and show that the value for the lifetime is not greater than 10^{-7} sec.

A detailed explanation of these curves is difficult. The initial drop seems best explained as dependent on the subordinate series radiation which was excited more or less continuously in the region screened from the photoelectric tube by the baffles and which was absorbed and reradiated by the excited atoms in the 5^3P states found in the unscreened part of the tube. The corresponding persistence would then be the same as the persistence of the 5^3P states in that part of the tube. The second drop in the curve, which occurred at high frequencies, would be explained in the case of the sharp series as due to the direct excitation to the 6^3S level (or 5^3D level for the diffuse series) of atoms in the unscreened region during the positive half-cycle of the alternating voltage and their radiation to the photoelectric tube either directly or with not more than one or two absorption-re-emission steps. For this radiation the persistence would be of the order of the mean lifetime of the level in question. Because of the uncertainties as to the exact processes involved in the measurements, the above results can probably be relied upon only as to the order of magnitude of the lifetimes.

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Production of Single Mesotrons by Non-Ionizing Radiation at Altitudes of 10,600 ft. and 14,200 ft.

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The production of single mesotrons in various materials was studied by means of an apparatus consisting of 46 Geiger-Mueller counters arranged in 10 different three-, four-, and fivefold coincidence sets. The producing layers consisted of different thicknesses of paraffin, iron, and lead. The results indicate that photons are the most probable agent for the production of the single mesotrons. The cross section for the mesotron production has been calculated for the various producing materials.

INTRODUCTION

IN 1938 Schein and Wilson[1] published a paper concerning the production of penetrating cosmic-ray secondaries in the atmosphere above 20,000 feet. They found considerable production at 25,000 feet and indicated that the secondary particles observed were produced by photons. Since then, many attempts have been made to identify the nature of the producing radiation. Shonka[2] found the production to be as high as 6.1 percent in a producing layer of 20 cm of lead at an altitude of 14,200 feet. Only 1.5 percent was attributed to penetrating radiation arising from photons. The other 4.6 percent was ascribed to neutral particles of greater penetration (neutrons). Schein, Jesse, and Wollan[3] undertook the investigation of the production of penetrating particles by non-ionizing radiation as a function of altitude. Their results indicated that an appreciable production takes place above 23,000 feet with increasing altitude. Because the intensity of the produced mesotrons followed the intensity of the soft component, photons were considered as the most probable producing agent. Rossi and Regener[4] studied the production of mesotrons at 14,200 feet. They found a definite production which was attributed to either neutrettos or high energy neutrons. They arrived at this conclusion because it appeared that the producing radiation had a large probability of

[1] M. Schein and Wilson, Phys. Rev. **54**, 304 (1938).
[2] F. Shonka, Phys. Rev. **55**, 24 (1939).
[3] Schein, Jesse, and Wollan, Phys. Rev. **56**, 613 (1939).
[4] B. Rossi and V. Regener, Phys. Rev. **58**, 837 (1940).

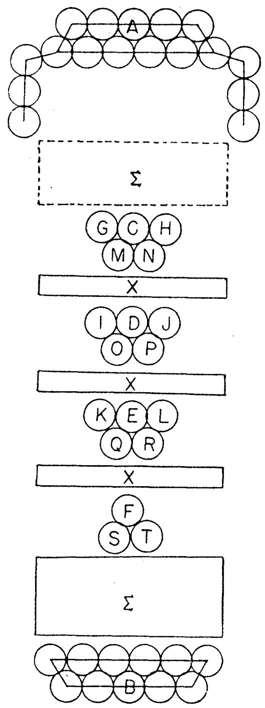

FIG. 1. Counter arrangement.

traversing several centimeters of lead without generating secondary ionizing particles. Regener,[5] in 1943, reported that the production of non-shower-producing particles by photons at altitudes up to 11,500 feet was as high as 10 percent of the total penetrating component. All these different investigations definitely showed that there exists a production of mesotrons by non-ionizing radiation. However, no definite evidence was available to indicate the nature of the mesotron-producing radiation.

The following experiment was carried out at Mt. Evans, Colorado (14,200 feet), in order to determine whether photons are able to produce single mesotrons. This seemed possible by investigating the absorption of the mesotron producing radiation as a function of thickness in materials of different atomic numbers.

APPARATUS

The counter arrangement used in the following experiment is schematically represented in Fig. 1. The forty-six counters were arranged into ten different three-, four-, and fivefold coincidence circuits. The seventeen counters A and also the eleven counters B were each connected in parallel. Counter batteries A and B completely covered and extended in both directions beyond the solid angle subtended by counters $CDEF$. The coincidence circuits were of a conventional type similar to those used by Schein, Jesse, and Wollan in their balloon flights. The resolving power of the circuits was tested and found to be approximately 10^{-5} sec. Hence, for the three-, four-, and fivefold coincidences chance coincidences were negligible. Each coincidence circuit operated an individual neon light which was photographed by a Simplex movie camera whenever a pulse occurred simultaneously in the so-called master coincidence set. Counters $CDEF$ constituted this master set. A coincidence pulse in the master set corresponded to the passage of a penetrating particle[6] through the lead layers X. Thus, by observing the neon lights which were photographed during each exposure on the same film, one could determine which of the various possible coincidence sets were tripped simultaneously with the master set.

All counters were 1 in. in diameter, but of two different lengths. The counter batteries A and B consisted of counters 13.5 in. long. All other counters were 6 in. long. The tubes were filled with a mixture of 90 percent argon and 10 percent alcohol. Each counter tube had a voltage plateau of at least 200 volts, and all were matched so that they had very nearly the same starting potential. They all were then connected to the same high voltage supply and were operated at 1240 volts. The counters were mounted in a wooden stand which contained various lead layers X and Σ' and provided space for the insertion of a producing layer. In Fig. 1 the producing layer is designated by Σ. This layer could be varied up to a thickness of 11.5 cm. Σ consisted of paraffin, iron, and lead. The three lead layers X were used to discriminate between penetrating particles and electrons, and each had a thickness of either 0.64 cm or 1.59 cm of lead. Since a thickness of 0.6 cm is very nearly equal to a radiation unit in lead, an electron passing through all three lead absorbers should have an extremely high probability of emerging

[5] V. Regener, Phys. Rev. **64**, 252 (1943).

[6] Since most of these particles are later shown to be mesotrons, they will be referred to as such in the rest of this paper.

as a cascade shower below each of the lead layers X. To determine whether the particle which tripped the master set was an electron or a mesotron, several groups of counters were arranged in seven separate coincidence sets so as to indicate the presence of showers below the various lead layers. Counters *GCHF* formed a fourfold and *MNF* a threefold coincidence set. Pulses in these sets showed the presence of a shower directly below the producing layer Σ. Counters *IDJF*, *KELF*, and *CFST* constituted three fourfold (coincidence sets), and counters *OPF* and *QRF* two threefold coincidence sets. Coincidence pulses from any of these counter arrangements indicated that showers were present below the lead layers X. It is to be noted, however, that a small percentage of the threefolds occurring below only one single layer X could be due to the presence of knock-on electrons kicked out of one of the lead layers by a mesotron.[7] The lead layer Σ', 6.98 cm thick, was used to absorb low energy mesotrons.

ACDEF formed a fivefold coincidence set. If this set was tripped, the presence of an ionizing particle traversing the producing layer Σ and the layers X was indicated. A coincidence in *CDEF* which was not accompanied by a coincidence in *ACDEF* generally meant the production of an ionizing particle in layer Σ by non-ionizing radiation. These produced particles were attributed to single mesotrons when such an event was unaccompanied by a pulse in any of the seven shower sets. The lower set of counters B was also connected with the master set *CDEF* in a fivefold coincidence. A coincidence in this set showed whether or not a particle tripping the master set had enough energy to traverse the 6.98 cm of the lead absorber Σ'.

With the six side-counters in bank A removed, some cases were found where ionizing particles entered from the side and were scattered in the producing layer in such a way that they tripped the master set. Such events appeared similar to the production of an ionizing particle in Σ. After adding the six "police" counters in A, however, the presence of side particles was detected as a coincidence *ACDEF* and hence did not represent a production process by non-ionizing radiation. Air showers had no effect on the production of single mesotrons because they were eliminated by tripping at least one of the shower sets in the neighborhood of counters *CDEF*. The efficiency of the banks of counters A and B was very nearly 100 percent. This high efficiency could be obtained only by using tubes of relatively small diameter, thereby reducing the single counting rate in each of the tubes in banks A and B.

[7] This effect proved to be negligibly small for the infrequent number of produced mesotrons.

EXPERIMENT

In order to determine if single mesotrons could be produced by non-ionizing rays, over 20,000 pictures of mesotrons tripping the master set were taken at Mt. Evans. From preliminary tests conducted at Echo Lake, Colorado (10,600 feet), it was determined that the frequency of the above process, if it existed at all, was a very small percentage of the frequency of the penetrating component. It was necessary to keep all the counters in a fixed position during the entire course of the experiment. Therefore, in the final arrangement, the only variables were the thickness of the lead layers X and the thickness and material of the producing layer Σ. The inefficiency of the upper bank of counters was tested by removing the producing layer Σ. When this was done, all the cases where only the coincidence set *CDEF* was tripped and which were unaccompanied by a simultaneous discharge in set *ACDEF* could then be attributed to inefficiency of A. Likewise, the inefficiency of the counter bank B was tested by removing lead layer Σ'. These inefficiency tests were repeated several times during the course of the experiment and were found to average 0.24 percent of the frequency of the penetrating component.[8] Since the position of the counters was not changed during the entire course of the experiment, the actual production of single mesotrons could be obtained by correcting the measured frequency of production processes for the inefficiency in A and B.

RESULTS AND INTERPRETATION

The results on production of single penetrating particles on Mt. Evans and Echo Lake are given in Table I. A slow particle refers to a mesotron or any other penetrating particle of lower energy

[8] The inefficiency did not exceed 0.4 percent during the entire course of the experiment.

TABLE I. Data obtained at Mount Evans and at Echo Lake.

	At Mount Evans													At Echo Lake	
Material used for the producing layer	Paraffin					Lead						Iron		Lead	Para.
Column	1	2	3	4*	5	6	7	8	9	10	11	12	13	14	15
Thickness of producing layer Σ in cm	1.27	3.81	11.40	11.40	11.40	1.27	3.81	11.40	0.64	1.27	11.40	1.27	11.40	10.10	11.40
Lead layer X in cm	1.59	1.59	1.59	1.59	0.64	1.59	1.59	1.59	0.64	0.64	0.64	1.59	1.59	1.59	1.59
Number of mesotrons incident on Σ per hour	0107	99.0	95.2	88.6	110	66.3	79.2	66.0	53.3	87.1	68.4	113	90.3	71.3	78.5
Produced penetrating mesotrons per hour**	0.61	0.41	0.66	0.74	1.09	0.05	0.39	0.11	0.09	0.25	0.12	0.00	0.30	0.11	0.26
Produced slow mesotrons per hour**	.06	0.32	0.42	0.19	1.30	0.41	0.22	0.23	0.63	1.64	0.37	0.02	1.04	0.22	0.16

* An additional 57.2 cm of paraffin was placed above counter bank A.
** Inefficiency has been subtracted from the apparent values of the production.

which trips set $CDEF$ but is unable to traverse the absorbing layer Σ'.[9] The experiment also gave interesting information about multiple production in different materials and cascade showers in lead. The results of these investigations will be reported at a later date.

The single particles which are produced and which traverse the master set $CDEF$ are penetrating particles, providing none of the shower sets is simultaneously tripped. Most of these penetrating particles must be mesotrons since protons would require an average energy of 4×10^8 ev to traverse the lead layers interposed between the counters, and there is no evidence for the existence of protons of such high energies at altitudes of Mt. Evans. Many cloud-chamber photographs have been taken by various observers, but only protons of lower energy ($E<10^8$ ev) were found.[10]

There are different lines of evidence which tend to throw light on the nature of the producing radiation. (1) Cosmic-ray photons are mainly absorbed by pair-production processes with a cross section which is proportional to the square of the atomic number Z. One should expect that if the mesotron-producing radiation consists of photons, it would be absorbed according to this law. Since the absorption of photons in lead ($Z=82$) is very great, one would expect the production by photons to reach saturation in a lead thickness of 2–3 cm. In paraffin, where Z is very much smaller, one would not expect saturation until a producing layer of about a meter is reached. One can see from Table I that in lead, and particularly in that part dealing with the production of slower mesotrons passing through the 0.64-cm lead layers X (columns 9, 10, 11), this effect is very well pronounced. The apparent decrease in production with 11.4 cm of lead is due to the self-absorption of the produced mesotrons in the 11.4 cm of lead. In 11.4 cm of paraffin this effect does not occur, and one sees that saturation is not reached in this thickness. In order to find out whether the production is saturated in a still larger thickness, an additional paraffin layer of 57.2 cm was placed above the upper counter bank A. This paraffin completely covered the solid angle of the four counters $CDEF$ of the master set. If saturation were reached, most of the produced mesotrons would originate in the 57.2-cm paraffin block, trip the counter bank A, and thereby enter the producing layer of 11.4 cm as an ionizing particle. One would, therefore, expect a very abrupt drop in the registered production of mesotrons by non-ionizing radiation. Referring again to Table I, one sees very distinctly, after comparing the total production of mesotrons in column 3 and 4, that this does not occur, showing that in paraffin there is no saturation effect with a thickness of 57.2 cm.

TABLE II. Number and energy of mesotrons produced in lead.

Single mesotrons produced per hr.	Av. energy of produced mesotrons
1.64	1.6×10^8 ev
0.41	2.1×10^8 ev
0.22	2.5×10^8 ev
0.37	3.1×10^8 ev
0.23	3.5×10^8 ev

(2) The energy range of the mesotrons pro-

[9] In the table a production of particles always refers to a production process by non-ionizing radiation.

[10] C. D. Anderson and S. Neddermeyer, Phys. Rev. **50**, 263 (1936). W. M. Bostick, Phys. Rev. **61**, 557 (1942). W. M. Powell, Phys. Rev. **61**, 670 (1942). W. E. Hazen, Phys. Rev. **65**, 67 (1944).

duced in lead which are stopped in Σ' are computed from the ionization loss in lead and are given in Table II. (The results were calculated from the number of produced mesotrons which were stopped in the lead layer Σ'). In this computation it was assumed that all the produced mesotrons originated from a layer one cm below the top of the producing lead block Σ. Table II shows that there is a considerable drop in the number of produced mesotrons at energies lower than 1.6×10^8 ev. It should be noted that in the photon spectrum at 10,000 and 14,000 feet altitudes a similar change occurs around energies of about 2×10^8 ev.[11] Assuming a mesotron rest mass of 200 electron masses, it takes at least 10^8 ev to create a single mesotron. If the probability of production does not change appreciably with photon energy in the neighborhood of 10^8 ev, there should then be a drop in the energy spectrum of the produced mesotrons at an energy of about 10^8 ev such as observed, provided the produced mesotrons are created by photons.

(3) The increase in production of single mesotrons between the altitudes of Echo Lake and Mt. Evans can be seen by comparing the data at Echo Lake (given in columns 14 and 15 of Table I), with the corresponding production at Mt. Evans (given in columns 3 and 8). This increase in the case of paraffin[12] amounts to a ratio of 2.6. The increase in production is roughly of the same order of magnitude as the increase in the intensity of the soft component (photons) between the two altitudes. This ratio is about 2 according to Greisen.[13]

Comparing the number of produced single mesotrons in lead found in this experiment with that obtained under very similar conditions in a stratosphere balloon flight carried out in collaboration with Dr. Schein in 1942, we find at 5 cm Hg pressure that the number of mesotrons produced in 2 cm of Pb is about 100 times the value (Table I, columns 6 and 7) obtained at Mt. Evans. In the same balloon experiment the increase in the photon intensity[14] for energies higher than 10^8 ev was measured and found to be 600 between sea level and altitudes corresponding to 5 cm Hg pressure. Since the photon intensity increases by a factor of eight between sea level and Mt. Evans,[13] one should, therefore, expect an increase in the production of mesotrons by non-ionizing radiation between Mt. Evans and an atmospheric height equivalent to 5 cm Hg to be $600/8=75$, which is in as good agreement as can be expected under the conditions imposed.[15] This comparison is very rough and represents only an order of magnitude consideration.

The arguments presented under 2 and 3, while not conclusive, definitely favor photons as possible producing agents of slower mesotrons. Argument 1 substantiates this conclusion strongly since photons are the only non-ionizing rays which are able to explain the observed differences in absorption between paraffin and lead.

Assuming photons as the producing agent, one can calculate the cross sections for the mesotron production for the various producing materials. From the data obtained in paraffin, it is considered probable that the mesotrons are created by collisions with the atomic nucleus of the producing material. Under these assumptions the cross section in smaller thicknesses of paraffin can be calculated from the formula,

$$N=N_0e^{-n\sigma t},$$

where σ represents the cross section for mesotron production by photons; N, the number of photons passing through the thickness t without being absorbed by mesotron production; N_0, the number of incident photons; and n, the number of nuclei per cc. Changing to logarithms and expanding, we get,

$$n\sigma t=\log\left(\frac{N_0}{N}\right)=\frac{N_0-N}{N_0}+\frac{1}{2}\left(\frac{N_0-N}{N_0}\right)^2+\frac{1}{3}\left(\frac{N_0-N}{N_0}\right)^3+\cdots.$$

Since the number of produced mesotrons (N_0-N) is very small in comparison with the number of photons N_0 striking the producing layer, the

[11] W. E. Hazen, Phys. Rev. **65**, 67 (1944).

[12] A similar comparison in lead cannot be made because the self-absorption in the producing lead layer overshadows the major production of slow mesotrons.

[13] K. Greisen, Phys. Rev. **61**, 212 (1942).

[14] The photon intensity was put proportional to the measured number of cascade showers produced in 2 cm of Pb by non-ionizing rays.

[15] The thickness of the producing layer and the counter geometry were not identical in the two cases.

higher order terms can be neglected and,

$$n\sigma t \simeq (N_0 - N)/N_0$$

and, therefore,

$$\sigma \simeq [(N_0 - N)/N_0](1/nt).$$

For paraffin this formula gives the correct value for the cross section for thicknesses in which the absorption of photons by pair production is negligible. This is very nearly the case for thicknesses of 1.27 cm and 3.81 cm. It was estimated that if we take the absorption of photons by pair production into account, the cross section would change by about 5 percent. In lead and iron the absorption of photons by pair production is appreciable even in the smallest thicknesses used. In this case the formula gives a value which may be considered a lower limit for the cross section for mesotron production by photons.

For monatomic substances $n = (6.02 \times 10^{23} \times \text{density})/\text{atomic weight}$. This gives for lead $n = 3.2 \times 10^{23}$ and for iron $n = 6.2 \times 10^{23}$ nuclei per cc. In order to get n for paraffin we use the formula C_nH_{2n+2}. This leads to a value for n of 1.0×10^{23} nuclei per cc.

From Hazen's experiments[11] the number of photons with energies higher than 10^8 ev is about 10 percent of the total number of mesotrons passing through 4.8 cm of lead. The value of N_0 was obtained from the measured number of mesotrons incident on the producing layer Σ and passing through 4.8 cm of lead.

Using the experimental values for N_0 and N, we get for the cross sections per atomic nucleus for this process:

$$\sigma_{\text{par.}} = 5 \times 10^{-25}\ \text{cm}^2; \quad \sigma_{\text{lead}} = 1 \times 10^{-24}\ \text{cm}^2;$$

$$\sigma_{\text{iron}} = 4 \times 10^{-25}\ \text{cm}^2.$$

These values are about equal to the areas of the corresponding nuclei calculated by using the approximate formula for the radius of a nucleus $r = r_0 Z^{\frac{1}{3}}$,[16] where r_0 is the range of the nuclear forces $= 1.4 \times 10^{-13}$. The areas calculated in this way are,

$$A_{\text{par.}} = 2 \times 10^{-25}\ \text{cm}^2; \quad A_{\text{lead}} = 2 \times 10^{-24}\ \text{cm}^2;$$

$$A_{\text{iron}} = 1 \times 10^{-25}\ \text{cm}^2.$$

This result favors the hypothesis that the mesotron production by photons has to be considered as a direct interaction between the photon and the atomic nucleus.

In conclusion the author wishes to express his appreciation to Dr. Marcel Schein for suggesting the problem and for his numerous suggestions and consultations throughout this work. He also wishes to express his thanks to General L. A. Lawson and Captain Innes-Taylor for their generous hospitality at Echo Lake, to Mr. George E. Cramner and Dr. William Hyslop for making possible the stay at Mt. Evans, and to Dr. A. H. Compton for his continuous support in these investigations.

[16] This formula can be considered only as a fair approximation for elements of higher atomic numbers, like Pb.