

$$I(\nu)=[\exp(1/\bar{\nu})-1]\exp(-\nu/\bar{\nu})$$

one has:

$$f(1)=B/\exp(-1/\bar{\nu}),\quad\text{where}\quad B=\frac{E\exp(-1/\bar{\nu})}{1-(1-E)\exp(1-/\bar{\nu})},$$

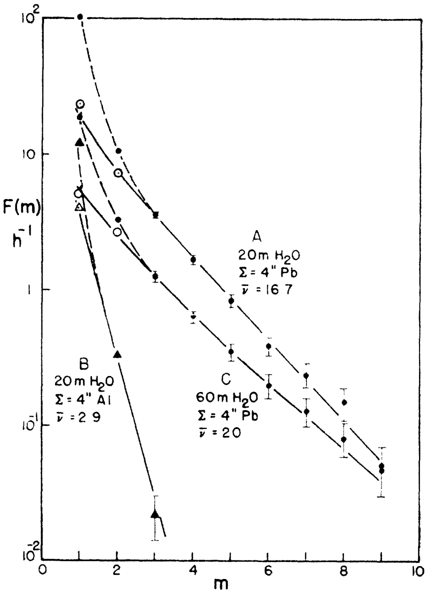

FIG. 4. Rates $F(m)$ recorded in the various channels at a given depth *vs* the order m of the channel (neutron multiplicity spectra). The solid symbols represent experimental points. The open symbols represent points corrected for effects due to μ-meson capture and (γ, n) reactions. The dotted lines connect the experimental points. The solid lines are the functions calculated in Sec. IV, assuming that the true neutron multiplicity spectra are exponential with average multiplicity $\bar{\nu}$.

$$\underset{m\geqslant2}{f(m)}=\frac{1-\exp(-1/\bar{\nu})}{E\exp(-2/\bar{\nu})}B^{m+1}(1-e^{-T/\tau})(1-e^{-2T/\tau})\cdots\times(1-e^{-(m-1)T/\tau})\Bigg[1+B\frac{1-e^{-mT/\tau}}{1-e^{-T/\tau}}+B^2\frac{(1-e^{-mT/\tau})(1-e^{-(m+1)T/\tau})}{(1-e^{-T/\tau})(1-e^{-2T/\tau})}+B^3\frac{(1-e^{-mT/\tau})(1-e^{-(m+1)T/\tau})(1-e^{-(m+2)T/\tau})}{(1-e^{-T/\tau})(1-e^{-2T/\tau})(1-e^{-3T/\tau})}+\cdots\Bigg]$$

where $T/\tau\approx1$.

The curve shown in Fig. 4 is the function $f(m)$ obtined with $\bar{\nu}=16.7$, multiplied by a factor $\mathcal{G}=37$. The agreement is satisfactory.

We therefore conclude that the frequency of the disintegrations occurring in the 4" Pb absorber at 20 m water, is $\mathcal{G}=37$ hr^{-1}, and that the average multiplicity of the neutrons released in them is ~17. The value of the average multiplicity $\bar{\nu}$ is determined with roughly the same precision as the efficiency E, i.e., $\sim\pm20$ percent. However, the condition that $f(m)$ fit the experimental data makes the value of the frequency $\mathcal{G}$ practically independent of the value assumed for E. The uncertainty of our estimate of $\mathcal{G}$, about 10 percent, is mostly due to the statistical errors in the experimental data.

Using the value of A_{Pb} given above, one deduces that the nuclear disintegrations are produced with a cross section

$$\sigma = 1.7\times 10^{-29}\ \mathrm{cm^2/nucleon}.$$

This value of σ would represent the cross section of the μ-mesons for producing nuclear disintegrations, if the contribution to the disintegrations due to the secondaries of the μ-mesons produced outside the absorber $\sum$ and interacting in it were negligible.

The effect of the secondary particles can be crudely estimated as follows:

with:

$\lambda_{\mu\ \mathrm{Pb}}$, the collision mean free path in Pb of μ-mesons for production of nuclear disintegrations (in g/cm²),

$\lambda_{\mu w}\approx\lambda_{\mu\ \mathrm{Pb}}$, the meson MFP in water,

$\lambda_{N\ \mathrm{Pb}}=160$ g/cm², the collision MFP in Pb of the nucleons and π-mesons secondaries of the μ-mesons,

$L_{Nw}=120$ g/cm², the absorption length in water of these secondaries,

$I_\mu(\theta)$ = the intensity of the μ-meson component at 20 m water, in direction θ,

$I_N(\theta)$ = the intensity of the secondaries, in direction θ.

The frequency $\mathcal{I}$ of the disintegrations produced in Σ is:

$$\mathcal{I}=\mathcal{I}_\mu+\mathcal{I}_N=2\pi\int_0^{\pi/2}I_\mu(\theta)S\cos\theta(h/\cos\theta)(1/\lambda_{\mu\ \mathrm{Pb}})\sin\theta d\theta$$
$$+2\pi\int_0^{\pi/2}I_N(\theta)S\cos\theta[1-\exp(-h/\lambda_{N\ \mathrm{Pb}}\cos\theta)]\sin\theta d\theta,$$

where S and h are surface and thickness of Σ. Assuming that the secondary particles have the same zenith angle dependence as the μ-mesons, ($I(\theta)=I_v\cos^2\theta$), one has:

$$\mathcal{I}\approx\frac{2\pi}{3}Sh\left[\frac{I_{\mu v}}{\lambda_{\mu\ \mathrm{Pb}}}+\frac{I_{Nv}}{\lambda_{N\ \mathrm{Pb}}}\times 0.72\right].$$

Owing to their short range, the secondaries are in equilibrium with the μ-mesons, i.e.:

$$I_{\mu v}/\lambda_{\mu w}\times n=I_{Nv}/L_{Nw},$$

where n is the average multiplicity of the secondaries produced by the μ-mesons outside the absorber Σ. This gives:

$$\mathcal{I}=\frac{2\pi}{3}Sh\left[\frac{I_{\mu v}}{\lambda_{\mu\ \mathrm{Pb}}}+0.72\frac{I_{\mu v}}{\lambda_{\mu w}}\frac{L_{Nw}}{\lambda_{N\ \mathrm{Pb}}}\right]\approx\frac{2\pi}{3}Sh\frac{I_{\mu v}}{\lambda_{\mu\ \mathrm{Pb}}}[1+0.67n].$$

The multiplicity n is unknown, but is likely smaller than 2.

Hence we conclude that $\mathcal{I}_\mu/\mathcal{I}_N\approx 1$, i.e., the contribution by the secondaries of the μ-mesons is not negligible, but of the same order or magnitude as that of the μ-mesons. Using this result, the cross section, σ_μ, of the μ-mesons for producing nuclear disintegrations is about $\frac{1}{2}$ of the σ given above, hence close to 0.8×10^{-29} cm²/nucleon.

The data obtained with the Al-absorber can be analyzed following the same path.

The number of negative μ-mesons stopping in Σ is $\sim$90 hr⁻¹. Assuming that the average number of neutrons produced in each capture is $\sim$1,[10] their contribution to channel "$m=1$" is $\sim$6 hr⁻¹, to channel "$m=2$," $\sim$0.1 hr⁻¹.

The number of neutrons caused by (γ, n) reactions is

$$C_{\gamma,n}=A_{\mathrm{Al}}\times\sigma_{\mu,\gamma,n}\times\bar{\nu},$$

where $A_{\mathrm{A}}=5.2\times 10^{29}$ cm⁻² hr⁻¹. Using $\bar{\nu}=1$ and $\sigma_{\mu,\gamma,n}=0.8\times 10^{-29}$ cm²/nucleon,[11] one has $C_{\gamma,n}=42$ hr⁻¹, which will produce about 2 counts in channel "$m=1$." The recorded rates, corrected for these two contributions (see the open triangle in Fig. 4), can be interpreted as due to the disintegrations induced in the Al-absorber by μ-mesons and their secondaries.

The function $f(m)$ that fits the data is shown in Fig. 4. The multiplication factor, hence, the true frequency of the events recorded, is $\mathcal{I}=24$ hr⁻¹, and the average neutron multiplicity is $\bar{\nu}\approx 3$.

The cross section for production of these disintegrations is

$$\sigma=\frac{\mathcal{I}}{A_{\mathrm{Al}}}\approx 4\times 10^{-29}\ \mathrm{cm^2/nucleon}.$$

The estimate of the contribution of the secondaries (using $\lambda_{N\ \mathrm{Al}}=80$ g/cm²) gives

$$\mathcal{I}=\frac{2\pi}{3}Sh\frac{I_{\mu v}}{\lambda_{\mu\ \mathrm{Al}}}[1+1.6n],\quad\text{hence}\quad\frac{\mathcal{I}_\mu}{\mathcal{I}_N}\approx\tfrac{1}{3},$$

i.e., the disintegrations produced directly by the μ-mesons in the Al-absorber are about $\frac{1}{3}$ of those produced by their secondaries.

Therefore, the cross section σ_μ for the μ-mesons is found again to be close to 1×10^{-29} cm²/nucleon. Of course, the large statistical errors and the size of the corrections introduced, make this result less reliable than that obtained from the data with lead. Anyway, within the accuracy of the results, the meson cross section per nucleon seems to be independent of the atomic number of the material in which the interaction occurs, as expected. For a definitive answer to this problem more accurate experiments are needed.

Our estimates of the contribution by the secondaries of μ-mesons, both for Pb- and Al-absorber, do not take into account the disintegrations induced by the photons in equilibrium with the μ-mesons. However, as shown by Hayakawa, the equivalent cross section for this process is about 10 times smaller than the cross section obtained above, hence the (γ, star) processes do not affect our results.

We are, therefore, led to conclude that at a depth of 20 m water (average energy of the mesons $\sim$6 Bev) μ-mesons produce nuclear disintegrations, by nuclear interaction, with a cross section $\sigma_\mu=(1\pm 0.5)\times 10^{-29}$ cm²/nucleon. This result is in agreement with that of George and Evans.

The data obtained at 60 m water for $\sum=4''$ Pb have also been analyzed. The experimental data are given in curve C, Fig. 4. The corrections in channel "$m=1$" are:

7 hr⁻¹ (for neutrons from μ-capture)

7 hr⁻¹ (for neutrons from (γ, n) reactions)

in channel "$m=2$" are:

0.6 hr⁻¹ (for neutrons from μ-capture)

0.3 hr⁻¹ (for neutrons from (γ, n) reactions).

A function $f(m)$ with $\bar{\nu}=20$ and $\mathcal{I}=10$ fits the corrected data, which gives $\sigma=\sim 1.8\times 10^{-29}$ cm²/nucleon hence,

$$\sigma_\mu=\sim 0.9\times 10^{-29}\ \mathrm{cm^2/nucleon}.$$

The ratio of the calculated frequencies of the dis-

[11] We thank Dr. Hayakawa for these estimates.

integrations occurring in $\sum$ at 20 and 60 m water is $37/10=3.7$, close to the ratio between the μ-meson intensities at the two levels, which is 4.

The poor accuracy of our data does not allow us to draw conclusions about the variation of the cross section with the μ-meson energy. In fact, according to the formula given by George and Evans, the cross section at 60 m water is expected to be higher than that at 20 m water only by a factor 1.5. We can only say that the energy dependence of the meson cross section is within the expected range.

According to that formula, the expected value of σ for μ-mesons at sea level ($\sim 10^9$ ev) would be $\sim 2\times 10^{-30}$ cm^2/nucleon, close to the limit set by Amaldi and Fidecaro.[1,12]

V. ANALYSIS OF THE DATA TAKEN AT DEPTH "0"

The data taken at depth "0" (260 m above sea level), corrected for background, are plotted in Fig. 5.

As shown in Sec. III, at this level μ-mesons cause only about 2 percent of the events observed, hence most of the disintegrations recorded are originated by the N-component. The corrections for neutrons arising from μ-capture and (γ, n) reactions are here practically negligible ($\sim$5 percent in channel "$m=1$").

Figure 5 shows that the thicker the absorber $\sum$, the flatter is the multiplicity spectrum of the neutrons recorded. This is in agreement with the results of a previous experiment,[5] and is caused by the increase, with increasing absorber thickness, of the number of secondary events in the nucleonic cascade which develops inside the absorber. In the quoted experiment, the requirement was made that at least one ionizing particle capable of emerging from the absorber and of penetrating at least 22 g/cm^2 of paraffin be produced along with the neutrons. This set a bias against low energy events, hence the disintegrations recorded in that experiment involved, on the average, higher energies than those selected here. The differences in the relative slope of the three curves are therefore less marked here than there. With the same analysis as given in Sec. IV, one can describe the slopes of the curves in Fig. 5, for $m\geqslant 3$, with exponential spectra whose average multiplicities are 4.5, 7 and 17 respectively. For the same thicknesses of Pb-absorber, in the quoted experiment we obtained average multiplicities 10, 17 and 50.

It is interesting to compare the shape of the neutron spectra for $\sum=4''$ Pb, obtained at depth "0" and at a depth of 20 m water. The distribution in the various

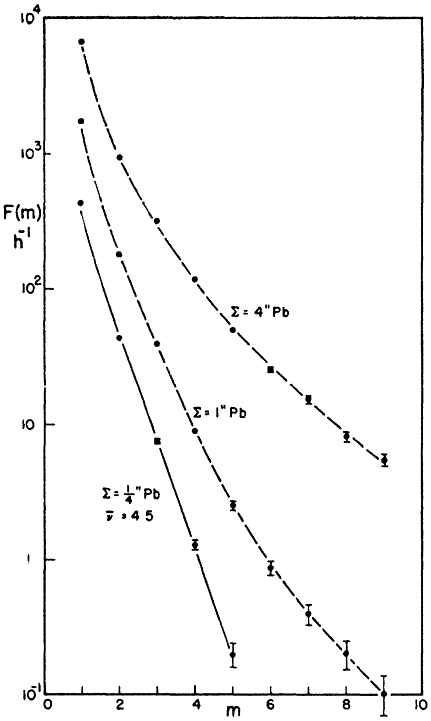

FIG. 5. Rates $F(m)$ recorded in the various channels at depth "0," for $\Sigma=\frac{1}{4}''$ Pb, $\Sigma=1''$ Pb and $\Sigma=4''$ Pb. The dotted lines connect the experimental points. The solid line is the function calculated to describe the results with $\Sigma=\frac{1}{4}''$ Pb.

channels of the neutrons recorded is practically the same at the two levels. After the corrections for μ-meson capture and (γ, n) reactions have been introduced, the shapes of the spectra are radically different for low values of m ($m=1$ and 2), but the same within the statistical errors for $m\geqslant 3$. The large number of events, leading to counts in channels $m=1$ and $m=2$ at sea level, are easily accounted for by the disintegrations due to the low energy tail of the N-component present in the atmosphere. The fact that the events in which a large number of neutrons are produced show approximately the same neutron spectrum both for nucleon-initiated and μ-meson-initiated events supports George and Evans's result that the heavy prong distribution of the stars observed at 60 m water does not differ much from that of the stars observed at mountain altitude.

The data obtained with $\sum=\frac{1}{4}''$ Pb, can be utilized to make an estimate of the absolute intensity of the N-component. In fact, in such an absorber, equivalent to only $\sim 1/20$ of an interaction MFP of the N-component, the effect of the nucleonic cascade is negligible, and the neutrons recorded are essentially those produced in the first interaction of the N-component with the Pb-nuclei. The solid line in Fig. 5 is the calculated curve which fits the data, with $\bar{\nu}=4.5$; the multiplication factor, i.e., the frequency of the disintegrations occurring in $\sum$, is $\mathcal{I}=1800$ hr^{-1}.

[12] Recently, measurements have been taken inside a salt mine at a depth of 1570 m water (average energy of the mesons $\sim 3\times 10^{11}$ ev) with the same apparatus as used at depth "0." With $\Sigma=4''$ Pb, the rate of counts in channel "$m=3$" was 3/335 hr^{-1}, while with $\Sigma=0$ the rate recorded in the same channel was 2/320 hr^{-1}. The background was too high to hope for any quantitative result. However, the rate 3/325 hr^{-1} can be used to estimate an upper limit for the meson cross section. Assuming that the neutron spectrum is the same as found at 60 m water, one deduces: $\sigma_{\mu\max}=12\times 10^{-29}$ cm^2. The expected value, using George and Evans' formula, is close to 3×10^{-29} cm^2.

If I_{Nv} is the vertical intensity of the N-component at the level considered, one has

$$\mathcal{G}=\int_0^{\pi/2} I_{Nv}\cos^n\theta S\cos\theta \times[1-\exp(-h/\lambda_{N\,\mathrm{Pb}}\cos\theta)]2\pi\sin\theta d\theta \cong \frac{2\pi}{n+1}Sh\frac{I_{Nv}}{\lambda_{N\,\mathrm{Pb}}}=73I_{Nv}.$$

We have assumed here $n=7$ and $\lambda_{N\ \mathrm{Pb}}=160$ g/cm^2. Therefore $I_{Nv}=6.86\times10^{-3}$ cm^{-2} sec^{-1} ster^{-1}, and the total intensity at 260 m a.s.l. is

$$I=2\pi/(n+2)I_{Nv}=4.75\times10^{-3}\ \mathrm{cm^{-2}\ sec^{-1}}.$$

Assuming the absorption length in air to be $L_{N\,\mathrm{air}}=150$ g/cm^2, the total intensity of the N-component at sea level is

$$I_0=\sim4\times10^{-3}\ \mathrm{cm^{-2}\ sec^{-1}}.$$

We attribute to this figure an uncertainty of about 10 percent.

As pointed out before, our figure refers to the N-component capable of producing a nuclear disintegration in which at least one neutron is released, i.e., to particles whose energy is larger than $\sim$10 Mev.

As the total μ-meson component at sea level is $\sim1.3\times10^{-2}$ cm^{-2} sec^{-1}, the N-component is found to constitute about 30 percent of the μ-meson component.

Our result can be compared with estimates of I_0, based on other experimental data. Of course, the comparison is necessarily crude, as each experiment sets a different bias against low energy particles.

The frequency of stars with 3 or more prongs, observed in photographic plates is, at sea level: $n_s\approx5\times10^{-6}$ sec^{-1} g^{-1}.[13] The discrepancies in the results of different authors give to this figure are uncertainty of about 20 percent. If the MFP for interactions in the emulsion is assumed to be $\lambda_{N,\,em}=120$ g/cm^2, one obtains $I_0=n_s\lambda_{N,\,em}(n+1)/(n+2)=5.3\times10^{-4}$ cm^{-2} sec$^{-1}=\sim4$ percent of the μ-mesons. This value of I_0 refers to particles having energies higher than $\sim$100 Mev. To compare with our result, one should include all the stars with 1 or 2 prongs, and also the events in which no ionizing particles but only neutrons are emitted. The extrapolation to stars of 1 or more prongs is very questionable, due to the correction needed for the inefficiency for the detection of small stars. Likely, the figure given above has to be multiplied by a factor larger than 2. Another factor of the same order or larger will probably arise from the addition of stars with no ionizing prongs, which must be very abundant. Therefore, though no agreement can be claimed, our result is not inconsistent with the estimate of the N-component intensity deduced from star frequency.

Our estimate can be more directly compared with the results of the measurements of the neutrons in the free atmosphere. From Yuan's[14] data one deduces that the rate of production in air of neutrons at sea level is $\sim1.0\times10^{-4}$ sec^{-1} g^{-1}. As the diffusion process of the neutrons in the atmosphere leads to practically no loss of particles, the above figure essentially represents the number of particles with energies of some Mev, produced in nuclear disintegrations in 1 g of air. With the assumption that the interaction MFP of the N-component in air is $\lambda_{N,\,\mathrm{air}}=80$ g/cm^2, one has

$$I_0\bar{\nu}=\sim7\times10^{-3}\ \mathrm{cm^{-2}\ sec^{-1}},$$

where $\bar{\nu}$ is the average number of neutrons released in each interaction in air. Agreement with our estimate of I_0 is obtained for $\bar{\nu}=1.7$, which is not unreasonable.

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