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The Internal Pair Production of γ-Rays of Mesonic Origin; Alternate Modes of π^0 Decay*

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The internal pair creation of the γ-rays in the processes

$$(1)\quad \pi^0\rightarrow\gamma+\gamma,$$
$$(2)\quad \pi^-+P\rightarrow\gamma+N$$

has been observed. The experimental conversion coefficient $\beta=0.0080\pm0.0016$ is to be compared to the theoretical prediction, 0.0063. In addition, we have obtained an upper limit on the fraction of neutral pions which decay directly into a pair: $\pi^0\rightarrow e^++e^-$. The limit is one in 2000.

I. INTRODUCTION

As in lower energy phenomena, mesonic processes usually resulting in γ-ray emission may instead produce an electron-positron pair. The characteristics of this pair are calculable in good approximation on the basis of quantum electrodynamics, and there is all reason for confidence in these theoretical results.[1,2] Since some of the theoretical findings are necessary in the analysis of the experiments which are here described, they will be stated briefly. (a) The internal conversion rate is expected to be

$$\beta\cong\frac{2\alpha}{3\pi}\left[\ln\frac{E}{mc^2}-1.4\right],$$

where $\alpha=1/137$, E=photon energy, and m=electron mass. (b) The electrons are emitted with angular correlation

$$P(\theta)d\theta\simeq\text{const}\times d\theta/\theta;\quad \theta>4mc^2/E.$$

Half of the pairs are emitted within the correlation angle $\theta_{\frac{1}{2}}=(8mc^2/E)^{\frac{1}{2}}$. For the following it may be pointed out that this distribution is slightly broader than that of pairs produced and scattered in 1 g/cm² Pb converter. (c) The electrons are emitted with a flat energy distribution from mc^2 to $E-mc^2$.

These properties are to good approximation independent of the nature of the recoil and the multipole character of the radiation.[1] In addition, it may be noticed that β is only weakly dependent on the γ-ray energy. For $E=130$ Mev, $\beta=0.0065$; for $E=70$ Mev, $\beta=0.0062$.[2] We have studied this conversion in the processes

$$\pi^0\rightarrow\begin{cases}\gamma+\gamma & \text{(1a)}\\ \gamma+e^++e^-, & \text{(1b)}\end{cases}$$

$$\pi^-+P\rightarrow\begin{cases}\gamma+N & \text{(2a)}\\ e^++e^-+N. & \text{(2b)}\end{cases}$$

The photons of process (1) have approximately 70-Mev energy; those of process (2) have 130 Mev. Pairs of electrons, probably the result of the π^0 decay in (1b) have been observed by Daniel, Davies, Hulvey, and Perkins[3] in cosmic-ray stars and by Lord, Fainberg, Haskin, and Schein[4] in π^- induced stars.

In addition, we consider the disintegration

$$\pi^0\rightarrow e^++e^-. \qquad \text{(1c)}$$

From a theoretical point of view, (1c) may proceed in 3 ways: (a) There is a specific meson-electron interaction. (b) The meson, possibly with the help of

* Research supported by joint contract of ONR and AEC.
[1] J. R. Oppenheimer and L. Nedelski, Phys. Rev. **44**, 948 (1939).
[2] R. H. Dalitz, Proc. Phys. Soc. (London) **A64**, 667 (1951).
[3] Daniel, Davies, Hulvey, and Perkins, Phil. Mag. **43**, 753 (1952).
[4] Lord, Fainberg, Haskin, and Schein, Phys. Rev. **87**, 538 (1952).

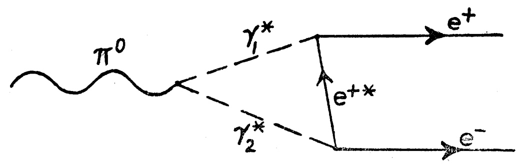

FIG. 1. Feynman diagram for the disintegration (1c) proceeding by way of two intermediate virtual photons.

intermediate nucleon states, produces a virtual photon which creates the pair. (c) The meson produces 2 virtual photons by means of the interaction responsible for 1(a) and 1(b) (see Fig. 1). The electrons are the secondaries of these photons.

Process (b) is of the same order in α as (1a) and might be expected to compete favorably. However, it may be shown that it is not possible to construct a gauge and Lorentz invariant interaction which absorbs the neutral meson of zero spin and emits a virtual photon. For spin-zero mesons, therefore, process (b) can make no contribution.[5] This is a more general statement of a result noticed on the basis of a more specific model using intermediate nucleons to obtain the coupling between meson and photon fields.[6]

Process (c) can be calculated on the basis of quantum electrodynamics. It is of the same order in α as the decay into two pairs (Fig. 2). Both processes are expected, therefore, to be $10^{-4}-10^{-5}$ times as probable as (1a).

II. EXPERIMENTAL ARRANGEMENTS

We have studied (1) and (2) experimentally, using negative mesons stopped in liquid hydrogen. It has been shown by Panofsky *et al.*[7] that on coming to rest in hydrogen, the pion is absorbed, probably from the K orbit, and the reactions (1a) and (2a) proceed at the relative rate: $0.93/1\pm20$ percent. We examine the radiation from the target in coincidence (10^{-8} sec resolving time) with the incident meson, especially as a function of the amount of lead converter between the target and the detector. Those particles observed without converter, after subtracting pairs produced in the target, target walls, and detector, are attributed to the internal conversion electrons. The experimental arrangements are shown in Figs. 3, 4, and 8. All five counters are in coincidence. It is important that the geometry is such that electrons which originate in the heavier parts of the target are excluded. This is the reason for the small vertical dimension of counter No. 3.

It is equally important to keep the radiation thickness of the target, its walls and the counter as small as possible. In our case, we have a total conversion thickness of 0.094 g/cm^2 Pb equivalent or, on the basis of the experiments of Lawson,[8] 0.0068 and 0.0080 mean free paths for γ-rays of processes (1) and (2), respectively. This contributes a background approximately equal to the expected effects.

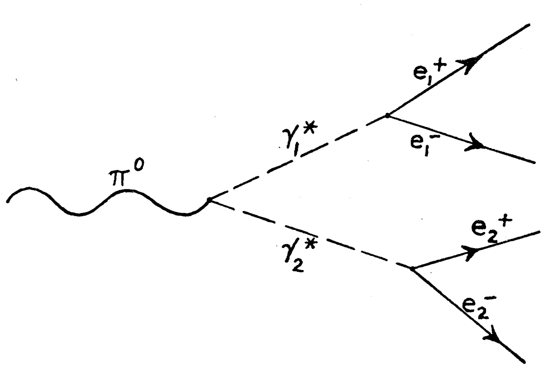

FIG. 2. Feynman diagram for the decay of a π^0 meson into two pairs.

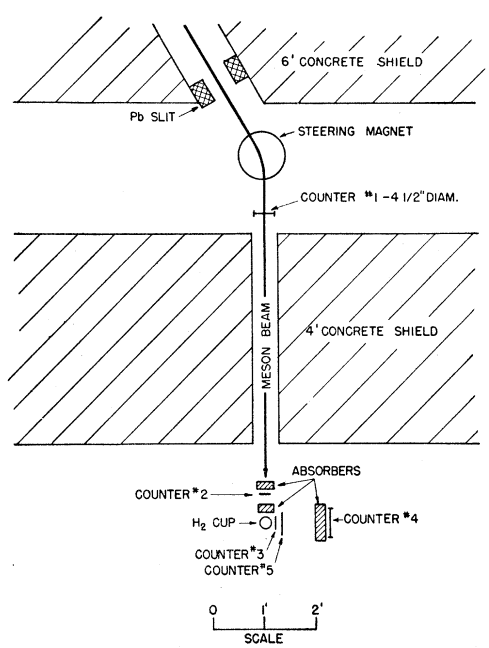

FIG. 3. Geometry, over-all.

III. EXPERIMENTAL RESULTS

A. Observed Events Caused by Mesons Stopped in H_2

The data exhibited in Fig. 5 (each point represents a subtraction filled cup—empty cup) show the variations of the coincidence rate with thickness of the absorber in the meson beam (absorber 1). The coincidences, both with and without converter, occur near the end of the range of the 70-Mev meson beam. The events are therefore produced by mesons *stopped* in hydrogen.

[5] Although for spin zero mesons these arguments forbid the decay into an electron pair by process (b), in the case of spin-one mesons, the decay into two γ-rays is forbidden and the decay into an electron pair is allowed.

[6] J. Steinberger, Phys. Rev. **76**, 1180 (1949).

[7] Panofsky, Aamodt, and Hadley, Phys. Rev. **81**, 565 (1951).

[8] T. Lawson, Phys. Rev. **75**, 433 (1949).

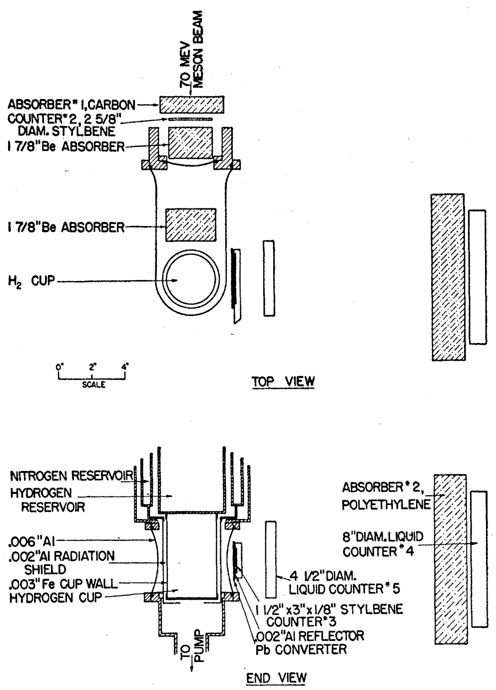

FIG. 4. Geometry, detail.

B. Conversion Characteristics

The conversion in lead of the radiation produced by the mesons stopping in hydrogen is shown in Fig. 6. Two points on this conversion curve were measured with greater accuracy to allow a more precise determination of the internal pair creation coefficient β. The data are given in Table I.

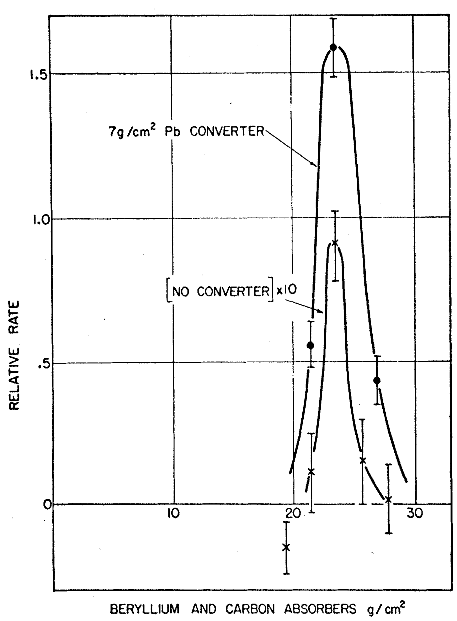

FIG. 5. Counting rates as a function of the incident meson range. Indicated errors are standard statistical fluctuation.

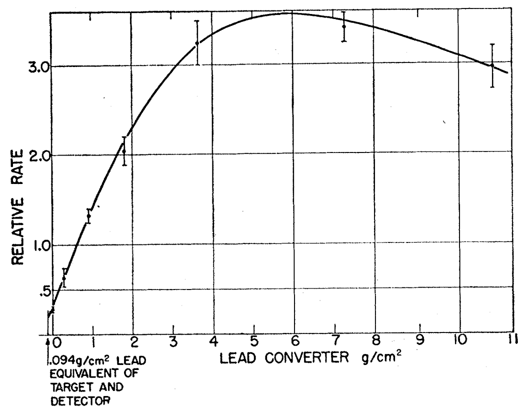

FIG. 6. Conversion characteristics of the radiation produced by mesons stopped in hydrogen. Indicated errors are standard statistical fluctuation.

The existence of the direct pairs is demonstrated in Fig. 6. If the conversion characteristics are extrapolated to that negative converter thickness which represents the conversion in the target and its walls, the remaining counting rate is the result of the internally converted pairs.

C. Electron Ranges

In Fig. 7 we present data on the attenuation in absorber No. 2 of the particles originating in hydrogen, both with and without 1 g/cm² Pb converter. Absorber thicknesses less than 55-Mev ionization loss equivalent are polyethylene, those in excess are a mixture of this and carbon.

Theoretically, we expect similar range curves with and without converter, since both the relative conversion rate of the two γ-ray groups as well as the energy spectra of the conversion electrons are very nearly the same in internal as in external conversion. This is in reasonable agreement with the experimental results.

D. 180° Coincidences

In process (1) the γ-ray or pair is accompanied by another γ-ray at an angle of between 168° and 180° in the laboratory system. The deviation from 180° is caused by the velocity of the neutral meson, approximately $(0.22\pm0.02)c$. Detection of this γ-ray can serve to distinguish between process (1) and process (2). We have detected 180° coincidences by replacing counter No. 5, Fig. 2, by a counter 8 in. in diameter, $6\frac{1}{4}$ in. from the center of the target, opposite telescope No. 3–No. 4 (see Fig. 8). The results are given in Table II.

TABLE I. Two points on the lead conversion curves. Absorber 2 is 5 g/cm² CH_2. Quoted error is standard statistical fluctuation.

Converter thickness	Counts per 10^6 incident particles: Target full	Target empty	Net due to H_2
None	4.95±0.31	0.47±0.13	4.48±0.34
0.96 g/cm² Pb	25.5 ±1.0	1.49±0.42	24.0 ±1.1

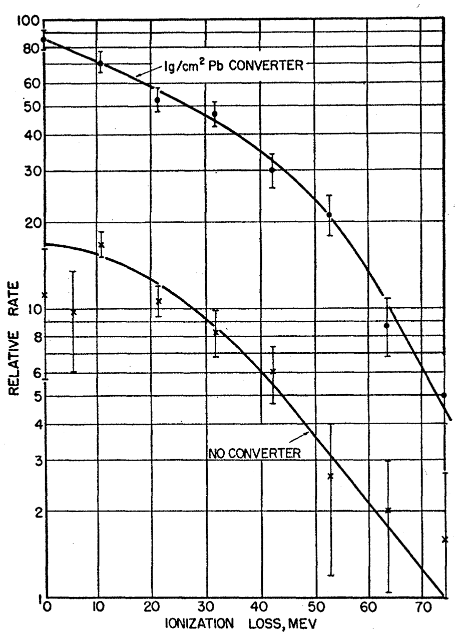

FIG. 7. Integral range of internal and external conversion electrons for two converter thicknesses. Indicated errors are standard statistical fluctuation.

IV. ANALYSIS OF THE EXPERIMENTAL DATA

A. Internal Pair Creation Coefficient β

In order to calculate the internal pair creation coefficient on the basis of the data (Table I), it is necessary to known: (a) the conversion probability of the γ-rays in the converter, (b) the conversion in the target, walls, and counters, (c) the relative efficiency for detecting the electrons produced by internal and external conversion.

Let

τ = conversion thickness of target, walls, etc.

$t=\tau+$converter thickness$=\tau+0.96$ g/cm^2 Pb.

λ_1 = mean free path for pair creation of 70-Mev γ-rays.

λ_2 = mean free path for pair creation of 130-Mev γ-rays.

ϵ_{γ^1}, ϵ_{γ^2} = efficiency for detecting one member of the externally converted pair of processes (1) and (2).

ϵ_{e^1}, ϵ_{e^2} = efficiency for detecting one of the internally converted γ-rays of processes (1) and (2), respectively.

η = fraction of γ-rays due to process (2)$=0.35\pm0.07$.[7]

$1-\eta$ = fraction of γ-rays due to process (1).

β = internal conversion coefficient.

Then the net counting rates, C.R., with and without converter, are

$$\begin{aligned}\text{C.R.}_t&=(1-\eta)\epsilon_{\gamma^1 t}(1-e^{-t/\lambda_1})+\eta\epsilon_{\gamma^2 t}(1-e^{-t/\lambda_2})\\&\quad+\beta[(1-\eta)\epsilon_{e^1 t}+\eta\epsilon_{e^2 t}],\\ \text{C.R.}_\tau&=(1-\eta)\epsilon_{\gamma^1\tau}(1-e^{-\tau/\lambda_1})+\eta\epsilon_{\gamma^2\tau}(1-e^{-\tau/\lambda_2})\\&\quad+\beta[(1-\eta)\epsilon_{e^1\tau}+\eta\epsilon_{e^2\tau}].\end{aligned}\tag{3}$$

Here we assume the thicknesses t and τ small enough so that secondary shower effects are negligible.

If

$$R\equiv\text{C.R.}_t/\text{C.R.}_\tau=5.36\pm0.46,$$

then

$$\beta=\frac{(t/\lambda)\epsilon_{\gamma t}-R(\tau/\lambda)\epsilon_{\gamma\tau}}{R\epsilon_{e\tau}-\epsilon_{et}},\tag{4}$$

where

$$(t/\lambda)\epsilon_{\gamma t}=(1-\eta)(1-e^{-t/\lambda_1})\epsilon_{\gamma^1 t}+\eta(1-e^{-t/\lambda_2})\epsilon_{\gamma^2 t}\tag{5}$$

and

$$\epsilon_{et}=(1-\eta)\epsilon_{e^1 t}+\eta\epsilon_{e^2 t}.\tag{6}$$

We proceed to the calculation of the several parameters.

(*1*) *Conversion in the Target and Detector* τ

The effective conversion thickness of target and detector is the following:

$$\tfrac{1}{4}\pi\times1.5\text{ in. }H_2+(4/\pi)\times0.0035\text{ in. Fe}+0.011\text{ in. Al}+0.062\text{ in. CH}.$$

The corresponding number of radiation lengths are

$$0.00172\text{ H}+0.0063\text{ Fe}+0.0032\text{ Al}+0.0028\text{ C}=0.0140\text{ radiation length}.$$

$\tau=0.0140\times5.9$ g/cm$^2\times1.12/0.98=0.0945$ g/cm^2 Pb equivalent, where the last factor is the measured ratio of pair creation cross sections in light elements and in lead.[8] $t=0.96+0.094=1.055$.

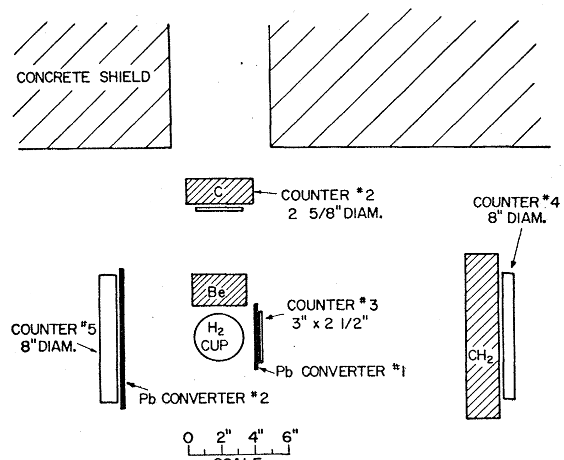

FIG. 8. Geometry of 180° coincidence experiments.

TABLE II. Experimental results on 180° coincidences (see Fig. 6). Errors tabulated are standard deviations.

Converter No. 1	Converter No. 2	Counts 1+2+3+4 per 10^6 incoming particles: Target full	Target empty	Net	Counts 1+2+3+4+5 per 10^6 incoming particles: Target full	Target empty	Net
none	none	21.7±1.0	9.4±1.2	12.3±1.6	0.525±0.17	0.15±0.15	0.37±0.25
1.85 g/cm² Pb	none	106 ±4.1	10.6±1.4	95 ±4.3	3.9 ±0.78	0.5 ±0.3	3.4 ±0.85
none	7.25 g/cm² Pb	23 ±1.0	8.8±0.9	14.2±1.4	1.86 ±0.26	0.13±0.09	1.73±0.28
0.96 g/cm² Pb	7.25 g/cm² Pb	65.3±2.2	10 ±1.5	55 ±2.7	10.8 ±0.9	0.2 ±0.2	10.6 ±0.9
1.85 g/cm² Pb	7.25 g/cm² Pb	112 ±4.3	9.9±1.4	102 ±4.5	16.6 ±1.7	0.33±0.25	16.3 ±1.7

(2) *Mean Free Path for Pair Production* λ

Again using Lawson's[8] data,

$$\lambda_1 = 11.8 \text{ g/cm}^2 \text{ Pb}; \quad \lambda_2 = 10.6 \text{ g/cm}^2 \text{ Pb}.$$

(3) *Detection Efficiencies* ϵ

The probability of detecting one of the electrons in a pair depends on the solid angle Ω of the detectors, on the probability s that the electron has sufficient range, and on the probability p that both members of the pair are detected. $\epsilon = s/(1+p)$; we drop the factor Ω which is common to all ϵ's, and consider a fixed photon energy. If $N(E)dE$ is the normalized energy distribution of the converted electrons, and if this corresponds to a normalized range distribution $M(R)dR$, then

$$s = \int_{R_{\min}} M(R)dR.$$

$R_{\min}$ is the minimum range necessary to traverse the counters and absorbers. If straggling is neglected in the following,

$$s = \int_{E_{\min}}^{E_{\max}} N(E)dE.$$

The factor p is the product of a geometrical factor g and a range factor r. r is the probability that particle 2 has sufficient range, given the fact that particle 1 does. Again, neglecting straggling,

$$r = \frac{1}{s}\int_{E_{\min}}^{E_{\max}-E_{\min}} N(E)dE = 2 - \frac{1}{s}, \tag{7}$$

the last because of the symmetry of $N(E)$ in pair production. g is the geometrical probability of finding the second electron within counter No. 4, averaged over the position of incidence of electron 1 in this counter. We have not succeeded in solving this problem exactly, but have derived an approximate relation for a Gaussian correlation.

Let $P(r) = \exp(-r^2/a^2)$ be the distribution function of particle 2 about particle 1, where r is the distance between the particles, both r and a in units of the radius of counter No. 4. Then

$$g \cong \frac{2}{\pi} E\left(\frac{1}{a}\right)\left\{a\left[\exp\left(-\frac{1}{a^2}\right)-1\right] + (2+a)E\left(\frac{1}{a}\right) - \frac{a^2}{2}E\left(\frac{2}{a}\right)\right\}, \tag{8}$$

where

$$E(x) \equiv \int_0^x \exp(-y^2)dy. \tag{9}$$

For the computation of s and r, we have taken $N(E) = 1/E_{\max}$, a good approximation for both external and internal pairs. $E_{\min} = 17.4$ and 15.6 Mev with and without converter, respectively. The average radiation loss has been included in $E_{\min}$. Then

$$s_{1t}=0.75, \quad s_{1\tau}=0.77, \quad r_{1t}=0.67, \quad r_{1\tau}=0.70,$$
$$s_{2t}=0.87, \quad s_{2\tau}=0.88, \quad r_{2t}=0.85, \quad r_{2\tau}=0.86.$$

In evaluating g we have replaced the distribution of the internal pairs by a Gaussian with the same median. Taking into account scattering in the converter, we have from (2)

$$g_{\gamma^1 t}=0.64, \quad g_{\gamma^1 \tau}=0.90, \quad g_{e^1 t}=0.36, \quad g_{e^1 \tau}=0.45,$$
$$g_{\gamma^2 t}=0.81, \quad g_{\gamma^2 \tau}=0.94, \quad g_{e^2 t}=0.51, \quad g_{e^2 \tau}=0.59,$$

and

$$p_{\gamma^1 t}=0.43, \quad p_{\gamma^1 \tau}=0.63, \quad p_{e^1 t}=0.241, \quad p_{e^1 \tau}=0.315,$$
$$p_{\gamma^2 t}=0.69, \quad p_{\gamma^2 \tau}=0.81, \quad p_{e^2 t}=0.43, \quad p_{e^2 \tau}=0.508,$$

so that

$$\epsilon_{\gamma^1 t}=0.525, \quad \epsilon_{\gamma^1 \tau}=0.473, \quad \epsilon_{e^1 t}=0.605, \quad \epsilon_{e^1 \tau}=0.586,$$
$$\epsilon_{\gamma^2 t}=0.515, \quad \epsilon_{\gamma^2 \tau}=0.486, \quad \epsilon_{e^2 t}=0.609, \quad \epsilon_{e^2 \tau}=0.585.$$

It should be observed that only the relative efficiencies for external and internal pairs enter in the expression (4) for β. We believe that these relative efficiencies are in error by less than 10 percent.

(4) *Compton Electrons*

In the expression (4) for β we have failed to include the contribution of the Compton electrons. Although in lead this is only a few percent of that resulting from pair production, Compton electrons of the light elements are not negligible. We must add in the numerator of (4) the term $\frac{1}{2}[f_{Ct} - Rf_{C\tau}]$, where f_{Ct} and $f_{C\tau}$ are the fraction of γ-rays detected by means of their Compton electrons, with and without converter, respectively. On the basis of the Klein-Nishina formula $f_{Ct}=0.0032$, $f_{C\tau}=0.0017$, and $\frac{1}{2}[f_{Ct}-Rf_{C\tau}]=-0.0030$.

(5) Result

We then obtain

$$\beta=\frac{(t/\lambda)\epsilon_{\gamma t}-(R_T/\lambda)\epsilon_{\gamma\tau}-0.0030}{R\epsilon_{e\tau}-\epsilon_{et}},$$
$$=\frac{0.0453-0.0210-0.0030}{3.14-0.607},$$
$$=0.0084\pm0.0016.$$

The possible errors in β are as follows:

(a) Photons are converted in the heavier portions of the target and scattered into the telescope by the first counter. This requires a scattering through at least 30° in 0.004 radiation length, and should contribute negligibly.

(b) Electrons from μ-e decay. The μ-mesons may be either a beam contamination or else a contamination resulting from the decay of π-mesons which competes with π-capture in hydrogen. The electrons are emitted with a mean delay of 2.2×10^{-6} sec and have a probability 1/200 of occurring within the 10^{-8} sec resolving time of the coincidence circuits. The μ-meson beam contamination is 5–6 percent, and has somewhat larger range than that of the π-mesons, so that an even smaller percentage, compared to the π-mesons would stop in the hydrogen. They should, therefore, contribute at most $0.02/200=0.0001$ electron per stopped π-meson, one percent of the observed effect. The competition of π-μ decay and π-capture has been studied in the cloud chamber filled with hydrogen at 20 atmospheres by Sargent and Reinhardt.[9] No π-μ decays were observed in 20 events of stopping pions. Therefore, in liquid hydrogen, this competition cannot affect our result.

(c) The subtraction for conversion in the target, altogether 0.53 of the counting rate without converter, may be in error to the extent of the measured cross sections,[8] as well as the measured target thicknesses. We believe that altogether this should not contribute to the error in excess of 5 percent.

(d) The neglect of secondary shower effects leads to an underestimate of β. We estimate this effect to be less than 1.

Combining the errors, we have the experimental result $\beta_{\text{exp}}=0.0084\pm0.0019$, which is to be compared with the theoretical value $\beta_{\text{theory}}=0.0063$. The discrepancy is somewhat larger than the experimental uncertainty, it is also larger than a reasonable estimate of the theoretical uncertainty.

[9] We wish to thank authors Sargent and Reinhardt for these as yet unpublished results.

B. Upper Limit on the Direct Decay into Two Electrons

The data on 180° coincidences allows an upper limit to be placed on the fraction of π^0 mesons which decay directly into a pair. The fraction of such events is

$$\frac{\text{C.R. without converters, and resulting from electrons}}{\text{C.R. with converters}}\times\frac{\text{efficiency for detecting }\gamma\text{-ray pairs}}{\text{efficiency for detecting electron pairs}}.$$

The rate with converter is $16.3\pm1.7/10^6$ incoming particles, without converter it is $0.35\pm0.25/10^6$ incoming particles. It is possible, however, in this geometry to count some γ-rays converted in the heavy target walls near counter No. 5 (see Fig. 8). Even neglecting this, a rate $0.20/10^6$ incoming particles is derived from the conversion of γ-rays in the target walls and counters. An upper limit for the number of direct pairs counted may be $0.2/10^6$ incoming particles. The detection efficiency for the pair is approximately unity. The photon detection efficiency is obtained from the computations of IVA, with the help of the data of Figs. 6 and 7. We obtain 0.14 for telescope 3–4 with $\frac{1}{16}$ in. converter, and 5 g/cm² CH_2 absorber, and 0.30 for $\frac{1}{4}$ in. converter and no absorber. The over-all efficiency for counting the pair is therefore 0.042. We obtain

$$\frac{\text{rate }\pi^0\rightarrow e^++e^-}{\text{rate }\pi^0\rightarrow\gamma+\gamma}\leqslant\frac{0.2\times0.042}{16.3}=0.0005.$$

This upper limit is still larger than that expected from the production of electrons with the help of intermediate photons (Fig. 1). It is therefore only possible to state that the specific meson-electron pair interaction is smaller by at least a factor 2 000 than the meson-photon pair interaction.

C. The Branching Ratio $\pi^0\rightarrow\begin{matrix}\gamma+\gamma\\ \gamma+e^++e^-\end{matrix}$

The data of Table II also permit a separate estimate of the internal conversion rate for the γ-rays of neutral meson decay. The computation is as in Part (A) of this section; it is only necessary to make a correction for the difference in geometrical detection efficiency for the γ-ray in counter No. 5, Fig. 8. The difference is the result of a difference in the theoretical angular correlation function for the two processes, and is small because counter No. 5 subtends a large angle (±33°). We calculate a geometrical efficiency of 0.81 in the case of external, and 0.77 in the case of internal conversion. It may be noted that line 5 of Table II provides a check on the calculated efficiencies. We observe 0.160 ±0.019 γ-rays detected in counter No. 5 per γ-ray detected in telescope 3–4. On the basis of the computations, we should expect $(1-\eta)\times 0.81\times 0.30=0.158$. (0.30 is the conversion efficiency, 0.81 the geometrical efficiency).

The data, lines 3 and 4, Table II, yield

$$R=\frac{(10.6\pm 0.9)\times 0.77}{(1.73\pm 0.28)\times 0.81}=5.83\pm 1.05;$$

$$\beta_{\pi^0}=\frac{(1-e^{-t/\lambda_1})\epsilon_{\gamma^1t}-R(1-e^{-\tau/\lambda_1})\epsilon_{\gamma^1\tau}+\frac{1}{2}[fc_t-Rfc_\tau]}{R\epsilon_{e^1\tau}-\epsilon_{e^1t}},$$

$$=0.00725\begin{matrix}+0.0040\\-0.0025\end{matrix};$$

$$\frac{\text{rate}(\pi^0\rightarrow\gamma+e^++e^-)}{\text{rate}(\pi^0\rightarrow\gamma+\gamma)}=0.0145\begin{matrix}+0.0080\\-0.0045\end{matrix}.$$

This agrees with the theoretical prediction of 0.012,[2] and with the findings of the Bristol group.[3]

D. Absolute Counting Rates

It is not uninteresting to see whether or not the observed γ-ray flux does account for most of the incoming π-mesons. Per incoming pion we expect

$$n=1.5\times\frac{2t\epsilon_{\gamma t}}{\lambda}\times(\Omega/4\pi)\times\delta\times\text{outscattering factor}, \quad (10)$$

where 1.5 is the number of γ-rays per captured pion; $t\epsilon_{\gamma t}/\lambda$ is the conversion and detection efficiency as in Sec. A and is 0.04 for 1 g/cm^2 Pb converter; Ω is the solid angle of detection and is 0.173 sterad; and δ is the fraction of mesons with proper range interval, approximately 0.16 from Fig. 5.

The outscattering factor is the hardest to estimate. If we include the effects of the size of counter No. 3 in this factor, and remember that the mesons are scattered rather badly near the end of their range, we estimate a factor $\frac{1}{8}$. Then $n=3.3\times 10^{-5}$; from Table I we see that 2.4×10^{-5} are observed. The observed photon flux, therefore, does account reasonably for the disappearance of the π^- mesons.

V. SUMMARY

We have observed the internal pair production of the γ-rays associated with π^- capture in hydrogen. The conversion coefficient is obtained on the basis of the experimental data, in conjunction with theoretical predictions on the angular correlation and energy distribution of the conversion electrons. The results are as follows: For the conversion of all photons, of which one-third result from the inverse photoeffect and are of 130 Mev, and two-thirds result from π^0 decay and are of ~70 Mev, the experimental conversion coefficient is $\beta=0.0084\pm 0.0019$, in rough agreement with the theoretical result $\beta=0.0063$. For the neutral meson alone the decay into a photon and electron pair proceeds $0.0145\begin{matrix}+0.0075\\-0.0045\end{matrix}$ of the time, compared to the theoretical result 0.012. If we combine these two results, the experiment gives $\beta=0.0080\pm 0.0016$.

In addition, we have obtained an upper limit of 0.0005 on the fraction of neutral pions decaying into an electron pair alone. No such decay processes can occur through the intervention of a single virtual photon for spin-zero mesons. The number expected through the intervention of two virtual photons should be of the order of five times less than the observed limit. The experimental result, combined with experimental estimates on the half-life of the neutral mesons,[10] permits an upper limit to be placed on the direct interaction of the neutral meson with an electron pair. If this interaction is of the form $f\bar{\psi}\gamma_5\psi\phi$, where ψ and ϕ are electron and meson wave functions, respectively, then

$$(f^2/4\pi\hbar c)<10^{-11}.$$

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[10] The experimental results on the lifetime of the neutral meson are not entirely in agreement. Lord *et al.* [reference 4 and Phys. Rev. **80**, 970 (1950)] have evidence that $\tau<2-3\times 10^{-15}$. Daniel *et al.* (see reference 3), as well as Kaplan and Ritson [Phys. Rev. **85**, 900 (1952)] find $\tau\simeq 10^{-14}$ sec. For the purposes of this discussion we take $\tau>10^{-15}$.