State University Research Foundation to the University for aid in fundamental research.

Note added in proof.—The low relative intensity of some beta-components allows large variation in upper energy limits. The presence of beta-ray of energy 2.3 Mev of 5 percent abundance was recently reported by D. E. Alburger *et al.* at the 1952 Annual Meeting of the American Physical Society in New York. The existence of this beta-ray would clearly modify the foregoing analysis of the Fermi plot of Ce^{144} and Pr^{144}.

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The Formation of Triplet Positronium in Gases*

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Positrons stopped in a gas annihilate with the emission of one, two, or three photons. One-photon annihilation has been calculated to occur less than 0.01 percent of the time in light gases.[1] Three-photon annihilation can occur in substantial amounts only for the positron and electron of a positronium atom[2] in a triplet state.[3] In the experiment to be described, the probability of three-photon decay from positronium is measured by comparing two-photon coincidence rates under circumstances which are identical except that in one case triplet positronium is allowed to annihilate, and in the other substantially all the positrons are forced to decay with two photons.

The apparatus is shown in Fig. 1. The magnetic field along the axis roughly doubles in the $\frac{5}{8}$ in. from the center to either pole tip. Because of the radial inhomogeneity, positrons from the $\frac{1}{2}$-mC Na^{22} source,[4] whose velocities lie in the central plane, move in helical orbits [Fig. 1 (B)]. A fraction of the positrons which have a component of velocity along the axis are trapped back into the central region by the axial inhomogeneity, which transfers energy of axial translation into rotation as the positrons adiabatically enter the stronger field. This greatly increases the annihilation rate around the central plane. The NaI(Tl) scintillation counters look for 180° coincidences in a portion of this region defined by the holes in the lead collimators. The lead shields the counters from the direct radiations of the source.

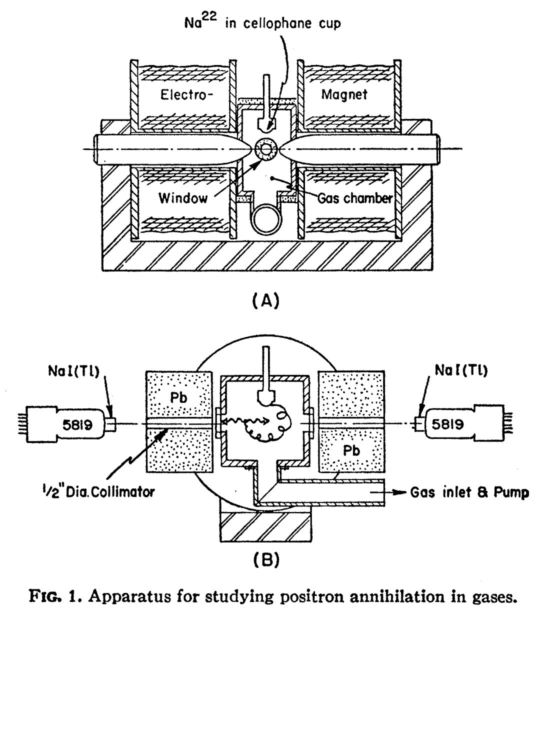

Fig. 1. Apparatus for studying positron annihilation in gases.

Table I. Fraction of positrons stopped in various gases in mean field of 5.62 kgauss, which decay from triplet state of positronium by three-photon emission.

Gas	H_2	N_2	A	He
Three-photon fraction	0.188	0.114	0.166	0.169
Standard deviation (percent)	7.5	4.4	8.5	8.8

A measure of the total number of positrons annihilating in view of the counters is obtained by adding a small amount of NO to the gas. The NO, because of its unpaired electron, gives rise to electron exchanges which can convert triplet to singlet positronium and vice versa.[2] Since the latter's lifetime is much the shorter, the annihilations will be with two photons. We find that adding NO increases the coincidence counting rate by a constant amount for concentrations greater than 0.6 percent. In a typical measurement, the coincidence counting rate is measured first in the gas (e.g., argon) with 3 percent NO added for a total pressure of 760 mm, and then in argon with 3 percent N_2 at the same total pressure. The difference between the two rates divided by the former is interpreted as the fraction of positrons that annihilate with three photons from the triplet state. The nitrogen is added in the latter case in order to ensure that the moderation conditions are as similar as possible.

Current and pressure controls are adequate to reduce counting rate variations caused by fluctuations in these quantities to less than 0.5 percent. The geometry and electronics are frequently tested by inserting a Na^{22} source into one of the collimating holes. All data are normalized to a standard counting rate under this condition. The gas mixtures were frequently changed to prevent changes in composition during the measurements as a result of reactions on the chamber walls. The chamber was filled with air after each exposure to NO, to eliminate an apparent evolution of NO in the subsequent run. Experiment shows that, at the field used, no positrons annihilate on the collimator windows in sight of both counters. Spurious coincidences caused by other effects are less than 1 percent of the total counting rate.

Preliminary data on the relative number of positrons stopped in various gases which decay from the triplet state of positronium with emission of three photons are shown in Table I. These measurements were made in a mean field of 5.62 kgauss. The determination of this field, as well as the correction necessary to reduce these data to zero field values, is discussed in reference 5.

It is a pleasure to thank Professor R. H. Dicke for suggesting this investigation and for his continued advice.

* Supported by the AEC and the Higgins Scientific Trust Fund.
† AEC Predoctoral Fellow, 1949–1951. This material is part of a thesis to be submitted to Princeton University.
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Fine Structure Splitting in the Ground State of Positronium*

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If a positronium atom in the 1^3S state is perturbed by a magnetic field, 1^1S wave function is mixed into the $m_j=0$ substate, while the $m_j=\pm1$ substates are unaffected. Hence two-

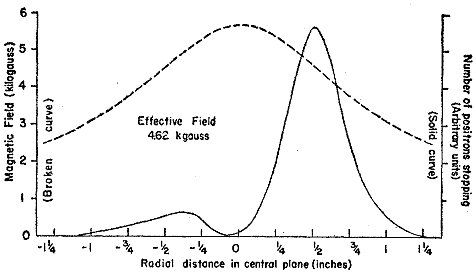

FIG. 1. Distribution of stopped positrons and radial variation of magnetic field in central plane.

photon decays from the former occur. The probability of such an event is approximately

$$[1+(\tau_1/\tau_3)(\Delta/2\hbar\omega_0)^2]^{-1}, \qquad (1)$$

when $\Delta \gg 2\hbar\omega_0 = 2\hbar eH/mc$. The quantities, with their theoretical values, are $\tau_1/\tau_3 = 8.96\times 10^{-4}$, the ratio of singlet and triplet half-lives;[1] and $\Delta = 0.845\times 10^{-3}$ ev, the fine structure splitting.[2] The field does not alter the character of the 1^1S decays because $\tau_1/\tau_3 \ll 1$. By studying the three-photon annihilation of positronium as a function of magnetic field, $\Delta^2\tau_1/\tau_3$ can be determined. With methods similar to those described below, Deutsch has studied this effect.[3]

In the apparatus already described,[4] the positron-trapping field has been used also as the perturbing field. At six magnet currents, the coincidence rates in N_2 at 760 mm with and without 3 percent of NO were compared, and the percentage of positrons annihilating with three photons determined. The magnetic field is necessarily inhomogeneous; hence, the positions in the field where the positrons annihilate must be determined to interpret the data. A piece of aluminum foil ¼ in. × ¼ in. × 0.0006 in. supported from below by a wire was placed on the axis of the volume seen by the counters, and the coincidence rate with one atmosphere of air in the chamber measured at various distances from the center. These measurements were repeated with only the wire in position. The difference between these coincidence rates is taken to be proportional to the number of slow positrons which stop in each particular region. This interpretation is supported by the observation that the difference varies linearly with the thickness of the foil up to 0.0015 in., and is independent of the orientation of the foil. The radial variation of the field in this region was measured with a small search coil and an electronic fluxmeter.[5] Typical position and field data are shown in Fig. 1.

With these data and the calculated values of τ_1/τ_3 and Δ, the three-photon annihilation probability for the $m_j=0$ substate at the various currents can be calculated. If this probability is substituted back into Eq. (1), the effective field for each current is determined. These points are shown in Fig. 2, together with results

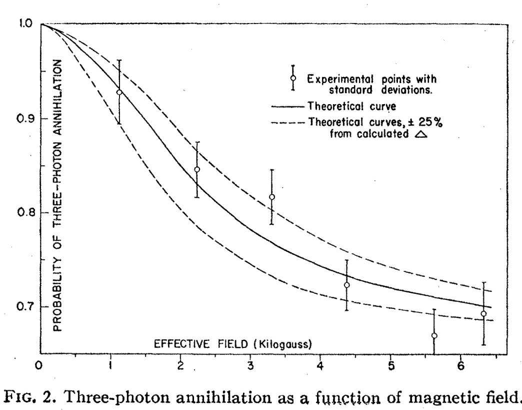

FIG. 2. Three-photon annihilation as a function of magnetic field.

of similar calculations with variations of ±25 percent from the calculated value of Δ. The probability varies between 1 and ⅔ because it is assumed that the triplet substates are equally populated.

Experiment shows that at all fields the number of positrons that annihilate on the windows over the collimators is negligible. Other possible mechanisms for spurious coincidences have been investigated experimentally. Of these, random time coincidences predominate. The data have been corrected for this effect. The correction amounts to less than 1 percent of the total coincidence rate at all fields.

The experimental data show that the number of positrons decaying with three photons decreases from 15.8 percent at 1.12 kg effective field to 11.8 percent at 6.32 kgauss In order to normalize these data to the calculated points, the average of the six points is set equal to the average of the corresponding theoretical values. The result is shown in Fig. 2. Within experimental error, the points lie on the curve calculated for the theoretical value of $\Delta^2\tau_1/\tau_3$. The assumption of equal populations is justified. These results are in agreement with those of Deutsch.[3] Deutsch[6] has also measured τ_3 and finds it in agreement with the calculation of Ore and Powell.[1] Thus it seems likely that the theoretical value of τ_1/τ_3 is substantially correct. Therefore, the data in Fig. 2 can be considered a measurement of Δ^2.

* Supported by the AEC and the Higgins Scientific Trust Fund.
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Photoproduction of Neutral Mesons from Deuterium*

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THE manner in which neutral mesons are coupled to nuclear matter may be determined by an experimental study of the photoproduction of neutral mesons from deuterium. This follows from the fact that the radiated meson waves may differ in phase depending on whether they arise from neutron or proton. The relative phase of this radiation is clearly controlled by the algebraic sign of the coupling. Thus, for meson wavelengths comparable to the separation of the particles in the deuteron, large interference effects may be expected.

Near threshold, meson production may be expected to lead to deuteron formation. For this case interference effects will be large. At higher energies, continuum states will be favored and the interference will be less.

We have calculated the cross section for neutral meson production when a deuteron is formed in the final state. The pseudoscalar meson theory with pseudovector coupling has been assumed, and we have treated the process according to perturbation theory. Although there is no straightforward way to do this, we have attempted to incorporate higher order meson processes by using the anomalous moments of the nucleons. Specifically, effects caused by exchange currents have been neglected but by using the anomalous moments we have, in a sense, included those virtual mesic effects not caused by the presence of a second nucleon. The nucleons have been treated nonrelativistically, and for simplicity the deuteron wave function has been taken as a Gaussian. In addition to this we have used plane waves in the intermediate states. The results are given in Fig. 1. It is found, as one might expect, that the principal contribution to the cross section is