incident atoms decreases, on the other hand, the hard-sphere model would become valid for more direct collisions and hence for an increasing fraction of the total number of collisions; therefore this mechanism would become relatively more important in the energy losses of low velocity particles than in the losses of high velocity particles, where it may justifiably be neglected.

On the basis of the hard-sphere model, elementary considerations show that a deuteron loses, on the average, about four times as much energy as does a proton of the same velocity, in a (glancing) collision with a heavy atom at rest. Clearly, then, this mechanism would contribute to an increased rate of energy loss for deuterons compared with that for protons, as observed.

IV. ACKNOWLEDGMENTS

I wish to thank Dr. S. K. Allison, in whose laboratory this work was done, for his constant interest and valuable advice in the course of the work. In addition, I wish to express my thanks for the very important and active help of Mr. C. N. Yang during the early phases of these investigations. Finally, thanks are due Messrs. D. S. Bushnell and G. W. Farwell for their assistance with the tedious but necessary job of taking the many data.

PHYSICAL REVIEW VOLUME 74, NUMBER 12 DECEMBER 15, 1948

Search for Photons from Meson-Capture*

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(Received August 27, 1948)

High energy photons (about 50 Mev) associated with mesons stopped in iron have been searched for. The experimental evidence shows that no such photons arise from the capture of negative mesons or from the free decay of positive ones.

EXPERIMENTS with delayed coincidences[1] have shown that no decay electrons are detected from negative μ-mesons stopped in materials with high Z. This was predicted by Tomanaga and Araki, in line with Yukawa's theory.[2] Their conclusion was that negative mesons at the end of their range should be attracted by the Coulomb field of the nuclei and then "captured" by the nuclei even for low values of Z and density of the absorber. The presence of decay electrons for both positive and negative mesons in light nuclei already indicates a strong departure from the predictions of Tomanaga and Araki and hence from Yukawa's theory, as far as μ mesons are concerned. However, the event following the capture of negative μ-mesons in a high Z absorber was somehow expected to undergo the process which was predicted on the basis of Yukawa's theory. This process should most likely lead to a nuclear disruption in which the outgoing particles would carry almost all of the 100 Mev rest energy of the mesons. From the absence of such stars in cloud chamber pictures, it was felt[3] that the idea sketched above does not correspond to the actual phenomenon.***[,4] Hence the present experiment

* Preliminary results of this work appeared in Phys. Rev. **73**, 411 (1948); a complete report was given in the Washington meeting of the American Physical Society, April 29, 1948.

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[1] Conversi, Pancini, and Piccioni, Phys. Rev. **68**, 232 (1945); G. E. Valley, Phys. Rev. **72**, 772 (1947).

[2] Tomanaga and Araki, Phys. Rev. **58**, 90 (1940).

[3] O. Piccioni, Phys. Rev. **73**, 411 (1948).

*** After this experiment was performed, Lattes and Gardner (see reference 4) reported that μ mesons had been detected with photographic plates exposed in the 184-inch cyclotron of Berkeley. Only a part (<50 percent) of the observed μ mesons produce a star at the end of their range, and these stars have mostly one prong. From the comparison with the Σ-stars, one has the impression that the μ-stars do not represent an energy of 100 Mev. Other information on this subject is available from the preliminary results of R. Sard and coworkers, who find neutrons associated with the stopping of mesons in lead. Unfortunately quantitative information is not available as yet.

[4] Lattes and Gardner, Am. Phys. Soc. **23**, No. 3, p. 42 (1948).

was performed, in order to investigate whether or not high energy photons ($50 \div 100$ Mev) are produced in association with the "capture" of a negative meson, giving account of the 100 Mev energy. While it seems unlikely that such high energy photons could be emitted by the excited nuclei,[5] they could be produced by the direct interaction between the negative meson and one single proton of the nuclei. As will be shown, the evidence arising from the present experiment stands against such hypothesis of high energy photons emitted after the capture of a negative μ-meson. At the same time, the apparatus provides a negative answer to the hypothesis of high energy photons accompanying the decay of positive stopped mesons.

DESCRIPTION OF THE APPARATUS

The apparatus, with counters, absorbers and screens, is shown schematically in Fig. 1. Mesons were collimated by the telescope AB and filtered through a lead absorber 6-inches thick. The 4-inch thick aluminum plate was there to prevent the mesons which reach the tray B with a small residual range from having a big angle of scattering. That would decrease the rate of mesons absorbed in the iron. The anticoincidence tray C selected events corresponding to the stopping of a meson in the iron absorber. Geometries like the one adopted here have been widely used in slow meson experiments,[6] so that one can assume that practically all the particles stopped in the absorber are meson of 200 electron masses and natural mean life 2.2 μsec.

The counters "H" formed a "Hodoscope" set. They were connected to an apparatus which indicated individually which one of them was discharged when an AB–C event took place. Such information was taken from a picture of a cathode-ray tube. In this way it was possible to indicate roughly the track of the ionizing particles, so that one could exclude spurious events which could give the appearance of a γ-event in a simple coincidence–anticoincidence arrangement. The counters "H" were brass counters 1-inch diameter, 10-inch useful length, with a 0.003-inch diameter tungsten wire. They were filled with pure argon at the pressure of 13 cm Hg, and worked as follows. The voltage between the wall and the wire was normally kept at -5 volt (wire negative). A 0.001 μf condenser was connected between the wire and ground. When a coincidence AB occurred, the wall received a negative pulse of about 1200 volts in amplitude, 2 μsec. long, rising time 0.2 μsec. If an ionizing particle went through any one of the "H" counters at the time when an AB coincidence occurred and the pulse was given, the counter would discharge, and its condenser would be charged at a potential of about -100 v respect to ground. In this way, each pulse appearing on the wires of the H counters represents automatically a coincidence with the trays A and B, within about 2 μsec., although the pulse itself may last for a time as long as 1 second. This feature and the big amplitude of the pulse makes it easy to detect individually which one of the counters H is discharged. In the present experiment, such information was given by a cathode ray scope, by means of a rotary-scanning switch and a synchronized sweep-circuit. The efficiency of the counters H,

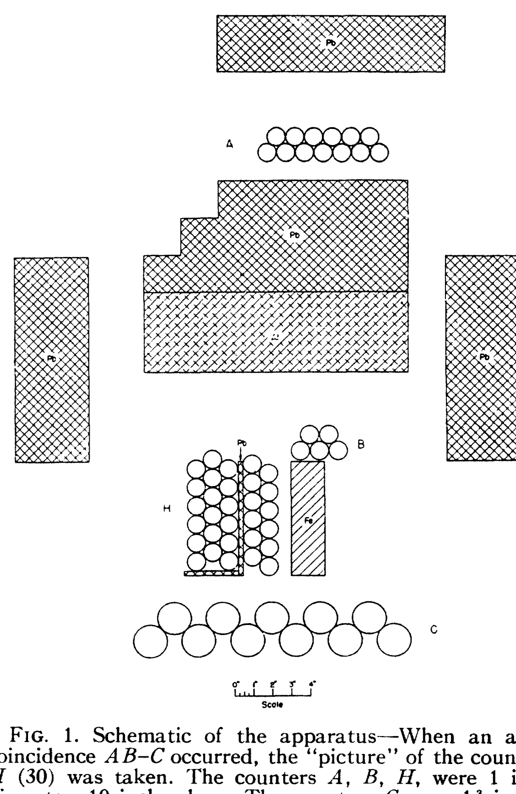

FIG. 1. Schematic of the apparatus—When an anticoincidence AB–C occurred, the "picture" of the counters H (30) was taken. The counters A, B, H, were 1 inch diameter, 10 inches long. The counters C were $1\frac{3}{4}$ inches diameter. 20 inches long.

[5] J. A. Wheeler, Phys. Rev. **71**, 320 (1947).
[6] F. Rasetti, Phys. Rev. **60**, 198 (1941).

TABLE I.

γ-energy in Mev	Fraction of γ-rays lost in iron	Ratio of useful solid angle to 4π	Max. useful thickness of lead in g/cm²	Actual thickness of lead in g/cm²		Fraction of γ-rays lost in lead		Efficiency of the useful thickness of lead		Total efficiency	
				Series I	Series II and III	Series I	Series II and III	Series I	Series II and III	Series I	Series II and III
50	0.46	0.075	11.4	7	14	0	0.22	0.48	0.65	0.019	0.02
100	0.49	0.075	15.1	7	14	0	0	0.62	0.8	0.024	0.03

working as outlined above, was proved to be better than 95 percent. Due to the geometrical disposition of the apparatus, this efficiency was more than sufficient for the purpose of the experiment. It should be noted that even if such efficiency would have been as low as, say, 75 percent, one might expect to get false pictures showing a pseudo γ-event, rather than to miss any substantial number of pictures of real γ-events. No distinction has been made between positive and negative particles. Such a distinction, which would have reduced the rate of occurrence of the investigated events, was left as a second stage of the experiment, in case evidence had been found for photons produced by stopped mesons. The type of apparatus used was particularly suitable to be transformed for that purpose, by the introduction of a magnetized iron piece and the addition of other "*H*" counters to indicate the deflection of the mesons in the magnetized iron. Since evidence was found that no high energy photons are produced by stopped mesons, the distinction between positive and negative mesons was obviously useless.

Expected Number of "Good γ-Events"

The hypothetical phenomenon which was being investigated consisted of the following: a meson which would stop in the iron and cause at least one high energy photon to be emitted with no preferential direction. Some of those photons will then come out of the iron and will be converted in the lead, giving, by pair-production, one electron and one positron, one of which may cross the three columns of "*H*" counters beyond the lead. Correspondingly as a "good γ-event" (g. γ. e.) was regarded an event selected by the anticoincidence circuit, which gave a picture showing no discharge in the two columns of the "*H*" counters placed between the iron and the lead converter, and showing a discharge in one counter for each of the three other columns. In addition it was required that the discharged counters showed a direction for the ionizing particle, compatible with the assumption of a photon coming from the iron and converted in the lead. This criterion of the direction allowed one to exclude false pictures due for instance to more than one particle crossing the apparatus simultaneously. The exclusion, however, could not be complete, and indeed it is felt that the small number of "g. γ. e." in Table II is due to such cases. On the other hand, the criterion tends to exclude also some good pictures —namely, in case the photo-electron emerging from the lead has been scattered by a big angle. However, this happens only for those electrons which emerge from the lead at the very last part of their range, so that their exclusion does not constitute a substantial reduction of the expected rate.

It is to be pointed out that it was not required that both the pair-produced electrons emerged from the lead converter. Of course, a picture compatible with the assumption of both particles emerging from the lead, if any such pictures had been found, was not subject to exclusion.

In order to evaluate the expected number of "g. γ. e." one has to take into account that when a meson is brought to rest in the iron, on the assumption that negative mesons release a high energy photon, the following conditions have to be fulfilled in order to register a "g. γ. e.".

(A) The photon has to have a direction contained in a certain solid angle.
(B) The photon has not to be absorbed in the iron.
(C) The photon has not to be absorbed in the first millimeters of lead which are in excess of the useful range of the *conversion* electrons.
(D) The photon has to be converted in the remainder part of the lead.

The detection of high energy photons emitted in the decay process was subject to the additional condition, *related* to the resolving time of the

TABLE II.

Series	Number of mesons stopped	Estimated number of negative mesons stopped	Estimated number of positive mesons stopped	Expected number of γ-events from negative mesons if γ-energy 50 Mev	γ-energy 100 Mev	Expected number of γ-events from positive mesons for γ-energy 50 Mev	Experimental number of "good γ-events"
I	2200	990	1210	19	24	12	2
II	3100	1400	1700	34	42	17	2
III	3200	1440	1760	35	43	17	0

apparatus: the decay process has to have an actual delay not bigger than 1.5 μsec.

The probability which corresponds to the condition (A) is simply the ratio of the useful solid angle, determined by the last column of the "H" counters, to the whole solid angle 4π. This ratio had the value 0.075. To the condition (B) is attached a probability which can easily be estimated from the Klein-Nishina cross sections for absorption and scattering and from the cross section for pair production.

We have to take into account that mesons are stopped uniformly at any point of a horizontal plane in the iron. This means that if Λ is the mean free path of the photons, the average probability that a photon will escape from the iron is

$$\frac{1}{T}\int_0^T e^{-t/\Lambda}dt=\frac{\Lambda}{T}(1-e^{-T/\Lambda})$$

where T is the thickness of the iron. The values of Λ for different photon-energies have been taken from Rossi and Greisen.[7]

The condition (C) is taken into account in the same way as (B), once it is established what is the useful range of the electrons, which of course plays the most important role for the evaluation of the probability corresponding to (D). Now, if the energy of the photon is W, the two particles of the produced pair will have a known distribution in energy. One particle will generally have more energy than the other one. We will take the average energy $\bar{U}$ of the most energetic particle, disregarding completely the less energetic one. For $\bar{U}$, we may take the value $0.75W$. Thus for a photon energy of 100 Mev, it will be equal to 75 Mev. The thickness of the counters is only 0.005-inch of brass, except for two or three rings $\frac{1}{8}$-inch wide, $\frac{1}{32}$-inch thick, so we do not need to take that into consideration.

In Table I are the numbers corresponding to the conditions (A)–(D), from which is derived the value of the total efficiency. The rate of stopped mesons, measured by the difference with and without absorber, was 20 per hour. A lead plate was placed below the counter "H" in order to prevent photo-electrons to discharge the anticoincidence counters, which would have caused the failure of detecting that event, with the consequence of a reduction of the efficiency.

In Table II are listed the total numbers of expected "g. γ. e." for photon energies of 50 and 100 Mev. The Series I and II differ in the thickness of the plate where the photons should be converted. The Series III has been obtained with the addition of other "H" counters, because it was felt that even the small number of "g. γ. e." appearing in Table II, Series I and II, was due to oblique rays. In Series III, in order to consider a picture as a "g. γ. e.," it was requested that the "H" counters placed in the way of the beam (Fig. 2) indicated, by their discharging, a path of

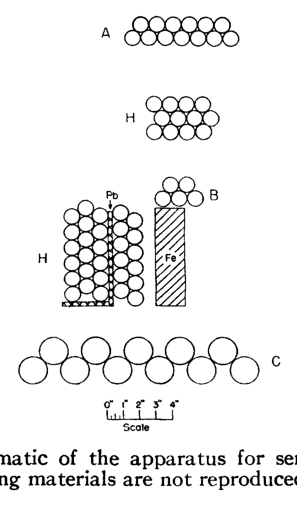

FIG. 2. Schematic of the apparatus for series III. (The screening materials are not reproduced here.)

[7] Rossi and Greisen, Rev. Mod. Phys. **13**, 240 (1941).

a single particle going toward the tray B. It was then found that pictures similar to those which constituted a "g. γ. e." in Series I and II had to be rejected, because the new "H" counters indicated that was not a straight vertical particle to cause the event. It has been checked that this new requirement did not reduce appreciably the overall efficiency of the apparatus.

DISCUSSION

Table I shows that the computation of the total efficiency comes out of the computations of various factors. One has then to be rather conservative about the precision of the assumed efficiency. However, it is to be noticed that the approximations used were mostly in the direction of underestimating the overall efficiency. For instance, in the calculation of the absorption of photons in the iron, it was assumed that the entire Klein-Nishina cross section for scattering is effective in removing photons, while it is clear that in the geometry used not all photons scattered miss the counters, and other photons which do not start in the direction of the counters may be scattered into a "useful" direction. Furthermore, it was entirely disregarded the less energetic particle of the pair. Therefore, considering that the result of the experiment does not depend on a high precision of the computed efficiency, but on a striking difference between the expected rate and the experimental one, one can conclude that the hypothesis that a big amount of the 100 Mev meson rest energy could be emitted as photons, is strongly contradicted by the experimental evidence. From the values reported in Table II, one sees that if any photons are emitted after the capture of a negative normal meson in iron, their energy must be appreciably less than 50 Mev. To set a lower limit of this energy, for which the experiment still would give a significant negative answer, one would need a more precise calculation of the efficiency of the apparatus. From a rough extrapolation of the numbers in Table II toward the low energies, one would exclude that as much as an energy of 20 Mev is irradiated after a meson stops in Fe. In the hypothesis of a neutral meson emitted, and subject to decay in two light-quanta, the present experiment indicates that the mean life of such a meson must be greater than, say, 10^{-10} sec., unless its rest-mass is much smaller than 50 Mev. Concerning the decay process of the positive mesons, if we take as a reference the value of 50 Mev for the energy of a hypothetical photon emitted, the experiment gives again a negative answer, which checks with the results of R. D. Sard and E. J. Althaus,[8] and E. P. Hincks and B. Pontecorvo.[9]

The author is indebted to Professor Bruno Rossi for the offer of a visiting research associateship at the Massachusetts Institute of Technology. In assembling the experiment and in taking data, the cooperation of Mr. John Harriman was most helpful. The writer also acknowledges with pleasure many stimulating discussions which he had with Professor V. Weisskopf and Doctor T. Welton. The experiment here reported was partially supported by Contract N5ori-78, U. S. Navy Department, Office of Naval Research.

[8] Sard and Althaus, Bull. Am. Phys. Soc. **23**, No. 2, p. 20 (1948).

[9] E. P. Hincks and B. Pontecorvo, Phys. Rev. **73**, 257 (1948).