ON THE ABSENCE OF PHOTONS AMONG THE DECAY PRODUCTS OF THE 2.2 MICROSECOND MESON

By E. P. Hincks and B. Pontecorvo

Abstract

An experiment is described which tests the hypothesis that the cosmic-ray meson with a mean life of 2.2 μsec decays into an electron and a photon. Geiger counter trays are used to select mesons incident on a graphite block, and to detect decay products emerging from the graphite. The electronic circuits record delayed coincidences that correspond to a decay event occurring between 0.6 and 5.3 μsec after a meson is stopped. The absence of delayed coincidences of a type that could be attributed to the simultaneous emission of an electron and a photon, each of ~50 Mev, shows that the above hypothesis of the meson decay process is incorrect. The experiment also demonstrates the absence of a hypothetical unstable neutral meson among the decay products.

Introduction

The decay process of the "ordinary cosmic ray meson"* has been the object of numerous investigations. The experimental study of the meson decay was encouraged by the theoretical work of Yukawa, and for many years seemed to give a brilliant confirmation of his views. According to Yukawa's meson theory of nuclear forces, a charged particle of about 200 electron masses and integral spin is responsible for the intense short range forces that hold together nucleons. When positive and negative mesons with masses close to 200 m, were later found to constitute the hard component of the cosmic radiation, they were naturally assumed to be the predicted Yukawa particles. In addition, according to Yukawa, the ordinary nuclear beta decay could be explained by a typically quantum two-step process—virtual creation of meson by nucleons and subsequent radioactive decay of the "virtual meson"—provided the free meson is itself unstable against emission of an electron and a neutrino.

It was recognized† that the mean life of a Yukawa particle that is required to explain quantitatively the beta process by the above mechanism is considerably smaller than the observed value—2.2 μsec (5, 23)—for cosmic-ray mesons. Nevertheless, many reasons, among which were the very instability (29, 35) of the meson, its mass, and the fact that the charged particles resulting from the decay of the meson at rest have a penetration through matter that

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3 Formerly member of United Kingdom Staff at Chalk River Laboratory; now at Atomic Energy Research Establishment, Harwell, England.

*There is strong evidence that this meson, which has a mass equal to ~200 electron masses and constitutes the bulk of the hard component of the cosmic radiation at sea level, is to be identified with the "μ-meson" observed by Lattes, Ochialini, and Pacelli (Nature, 190: 455, 1947) among the products of disintegration of a heavier meson. In this paper the word meson will refer to the ~200 electron mass particle, unless otherwise stated.

†See, for example, reference (11).
cannot be very different from that of 50 Mev. electrons (6), supported the view that the meson decays into an electron and a neutrino, each of about 50 Mev., and is to be identified with the Yukawa particle. This picture of the meson decay process was generally accepted until, in 1947, Conversi, Pancini, and Piccioni (4) showed experimentally that the meson has an extremely weak interaction with nucleons and cannot be responsible for nuclear forces in the Yukawa sense. The strength of the interaction was found (8, 33, 34) to be $\sim 10^{-12}$ times that required by the Yukawa theory. A consequence of the experiment of the Rome group is that the Yukawa interpretation of beta decay fails as well, since it would now predict much too long beta lifetimes. The meson is then no longer the particle responsible for the nuclear beta process.* Consequently there is no reason to assume that charged mesons have integral spin (as the Yukawa explanation required), and, in particular, there is no strong reason for the assumption that the meson decays with emission of a beta particle and a neutrino.

The hypothesis may therefore be considered that the meson has a spin equal to $\frac{1}{2} (h/2\pi)$. Such a spin value would be required, for example, if the process of nuclear absorption of a single meson is accompanied by the emission of one neutrino in analogy with the process of electron capture by nuclei, as was first pointed out by one of the authors (28). This analogy between the processes of meson absorption and ordinary K-capture is suggested by the following facts. (i) The probability of capture of a bound negative meson (about $10^6$ sec. -1, according to the experiment of Conversi and collaborators) is of the order of the probability of the ordinary K-capture process, when allowance is made for the difference in the disintegration energies and the difference in the volumes of the electron K-shell and of the meson orbit. (ii) Among a few pictures of a meson stopping in the gas of a cloud chamber, no star has been observed at the end of the meson track.† The absence of stars can be explained by the assumption (28) that a neutral particle, the neutrino, carries away most of the energy.

A meson of spin $\frac{1}{2} (h/2\pi)$ could, a priori, decay in a number of ways. One possibility would be the decay into one electron and two neutrinos.‡ Another possibility would be that the 2.2 $\mu$sec. decay process consists of the emission of one photon and one electron, each of about 50 Mev. according to the laws of conservation of energy and momentum. Radiative decay of mesons has been discussed by several authors (7, 9) from the theoretical point of view.

It must be acknowledged that there is already some experimental evidence

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*The nuclear beta process can alternatively be described according to the original Fermi picture (without mesons). However, it must be noted that the failure of the Yukawa theory in explaining the beta process, which is being discussed here, concerns the particular meson of $\sim 200$ electron masses. It may well be that the Yukawa picture is correct, but that another type of meson is involved.

†See, for critical surveys, references (80, 85).

‡At the time of writing this paper, the electron plus two neutrinos hypothesis, mentioned in 1941 by Nordheim (34), is in favor, being strongly substantiated by the experimental observation of the form of the (continuous) energy spectrum of the decay electrons.
against the electron–photon hypothesis. The available analysis (3, 24) of the soft component of the cosmic radiation in equilibrium with its primary meson component suggests strongly that only a fraction of the meson energy is spent in “ionizing” radiation (including \(\gamma\)-radiation). However this argument, though strong, is indirect and, considering the uncertainties in our knowledge of meson physics and the interest of the problem, it was thought worthwhile to test in a straightforward way the electron–photon hypothesis. The experiment that was undertaken is reported in this paper; a preliminary note has already been published (13). Another experiment designed to detect photons in the meson decay has been published independently by Sard and Althaus (31, 32).

In this paper it is assumed that the charged particle emitted in the meson decay is an electron. Recent experimental evidence obtained by the authors (16, 17, 18) after the completion of the work described here has confirmed the accuracy of this assumption.

**The Principle of the Experiment**

Two ways of designing an experiment capable of detecting photons in the meson decay have been considered. First, one may look for a delayed event that could only be due to the emission of the hypothetical photon after the stopping of a meson, without detecting the decay electron. Alternatively, one may look for the delayed coincidence due to the simultaneous emission of photon and electron in opposite directions. It is interesting to notice that the information given by the two methods is of somewhat different character, as will be explained later, and the two methods are complementary.

The first method was selected by Sard and Althaus (31,32); the second method was chosen by the writers. From an instrumental point of view, it may be anticipated here that the first method requires an efficient anticoincidence system (implying a large number of counters), while the second method probably requires more electronic apparatus. This consideration has influenced our choice. A more fundamental difference is discussed in the conclusion of this paper.

After the method of electron–photon coincidences was selected, consideration was given to the most advantageous geometry. The essential condition to be achieved is that a vertical meson beam selected by a counter telescope be allowed to fall on an absorber whose minimum dimension is not large compared to the average range of the decay electrons. It should then be possible to detect electrons, and photons if they are present, emerging from opposite faces of the absorber. The two possibilities are illustrated in Fig. 1 (a) and (b). In (a) the meson is brought to rest in a “thick but narrow” absorber, while in (b) the meson is stopped in a “thin but wide” absorber. It turns out that arrangement (b) has a considerably greater “luminosity” than (a), essentially because of the divergence of the incoming meson beam. The arrangement illustrated in (b) has some unusual characteristics that will be discussed later.
**Fig. 1.** Alternative orientations of meson absorber and decay particle counters for a vertically incident meson beam. The "thin but wide" absorber arrangement (b) was selected for the present experiment.

**The Experimental Arrangement**

The counter arrangement, which was placed in a concrete house in the Chalk River Laboratory (near sea level), is illustrated in the left part of Fig. 2. A photograph of the apparatus is presented in Fig. 3. A 15 cm. thickness of lead above the apparatus has the function of absorbing the soft component and also of increasing (30) the number of slow mesons impinging on the meson telescope. The telescope is formed by the counter trays A and B. The mesons (about 0.4% of the incoming beam) that are stopped in a graphite block 38 cm. by 19 cm. by 8.5 gm. per cm.$^2$ thick, undergo decay. Graphite was selected because both positive and negative mesons decay when brought to rest in carbon (4). Decay electrons may be detected in either tray B or tray C. Decay photons, if present, will also be detected in either of these trays (B or C) whose efficiency for gamma radiation is increased by introducing 2.1 mm. of lead between the graphite and both B and C.
A coincidence between $A$ and $B$—which is referred to as an event $(AB)$—defines the passage of a meson. Coincidences between $B$ and $C$ delayed with respect to the event $(AB)$ would result from the hypothetical electron–photon emission in the meson decay. The circuits were actually arranged so as to record the following delayed events.

Fig. 3. Photograph showing the experimental arrangement with the counter trays $A$, $B$, and $C$ in position.

1. $(B)_{det}$, or discharges of tray $B$ occurring between 0.6 and 5.3 μsec. after $(AB)$.
2. $(C)_{det}$, or discharges of tray $C$ occurring between 0.6 and 5.3 μsec. after $(AB)$.
3. $(BC)_{det}$, or coincidences of $B$ and $C$ occurring between 0.6 and 5.3 μsec. after $(AB)$.

The function of the circuits is shown diagrammatically in relation to the counter arrangement in Fig. 2. It must be noticed that tray $B$ has a twofold function: first, detection of the passage of a meson by a coincidence with $A$ (event $(AB)$) and second, detection of a decay electron (or photon) following $(AB)$. The use of tray $B$ in this way was required by the adoption of the method $(b)$ discussed in the previous section, giving high luminosity. Furthermore, such an arrangement results in a considerable economy in the number of counters. A slight disadvantage is, of course, that one of the eight counters
of tray $B$, that through which the meson has passed, is insensitive to a decay particle because of the long dead time characteristic of Geiger counters.

**Electronic Circuits**

The electronic recording of $(B)_{del}$ events presents an interesting problem associated with the twofold function of tray $B$. In order to detect an event $(B)_{del}$ following a first event $(B)$ by, let us say, 1 μsec., it is clear that one could generate narrow ($< 1 \mu\text{sec.}$) pulses and use circuits with a dead time smaller than 1 μsec. While such circuits can be designed, a solution of the problem by the use of short dead-time circuits would have prevented the use of much standard apparatus available in the laboratory. A different and simpler solution, which allows the use of long dead-time standard circuits, was adopted. The initial and the delayed pulse at the output of the Geiger-Müller tray are distinguished as follows. In order that the first pulse should not trigger the input of the delay channel circuit, it is arranged that each delayed pulse is superposed upon the (properly shaped) initial pulse, and so rises to an amplitude double that of a single pulse. Amplitude discrimination between initial and delayed pulses becomes possible in this way. Each Geiger counter of tray $B$ is connected to a single pentode, which is rapidly cut off by the beginning of a Geiger discharge. The square pulses of about 10 μsec. duration which are thus produced at the plates are then mixed in a proportional stage. While the single pulse output, or “normal output”, is fed to the coincidence mixer detecting the event $(AB)$, the “threshold output”, at which the first pulse is biased off, feeds the delay channel. A full description of the circuit is presented elsewhere (18).

A complete block diagram of the circuit functions is shown in Fig. 4. The amplifiers have a gain of about 1000, and saturate on all Geiger pulses. Their

![Diagram](image-url)

**Fig. 4.** Detailed block diagram of circuits used to record the delayed coincidences.
purpose is to steepen the rise of the pulse so that the mixer inputs are triggered with negligible delay (\(\ll 0.1\ \mu\text{sec.}\)).

The coincidence mixers are of fairly standard design, and are very similar to that described by Jelley (19).

In the delay mixer, the circuit of which is given elsewhere (18), the input pulse corresponding to the event \((AB)\) initiates a gating pulse 4.7 \(\mu\text{sec.}\) in width and delayed 0.6 \(\mu\text{sec.}\). This gating pulse is then mixed separately with pulses from the \(B\) threshold output and from the \(C\) output, so that if a decay particle passes through \(B\) or \(C\), between 0.6 and 5.3 \(\mu\text{sec.}\), after an event \((AB)\), a delayed coincidence \((B)_{\text{del}}\) or \((C)_{\text{del}}\) is registered. The delay mixer has, in fact, a third channel which was designed to register events \((A)_{\text{del}}\) from a threshold output in the \(A\) tray. Registration of the \((A)_{\text{del}}\) events would have reduced the chance delayed rate by cancellation of all events \((BC)_{\text{del}}\) accompanied by \((A)_{\text{del}}\) these \((ABC)_{\text{del}}\) events being produced by mesons discharging the three trays between 0.6 \(\mu\text{sec.}\) and 5.3 \(\mu\text{sec.}\) after \((AB)\).* However, since significant results were obtained without taking this step, no threshold output was added to \(A\) and the third channel was not used in the present experiment.

The numerators consist of a mechanical register driven by a thyratron. Every delayed event is recorded in two separate numerators, one of which (only one is shown in Fig. 4,) supplies pulses to operate a pen recorder.

The resolving times of the various mixers, and the initial delay and the gate width in the delay mixer, were measured with a calibrated oscilloscope, using a pulse generator which produced pairs of pulses whose time separation could be varied. The oscilloscope time calibration was checked by measuring

\[
\begin{array}{|c|c|}
\hline
\text{Initial delay of the delay mixer} & 0.6 \ \mu\text{sec.} \\
\text{Position 1} & 1.6 \ \mu\text{sec.} \\
\text{Position 2} & 4.7 \ \mu\text{sec.} \\
\text{Gate width of delay mixer} & 0.7 \ \mu\text{sec.} \\
\text{Resolving time of} \ (AB) \text{coincidence mixer} & 7.0 \ \mu\text{sec.} \\
\text{Resolving time of} \ (BC)_{\text{del}} \text{coincidence mixer} & \\
\hline
\end{array}
\]

Table I are given the measured values of various significant time intervals characteristic of the apparatus.

* The 1.5 cm. of lead between trays \(A\) and \(B\) was introduced to prevent a decay electron from discharging both \(B\) and \(A\), at the time when it was planned to record \((A)_{\text{del}}\) events, in addition to \((B)_{\text{del}}\) and \((C)_{\text{del}}\).
The Geiger Counters

The Geiger-Müller counters used in trays B and C (eight per tray) are all metal (copper cathodes) of the self-quenching type, 15 in. long (effective) and 1 in. diameter. In tray A eight glass counters, self-quenching, 8 in. long and 2 in. diameter were used because of their availability when the experiment was initiated. With their large diameter, the glass counters would not have been suitable for counting delayed events, on account of the counter time lags. For the detection of mesons, however, they were satisfactory.

All counters are mounted inside aluminum boxes for mechanical support and electrical shielding. Fig. 5 is a photograph of one of the trays of copper counters with the lid removed.

![Fig. 5. View of eight copper counters mounted in aluminum box. (Tray C).](image)

The H.T. voltage, which is obtained from batteries, is applied to each counter wire through a separate resistor (107 ohms). In trays A and C the pulse from each counter is fed through a separate high voltage condenser (50 μF) to the common output. In tray B, instead, each counter is connected by a condenser to the corresponding pulse-shaping tube of the “threshold amplifier”.

Each counter was selected by measuring the plateau and by inspecting the pulse shape with an oscilloscope. For trays B and C a satisfactory plateau for the complete tray was achieved with a single voltage for the tray, but tray A was less satisfactory, and three different voltages were required.

Counter lags, i.e., lags of the output pulses with respect to the passage of the ionizing particles, were investigated with a triggered oscilloscope. It was found that lags > 0.2 μsec. were sufficiently rare to warrant the use of the counters for the present work. It should be noticed, moreover, that the most significant of the rates, the (BC)delay rate, can hardly be influenced by lags even with a delay as short as that which was used.
Control Experiments

The following controls were periodically made.

The total counting rate for each tray, and also the rate of "triggering events", \((AB)\), were measured twice a day without interrupting measurements. Typical values are given in Table II to give an idea of the intensities.

<table>
<thead>
<tr>
<th>Meson absorber</th>
<th>(A)</th>
<th>(B)</th>
<th>(C)</th>
<th>(AB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No graphite + lead between (B) and (C)</td>
<td>1290</td>
<td>1215</td>
<td>1335</td>
<td>360</td>
</tr>
<tr>
<td>Graphite + lead between (B) and (C)</td>
<td>1290</td>
<td>1000</td>
<td>1230</td>
<td>360</td>
</tr>
</tbody>
</table>

Once a day the voltages on the counters were measured and the pulses from each counter tray inspected with an oscilloscope.

On two occasions runs were intentionally taken with no voltage on the counters: no pulses were registered in 24 hr.

The transmission of each branch of the circuits was checked occasionally in order to verify that the counting rates at the input and the output of the branch were the same.

The significant resolving times, and especially the initial delay and the gate width in the delay mixer, were checked periodically.

One experiment with an initial delay of 1.6 \(\mu\text{sec.}\) (position 2 in the delay mixer), and with the usual gate width of 4.7 \(\mu\text{sec.}\), was performed as a check. The ratio of the net measured rate \((B)_{\text{det}} + (C)_{\text{det}}\) due to the graphite plus lead absorber, to that with 0.6 \(\mu\text{sec.}\) delay, was consistent with a meson mean life of 2.2 \(\mu\text{sec.}\).

Sufficient controls were also available to avoid any possible misinterpretation of results due to power failures.

The behavior of the threshold amplifier was checked periodically by measuring the bias curve (number versus bias) for the threshold output. This curve is discussed elsewhere (18) in detail.

The constancy within the statistical error of rates \((B)_{\text{det}}\) and \((C)_{\text{det}}\), as well as the distribution in time of the delayed events as shown by the records of the pen recorders, were good indications of the proper behavior of the apparatus.

The Casual Rates

The \((B)_{\text{det}}\) and \((C)_{\text{det}}\) rates not due to decay—the casual rates—are produced first by threshold amplifier lags* in tray \(B\), and random counter lags, mainly

* The term "lag" is used to refer to an accidental delay in the detection of a pulse due to a prompt event. Counter lags in tray \(B\) contribute little to the casual rate because at least one pulse must appear from \(B\) before a triggering event is established, and only a meson discharging two counters of \(B\), one discharge occurring with a lag, could give a delayed count. "Threshold amplifier lags" may occur in cases in which the second \(B\) pulse has an abnormally low rising time.
in tray C, and second, by random particles discharging a tray between 0.6 and 5.3 μsec. after the triggering event. The magnitude of the latter effect (the chance rate) can be calculated by a knowledge of the circuit characteristics, and of the various relevant undelayed rates, while the contribution from the first effect cannot be estimated a priori.

However, the experiment when done without graphite plus lead between B and C should give the total (B)_{del} and (C)_{del} casual rates, except for a small contribution which arises from mesons stopped and decaying in the counter walls. By an analysis of all observations, and by computing the chance rates, the approximate values of the casual rates given in Table III were obtained, for the condition "without graphite plus lead". The (B)_{del} and (C)_{del} casual rates in the condition "with graphite plus lead" are expected to be 10 to 20% smaller than without graphite plus lead, because of the reduced prompt rates (B) and (C). The (BC)_{del} casual rate, however, is the same for the two conditions.

### Table III

**Casual rates (counts per hour)**

<table>
<thead>
<tr>
<th>Origin of casual counts</th>
<th>(B)_{del}</th>
<th>(C)_{del}</th>
<th>(BC)_{del}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Threshold amplifier lags</td>
<td>3.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Counter lags</td>
<td>1.0</td>
<td>3.1</td>
<td></td>
</tr>
<tr>
<td>Chance</td>
<td>1.7</td>
<td>0.9</td>
<td>0.20 ± 0.02</td>
</tr>
<tr>
<td>Total casual rate</td>
<td>6.3</td>
<td>4.0</td>
<td>0.20 ± 0.02</td>
</tr>
</tbody>
</table>

The chance (B)_{del} and (C)_{del} rates are obtained from the following formulae:

\[
(B)_{del}^{\text{chance}} = [(AB) - (ABB)] [\frac{1}{3} (B)] \tau \text{ counts per hr.}
\]

\[
(C)_{del}^{\text{chance}} = [(AB) - (ABC)] (C) \tau \text{ counts per hr.}
\]

where the prompt rates (Tables II and IV) are given in counts per min. and \( \tau \) is the delay mixer gate width in seconds. The justification for the above formulae will be found, by analogy, from the considerations given below regarding the (BC)_{del}^{\text{chance}} rate.

In Table III the casual (BC)_{del} rates have been included. These need some discussion as they are extremely important in the interpretation of the experi-

### Table IV

**Prompt rates (counts per min.)**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>(ABC)</td>
<td>214</td>
</tr>
<tr>
<td>(BC)</td>
<td>373</td>
</tr>
<tr>
<td>(ABB)</td>
<td>33.4</td>
</tr>
<tr>
<td>(ABBC)</td>
<td>14.5</td>
</tr>
</tbody>
</table>
First, it can be stated that there is no contribution to the casual 
\((BC)_{de}t\) rate due to counter lags and threshold amplifier lags, because 
the probability of simultaneous lags in \(C\) and \(B\) is negligible. As for the chance 
\((BC)_{de}t\) it must be noted that \((AB)\) events in which tray \(C\) is discharged simultaneously 
(chiefly due to mesons passing through the three trays) can never be 
associated with a chance \((C)_{de}t\) event, nor therefore with a chance \((BC)_{de}t\) 
event. This is so because of the long dead time associated with the \(C\) branch 
of the mixing circuit.* Then, to a first approximation, the number of chance 
\((BC)_{de}t\) events is \(\frac{1}{2} (AB) - (ABC) \) \((BC)\) \(\tau\) counts per hr., where the prompt 
 rates (counts per min.) are given in Tables II and IV. However, corrections 
must be introduced to the above expression for the following reasons.

1. One of the counters of tray \(B\) is insensitive after having been discharged 
in the triggering event: a factor 7/8 is therefore included to express the 
fact that for a subsequent particle only seven counters are available.

2. An oblique particle discharging in addition to \(A\) two counters of tray \(B\) 
(event \((ABB)\)) will give both a normal and a threshold output, making the 
\(B\) branch of the delay mixer insensitive to a subsequent pulse.

Taking into account these considerations, the chance \((BC)_{de}t\) rate may be 
written

\[
(BC)_{de}t^{\text{chance}} = \frac{1}{2} (AB) - (AB) - (ABB) + (ABBC) \]

\[
\times \frac{1}{2} (BC) \quad \tau \text{ counts per hr.}
\]

The relevant prompt rates not already given in Table II are given in Table IV; 
they do not change significantly with the insertion of the graphite plus lead 
between \(B\) and \(C\). Evaluating the above expression we find finally:

\[
(BC)_{de}t^{\text{casual}} = (BC)_{de}t^{\text{chance}} = 0.20 \text{ counts per hr.,}
\]

with an estimated error \(\sim \pm 10\%\).

**Results and Discussion**

Runs with and without the graphite plus lead absorber between \(B\) and \(C\) were 
alternated, and the measured counting rates with their standard deviations 
are given in Table V.

The observed rate \((BC)_{de}t\) could be due to the following causes:

(i) Genuine electron—photon coincidences from the meson decay, i.e., the 
effect looked for;

(ii) Single decay electrons which traverse both trays \(B\) and \(C\);

(iii) Casual events.

The casual \((BC)_{de}t\) rate given in Table III is expected to be, to a very good 
approximation, independent of the presence or absence of graphite plus lead, 
as mentioned before. An inspection of Table V shows that while the observed

* It is on account of this fact—the "anticoincidence function" of long dead-time circuits—that 
an anticoincidence \((AB - C)\) was not used as a triggering event. For the same reason the chance 
\((B)_{de}t\) rate is greater than the chance \((C)_{de}t\) rate (Table III).
(BC)_{del} rate with the graphite plus lead absorber is about equal to the estimated casual rate, the (BC)_{del} rate without the absorber is substantially higher than the casual rate. This increase observed in the absence of absorber must be due to a delayed radiation considerably absorbed by the thickness of graphite plus lead used. To verify that single decay electrons (cause (ii)) are responsible for this effect a subsidiary experiment was performed.

### Table V

<table>
<thead>
<tr>
<th>Meson absorber</th>
<th>(B)_{del}</th>
<th>(C)_{del}</th>
<th>(B)<em>{del} + (C)</em>{del}</th>
<th>(BC)_{del}</th>
</tr>
</thead>
<tbody>
<tr>
<td>With graphite plus lead — (104.2 hr. of observation)</td>
<td>11.93 ± 0.34</td>
<td>12.26 ± 0.34</td>
<td>24.19 ± 0.48</td>
<td>0.21 ± 0.05</td>
</tr>
<tr>
<td>Without graphite plus lead — (77.2 hr. of observation)</td>
<td>6.48 ± 0.29</td>
<td>4.64 ± 0.25</td>
<td>11.12 ± 0.38</td>
<td>0.43 ± 0.08</td>
</tr>
<tr>
<td>Net effect due to decay electrons from graphite plus lead</td>
<td>5.45 ± 0.45</td>
<td>7.62 ± 0.42</td>
<td>13.07 ± 0.62</td>
<td></td>
</tr>
</tbody>
</table>

Consider the counter arrangement (Fig. 2) without the graphite plus lead absorber. Decay electrons which discharge both B and C, contributing to (BC)_{del}, must be attributed to the decay of mesons which having traversed A and B are stopped in material below C, but do not discharge C.* Some decay electrons from such mesons will travel upwards through C and B. The number of mesons “leaking” through tray C without discharging it was increased by removing the voltage from some of the counters of tray C, while the fraction stopping just below C was increased by placing a thickness (8.5 gm. per cm.²) of graphite below C. The delayed rates were measured and an analysis of the results shows that the excess (BC)_{del} rate noted in our experiment without graphite plus lead absorber may be attributed to this cause (ii). In the presence of graphite plus lead, the effect is not detected because, with the geometry used, the thickness of absorber between B and C is sufficient to reduce substantially (15) the number of decay electrons which can traverse both B and C.

It is apparent, therefore, that the change in contribution of effect (ii) to the (BC)_{del} rate prevents an estimate of effect (i)—electron–photon coincidences—being made by comparing the rates (BC)_{del} with and without graphite plus lead. Consequently it is necessary to compare the measured rate (BC)_{del} with graphite plus lead with the estimated casual rate, (BC)_{casual}^{est}. The difference—observed (BC)_{del} rate with graphite plus lead minus casual rate (BC)_{casual}—is

\[
\Delta = 0.01 \pm 0.06 \text{ counts per hr.}
\]

* Because of the long dead-time anti-coincidence function of the C circuit.
\( \Delta \) is to be interpreted as the observed contribution of the hypothetical decay into an electron and a photon, and must be compared with the expected effect from such a decay process.

This effect can be estimated by taking as a starting point the observed numbers of decay particles \((B)_{\text{det}}\), \((C)_{\text{det}}\), from graphite plus lead, which are given in the last line of Table V. Let \( \xi \) be the efficiency of one of the lead covered trays for gamma radiation of 50 Mev., and, assuming the photon hypothesis, let \( \beta \) be the probability that when a decay electron is detected in \( B \) the accompanying photon impinges on the lead covering \( C \), and let \( \gamma \) be the probability that when a decay electron is detected in \( C \) the accompanying photon impinges on the lead covering \( B \). The rate \((BC)_{\text{del}}\) due to electron-photon coincidences will be

\[
\Sigma = \beta \xi (B)_{\text{det}} + \gamma \xi (C)_{\text{det}} \text{ counts per hr.}
\]

Apart from a small correction due to the absorption of photons in graphite, \( \beta \) and \( \gamma \) are essentially geometrical factors which were estimated to be approximately 0.6 and 0.5 respectively. These figures represent averages over the absorber; the difference is due to the "dead counter" effect in \( B \).

The gamma efficiency \( \xi \) of a counter tray covered by 2.1 mm. lead for 50 Mev. photons can be estimated in a straightforward way. Pair production is by far the main contribution to the total absorption process for such photons in lead. Since the thicknesses of lead involved are small compared with the range of the most energetic electron (positive or negative) of the pair, the efficiency is only very slightly less than the probability that a photon produces a pair in the lead covering the tray. The absorption coefficient for a 50 Mev. photon in lead is taken to be 1 cm.\(^{-1}\) (12), from which we find that \( \xi \) is between 15\% and 20\%. We can now arrive at the value \( \Sigma = 1 \) count per hr. with an estimated uncertainty of about \( \pm 30\% \).

**Conclusion**

A comparison of the "expected value" \( \Sigma \) of the rate \((BC)_{\text{del}}\) with the observed value \( \Delta \) leads to the conclusion that the 2.2 \( \mu \)sec. meson decay process does not consist of the emission of an electron and a photon, each of about 50 Mev. according to the laws of conservation of energy and momentum.

Our result refers to both positive and negative mesons, because in carbon mesons of both signs undergo decay. This is in agreement with the results of Sard and Althaus (31, 32) and of Piccioni (26, 27), which, however, refer only to positive mesons.

The results of the present experiment and of the independent experiment of Sard and Althaus are also complementary. Substantially different gamma efficiencies and different "sources" of decay particles were used. In addition a rather fundamental difference should be emphasized. Sard and Althaus' experiment is an attempt to detect delayed gamma radiation in the meson
decay process, without any correlation with the decay electron. In this sense their experiment is more general than the present experiment. On the other hand, the present experiment was designed with the intention of minimizing the chances of detection of bremsstrahlung from the decay electron:* in fact bremsstrahlung photons would be emitted primarily in a forward direction by the electron while our experimental arrangement is sensitive only to simultaneous emission of an electron and a photon in approximately opposite directions. The negative result obtained in this research has permitted the authors to design another experiment to detect the bremsstrahlung from the decay particles. This will be reported in a separate paper (18).

Another conclusion which can be reached from the results of this experiment concerns the stability of a hypothetical neutral meson. Several authors (2, 22) have ventured the hypothesis that the decay of the meson might involve the emission of a neutral meson of mass about 70 Mev. This was mainly suggested by two cloud chamber pictures (1, 2) of decay electrons whose energy was about 25 Mev. Greisen (10) has argued that "numerous phenomena which have defied even qualitative explanation up to the present are made understandable in the light of the neutral meson hypothesis", provided the neutral meson decays immediately into two photons. The gamma instability of a neutral meson has been predicted on theoretical grounds (7, 9). The experimental results reported here lead to the conclusion (11) that either the neutral meson is not emitted in the 2.2. μsec. meson decay process, or, if it is emitted, it does not decay into two photons with a mean life \( \leq 10^{-10} \) sec. A similar conclusion, referring only to positive meson decay, was reached by Sard and Althaus (32).

The absence of photons in the 2.2. μsec. decay process is in agreement with the evidence arising from an analysis (3, 24) of the genetic relationship between hard and soft components of the cosmic radiation in the lower atmosphere. Actually it would have been difficult to interpret the cosmic ray results on this topic if the total energy of mesons decaying in flight were emitted in the form of ionizing radiation.

Our result definitely eliminates one of the decay processes that could have been postulated for a meson of spin \( \frac{1}{2} (h/2\pi) \). However, a half-integral meson spin still presents a considerable attraction as was pointed out in the introduction to this paper, and in more detail in reference (28). Another process involving such a value for the meson spin, and currently in favor, is disintegration into an electron and two neutrinos. Recent experimental evidence supporting this hypothesis includes (a) the establishment of the fact that the charged decay particles have electronic mass (16, 17, 18), and (b) the form of the energy spectrum of the decay electrons (21).

* In the experiment of Sard and Althaus the bremsstrahlung was discriminated against by having an anticoincidence counter tray on the path of the photon which would be discharged by an accompanying electron. However this discrimination is much less severe than the one used in the experiment described here.
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