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Annihilation of Positrons in Flight*

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The cross section for annihilation of positrons in flight has been measured for positron energies of 0.765, 1.02, 2.2, and 3.33 Mev. Positron energies were selected by means of a magnetic lens monochromator. A differential energy interval of about 0.1 Mev was defined by the pulse height from an anthracene crystal in which annihilation occurred. The annihilation radiation was detected in a scintillation counter biased to record only quanta above 0.51 Mev. The angular distribution of the annihilation radiation and the total annihilation cross section, at all energies, agrees with the theoretical values within the experimental accuracy, estimated to be about $\pm 5\%$.

A. INTRODUCTION

THE annihilation of a negatron and a positron in free space with the resulting emission of two quanta is one of the fundamental processes of quantum electrodynamics. Very few direct quantitative measurements of the rate or cross section for this process have been reported in the literature.

Colgate and Gilbert[1] have measured the transmission of positrons and negatrons of 50-, 100-, and 200-Mev energy through thin beryllium foils. The larger attenuation of the positron beam was in agreement with the theoretically expected rate of annihilation within the experimental error. The interpretation[2] of the annihilation rate for positrons stopped in gases or in solids involves the unknown electron wave functions and probably throws more light on these than on the fundamental process. The two-quantum annihilation rate at low velocities may be deduced from the magnetic quenching of the three-quantum decay of ortho-(triplet) positronium using the measured ortho-positronium lifetime and the ortho-para splitting. The result agrees with theory within the accuracy of the experiments ($\pm 10\%$).

Several estimates of the annihilation cross section in the 1-Mev region have been made from the number of positron tracks disappearing in cloud chambers or emulsions before reaching the end of their range, or from the integral intensity of gamma rays with energy exceeding m_0c^2 produced by the continuous positron spectrum from a radioactive source. Gerhart, Carlson, and Sherr[3] have used a scintillation spectrometer to study the continuous gamma-ray spectrum produced by the positrons from Ne^{19} and from A^{35} stopped in a thick absorber. These results are generally quite rough, either because of the small number of counts when individual events are observed or because of the complexity of the situation in the integral experiments.

Shearer[4] performed a measurement of the differential probability of annihilation of positrons at several energies from 0.5 to 1.2 Mev. His results showed the expected energy and angular dependence of the cross section, but indicated absolute values about 40% smaller than predicted theoretically. So large a discrepancy seemed inconsistent with the established validity of the approximations involved in the theory. A careful re-examination of Shearer's experiments indicated the probability of systematic experimental errors as well as some inconsistencies in the evaluation of the data. We have therefore performed a new series of experiments employing the general method and some of the equipment used by Shearer and find good agreement, within an experimental error of $\pm 5\%$, between the experimental and theoretical annihilation probability in anthracene for positrons with kinetic energies of 0.765, 1.02, 2.22, and 3.3 Mev.

The experimental arrangement is illustrated schematically in Fig. 1. Positrons of mean energy E,[5] starting in a certain angular range from the source, are focused by the magnetic lens on an anthracene crystal C. The light of the scintillation produced in C is reflected within the Lucite light pipe and from an aluminum reflector to an RCA 6199 photomultiplier. This is referred to as the beta counter. The gamma counter consisting of a NaI crystal mounted on a 6199 photomultiplier with appropriate lead shielding registers annihilation radiation originating in the anthracene crystal and can be rotated in a plane perpendicular to that of the figure about an axis through C.

In the absence of scattering or annihilation in C, all pulses in the beta counter should have the same magnitude representing the total positron kinetic energy E. (If the positron range exceeds the crystal thickness, the pulse height represents only the energy loss in C, but the argument is unchanged.) Actually some pulses of smaller magnitude are observed, showing that some positrons do not expend their entire energy in C. Some

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† National Science Foundation, Postdoctoral Fellow.
[1] S. A. Colgate and F. C. Gilbert, Phys. Rev. 89, 790 (1953).
[2] See M. Deutsch, *Progress in Nuclear Physics* (Pergamon Press, London, 1953), Vol. 3, p. 131, for a more complete discussion of the results mentioned in this paragraph.
[3] Gerhart, Carlson, and Sherr, Phys. Rev. 94, 917 (1954).
[4] J. W. Shearer and M. Deutsch, Phys. Rev. 82, 336 (1951).
[5] We use the notation of W. Heitler, *The Quantum Theory of Radiation* (Oxford University Press, Oxford, 1954), third edition. E is the total energy including rest mass, P is $c \times$ momentum, having the dimensions of energy, referred to here as the momentum.

of these smaller pulses are due to positrons which are annihilated in the crystal after having lost only a small fraction of their energy. By selecting a certain pulse-height range in the beta counter we register only positrons with an energy loss between E_0 and $E_0+\Delta E$ in C before annihilation. We find a considerable number of pulses in this energy range due to positrons scattered out of the crystal and to other effects discussed in more detail in Sec. C. Therefore, only those pulses are counted which coincide with a gamma ray of energy greater than m_0c^2 registered in the gamma counter. This procedure eliminates practically all counts due to events other than annihilation in the energy range ΔE. The over-all efficiency of the gamma counter is determined by a separate calibration. It should be noted that within a given range of pulse heights, the energy loss for all positrons in the same interval is ΔE and is independent of scattering. The counting rate at each angle of the gamma counter may be compared with the rate predicted using known scattering theory and the differential annihilation cross section for the energy range ΔE at E. The scattering, together with the variation of gamma-ray energy as a function of the angle of emission, complicates the calculations (see Sec. B).

B. THEORY

The differential electron cross section for the annihilation of a positron is given in Heitler[5] in the center-of-mass coordinate system.

A Lorentz transformation yields the differential cross section per unit solid angle $d\sigma/d\Omega$ for annihilation of a positron of energy E and momentum P with an electron at rest in the laboratory coordinate system, with emission of a gamma ray of energy k_1, in a direction defined by the polar angles θ_1,ϕ with respect to the incident positron momentum

$$\frac{d\sigma}{d\Omega}=-\frac{e^4(E+\mu)}{P}\left\{\frac{1}{(E+\mu-P\cos\theta_1)^2}-\frac{3\mu+E}{2\mu(E+\mu)(E-P\cos\theta_1)}+\frac{(E+\mu-P\cos\theta_1)^2}{2(E+\mu)^2(E-P\cos\theta_1)^2}\right\}, \quad (1)$$

where μ is the electron rest energy The energy k_1 of the gamma ray is

$$k_1=\mu\left[1-\frac{E-\mu}{E+\mu}\cos\theta_1\right]^{-1}, \quad (2)$$

while the second quantum emitted in the process has an energy

$$k_2=E+\mu-k_1.$$

Equation (1) neglects the Coulomb field between the positron and electron and the effects of binding. It should be a good approximation when $\alpha ZE/P\ll 1$; in our experiments

$$\alpha ZE/P\lesssim 0.05.$$

In the experiment, the energy loss of the positron before annihilation is measured rather than the distance traveled. It is therefore convenient to define $W(\theta_1,E)$ as the probability of annihilation of a positron of energy E per unit energy loss in an absorber, radiating a photon k_1 at an angle θ_1 with the positron momentum, per unit solid angle.

This is related to the differential annihilation probability $NZd\sigma/d\Omega$ (yielding gamma ray k_1 at θ_1) per unit path length for a positron traveling in a material of N atoms/cm^3 and (effective) atomic number Z by

$$W(\theta_1,E)=NZ(d\sigma/d\Omega)/(-dE/dx), \quad (3)$$

where $-dE$ is the energy loss in a thickness of absorber dx.

The expression for $(-dE/dx)$ has been calculated for the predominant process of ionization by inelastic collision and is given in Heitler[5]

$$-dE/dx=NZ2\pi r_0^2\mu(E/P)^2 \times\{\ln[(E-\mu)P^2/2\mu I^2Z^2]+(\mu/E)^2\}, \quad (4)$$

where $r_0=e^2/\mu$ and IZ is the mean excitation energy. I is about 15 ev[6] for most light materials. The ratio of energy loss by radiation to loss by inelastic collisions is <0.03 for the range of positron energies used in the experiment, as calculated from an estimate by Bethe and Heitler.[7]

In addition to the energy loss by the positrons by inelastic collisions in the absorber, they also undergo many small deflections, which give rise to an uncertainty in the positron direction in the laboratory at which annihilation occurs. The calculations of Williams[8] of the effects of multiple scattering are accurate within a few percent[9] and are sufficient for the present experiment.

The intensity distribution of the scattered positrons having lost energy ΔE, at an angle θ_s with the incident direction, is

$$I(\theta_s)=(2/\pi^2\bar{\theta}_s^2)\exp(-\theta_s^2/\pi\bar{\theta}_s^2). \quad (5)$$

$\bar{\theta}_s$, the arithmetic mean scattering angle, is given by

$$\bar{\theta}_s=0.921(\mu^{\frac{1}{2}}/P)(\Delta E_sZ_{\mathrm{eff}})^{\frac{1}{2}}, \quad (6)$$

where ΔE_s is the energy loss in the absorber and Z_{eff} is the effective Z of the absorber. The probability of small angle scattering is proportional to Z^2,[9] so that for anthracene, $(C_{14}H_{10})$, $Z_{\mathrm{eff}}=(14\times6^2+10)/(14\times6+10)=5.5.$

[6] See H. A. Bethe and J. Ashkin, *Experimental Nuclear Physics* edited by E. G. Segre (John Wiley and Sons, Inc., New York, 1953), Part II.

[7] H. Bethe and W. Heitler, Proc. Roy. Soc. (London) **A146**, 83 (1934).

[8] E. J. Williams, Proc. Roy. Soc. (London) **169**, 531 (1939).

[9] N. F. Mott and H. S. W. Massey, *The Theory of Atomic Collisions* (Oxford University Press, New York, 1950), second edition.

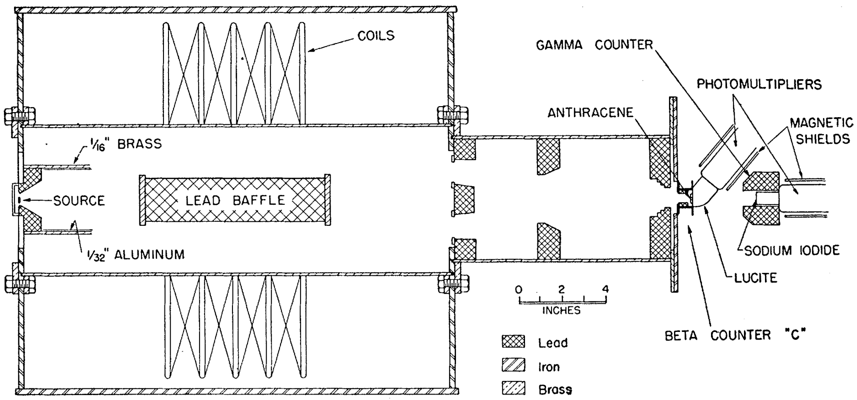

FIG. 1. Beta-ray spectrometer showing arrangement of baffles and detectors.

The flux of positrons per unit solid angle focused on the anthracene crystal by the spectrometer may be approximated by a Gaussian distribution of mean angle $\sigma=9.1$ degrees. The arithmetic mean angle α of the final Gaussian distribution of positron directions at annihilation may be found by combining this initial distribution with Williams' expression for the Gaussian mean scattering angle $(\pi)^{\frac{1}{2}}\bar{\theta}_s$:

$$\alpha=(\bar{\theta}_s^2+\sigma^2/\pi)^{\frac{1}{2}}. \quad (7)$$

The final positron intensity distribution is given by Eq. (5) with α replacing $\bar{\theta}_s$.

The quantity measured directly in our experiments is the number of coincidences per positron observed at a given laboratory angle θ with the spectrometer axis, for a given positron energy E, with energy loss in the interval E_0 to $E_0+\Delta E$, using a gamma counter (subtending solid angle Ω) of measured efficiency $\epsilon(k_1)$, a function of the gamma energy. To develop a theoretical expression to compare with experiment, we define $N(k_1,\theta)$ as the number of gamma rays per unit solid angle per unit positron energy loss per unit gamma-ray energy k_1, at the laboratory angle θ. This is given by

$$N(k_1,\theta)=W(\theta_1,E)\sin\theta_1(d\theta_1/dk_1)(2/\pi^2\alpha^2)\times\int_0^\pi \exp(-\theta_s^2/\pi\alpha^2)d\phi. \quad (8)$$

The integration in (8) is carried out at constant θ_1 (or k_1) and θ. From Eq. (2) we find

$$\sin\theta_1(d\theta_1/dk_1)=(E+\mu-P\cos\theta_1)^2/\mu(E+\mu)(E^2-\mu^2)^{\frac{1}{2}}. \quad (9)$$

The three angles θ, θ_1, and θ_s form an oblique spherical triangle and are related by the expression

$$\cos\theta_s=\cos\theta\cos\theta_1+\sin\theta\sin\theta_1\cos\phi,$$

where ϕ is the dihedral angle between the planes containing θ_1 and θ, respectively.

Now, if $\epsilon(k_1)$ is the over-all efficiency (including solid angle) of the gamma counter for detecting isotropic radiation of energy k_1, then the total counting rate at the laboratory angle θ for a positron energy loss ΔE is given by

$$N_c(\theta,E)=\int_{k_1} 4\pi\epsilon N(k_1\theta)\Delta E dk_1. \quad (10)$$

Evaluating $N(k_1,\theta)$ from Eqs. (9), (8), (3), (4), (1), we find

$$N_c(\theta,E)=\int_{k_1}(S_1/S_2)(4\epsilon\Delta E/\pi^2\alpha^2)\times(E+\mu-P\cos\theta_1)^2/E^2\int_0^\pi \exp(-\theta_s^2/\pi\alpha^2)d\phi dk_1, \quad (11)$$

where θ_1, k_1 are related by Eq. (2) and

$$S_1=-1/(E+\mu-P\cos\theta_1)^2+(E+3\mu)/2\mu(E+\mu)\times(E-P\cos\theta_1)-(E+\mu-P\cos\theta_1)^2/2\times(E+\mu)^2(E-P\cos\theta_1)^2,$$

$$S_2=\ln[(E-\mu)P^2/2\mu I^2Z^2]+(\mu/E)^2.$$

In S_2, Z is taken as 6 as it occurs in a logarithmic term.

Equation (11) must be evaluated to give a theoretical result to be compared with experiment.

The integral contained in Eq. (8) was evaluated numerically using Simpson's rule. The number of intervals was chosen so that doubling this number did not change the value of the integral by more than 1%. Integrations over the range of ϕ, where the integrand was smaller than 1% of its maximum value ($\phi=0$), were neglected as the error involved is considerably smaller than 1%. In most cases this range was smaller than $\frac{1}{2}\pi$.

For experimental reasons, it was not convenient to accept pulses from the beta counter of very low pulse height. A minimum energy loss E_0 was chosen in the range from 60–75 kev and annihilation data accepted for energy loss between E_0 and $E_0+\Delta E$, where ΔE has been previously defined. The ΔE_s which enters Eq. (6) is the mean energy loss in the "window" ΔE and is thus $F_0+\frac{1}{2}\Delta E$. For example, if coincidences are registered only for positrons which have lost from 60 to 138 kev,

$$\Delta E = 138 - 60 = 78 \text{ kev};$$

whereas $\Delta E_s = 100$ kev.

Because, in Eq. (11), the function $\epsilon(k_1)$ is experimentally determined, and the scattering integral is calculated only at discrete points, the evaluation of $N_c(\theta,E)$ must be by numerical or graphical methods. We have used a graphical integration.

An exact evaluation of the errors introduced during the numerical and graphical integrations is difficult. All computed or tabular quantities were known to better than one percent. A limit of error in the final values of $N_c(\theta,E)$ is considered to be about 6%.

C. APPARATUS AND EXPERIMENTAL PROCEDURE

A conical brass, lead, and aluminum shield was mounted at the source, within the spectrometer, to allow positrons which could not be focused on the beta counter to be annihilated in a region where the annihilation radiation could be shielded from the beta-counter. Three 1-in. thick lead shields at the detection end of the spectrometer effect this shielding; see Fig. 1. The $\frac{1}{2}$-in. lead defining baffle in front of the anthracene crystal prevents positrons from striking the edge of the crystal and scattering out.

For positron kinetic energies of 765 kev and 1020 kev, the radioactive source used was Co^{56}, deposited on a Pt foil, to increase the number of positrons by backscattering. Ga^{66} ($9\frac{1}{2}$ hr) served as the source of higher-energy positrons up to the maximum used in the experiment. The source gave initially about 4.4×10^5 focused positrons per minute at 2.22 Mev. The anthracene crystal was mounted within the vacuum system to avoid the additional scattering and energy loss in a window. The photomultiplier was mounted externally with the 45° Lucite light pipe serving also as the vacuum system seal.

The 6199 photomultiplier was shielded from the magnetic field of the spectrometer with a double shield of mu metal and nicoloi. Varying the spectrometer current over its maximum range made no detectable change in the photomultiplier amplification.

The gamma counter consisted of 1 in.$\times$1 in. cylinder of NaI(Tl) using a 6199 photomultiplier with shields of mu-metal and $\frac{1}{8}$ in. thick soft iron. The amplification of this tube was independent of counter position at maximum spectrometer current.

A block diagram of the circuits is shown in Fig. 2. The pulses from the beta and gamma counters, after amplification and pulse-shaping to 0.3 μsec, each triggered blocking oscillators whose output pulses are fed to a 6AS6 coincidence circuit. A beta-gamma coincidence triggered a blocking oscillator whose output opened a linear four-diode clamp for a period of 0.3 μsec. The opening of the clamp allowed the pulse from the beta amplifier (slightly delayed to allow the clamp to open fully) to proceed to a pulse stretcher and a gain

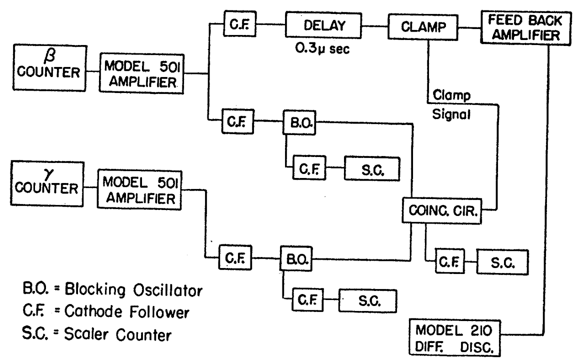

FIG. 2. Block diagram of the electronic equipment.

of 100 amplifier. The amplifier output went to a single-channel differential discriminator, which thus had to accept pulses only at the relatively low rate of occurrence of coincidences rather than at the full beta counting rate.

The clamp circuit was a symmetrical, four-diode bridge, normally biased so as to be nonconducting. A square pulse from the coincidence triggered blocking oscillator was applied through a small pulse transformer to unclamp the bridge. In principle the symmetrical arrangements prevent a clamp "pedestal" from appearing at the output. In practice a small pedestal was transmitted; its amplitude was less than 50% of the minimum usable signal and its effect was included in the circuit calibration.

Because of the use of radioactive sources whose half-lives were not large compared with the duration of data-taking, separate scalers recorded the total number of β^+ counts, gamma-ray counts, and coincidences (regardless of pulse height), during a run.

Because the region of β^+ energy loss ΔE for detection enters directly into the theoretical expression, both as a multiplicative constant and in the determination of the mean scattering angle, it is important to measure this quantity as accurately as possible. Thermal noise from the photomultiplier set a lower limit to the usable β^+ energy loss. The discrimination level of the β^+ blocking oscillator was set so as to reject all noise, and the lower edge of the window was set to register energy loss between E_0 and $E_0 + \Delta E$, where E_0 exceeded the discrimination level by about 20 kev. The gated pulse-height window was calibrated by making the coincidence circuit operative on positron pulses alone (self-coincidence). The entire clamp-amplifier-differential discriminator circuit is linear to better than 4%.

Energy calibration of the window used positrons of a known energy selected by the spectrometer. With the coincidence-clamp circuit set on self-coincidence, the pulse-height distribution was found by using a narrow window. The peak position was then the calibration point for the chosen energy. After a complete energy calibration of the window, a point at an intermediate

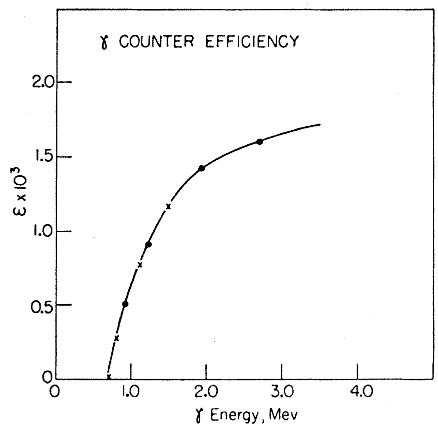

FIG. 3. Efficiency ϵ of the gamma counter. Circles are measured points. Crosses are interpolated points.

energy was checked after each data-taking run to insure that the energy calibration remained constant throughout a series of runs.

The energy resolution of the beta counter did not enter into the calculations. Nevertheless, it was desirable that the resolution of the beta detector be as high as possible in view of the low pulse heights encountered. The conversion electron line from Cs^{137} (630 kev) was resolved as a peak whose width at half-maximum was 16–17%. This was considered satisfactory in view of the relatively complex optical system. Using spectrometer selected electrons of lower energy, the width of the line resolved by the counter (corrected for spectrometer resolution) followed the expected linear variation with $\sqrt{E}$ down to 50 kev. No effect of the nonlinearity of light output of the anthracene was noted, but the accuracy ($\sim$20%) was not sufficient for it to be clearly seen.

TABLE I. Coincidences per 10^6 positrons.

	θ	Theory	Experiment[a]	Background
$E=2\frac{1}{2}\mu$	0°	12.6	12.4 $\pm$0.5	1.5
$T=0.765$ Mev	20°	11.1	10.9 $\pm$0.5	0.9
$\Delta E=78$ kev	40°	7.31	7.35$\pm$0.3	0.5
	60°	3.40	2.86$\pm$0.3	0.4
$E=3\mu$	0°	19.0	19.1 $\pm$0.75	1.7
$T=1.02$ Mev	20°	15.0	14.95$\pm$0.85	0.9
$\Delta E=78$ kev	40°	8.09	7.75$\pm$0.37	0.5
	60°	3.10	2.60$\pm$0.28	0.4
$E=3\mu$	0°	23.2	22.9 $\pm$0.9	2.5
$T=1.02$ Mev	20°	19.4	18.0 $\pm$1.2	1.3
$\Delta E=115$ Mev	40°	11.2	11.0 $\pm$0.68	0.7
	60°	5.47	3.52$\pm$0.3	0.6
$E=5.35\mu$	0°	56.0	57.5 $\pm$2.4	...
$T=2.2$ Mev	20°	34.3	31.5 $\pm$1.9	...
$\Delta E=115$ kev	40°	11.7	10.54$\pm$0.7	...
	60°	2.70	4.61$\pm$0.58	...
$E=7.5\mu$	0°	67.3	69.0 $\pm$3.2	...
$T=3.3$ Mev	20°	31.0	30.1 $\pm$1.6	...
$\Delta E=115$ kev	40°	6.9	7.7 $\pm$0.96	...
	60°	1.50	0.38$\pm$0.11	...

[a] Corrected for background.

"Smearing out" of the window edges by the finite resolution would not, in itself, affect the mean width or position of the window except for the energy variation of the resolution over a region of the window. The correction for this effect, which would tend to increase the counting rate, was expected to be small as the resolution width was small compared with the entire window.

Annihilation was detected for positron energy loss between 60 and 138 kev. ($\Delta E=78$ kev) at positron energies of 0.765 and 1.02 Mev, and for an energy loss between 75 to 190 kev ($\Delta E=115$ kev) at 1.02 Mev, 2.2 and 3.3 Mev.

The gamma-ray counter efficiency enters directly into the final theoretical expression. $\epsilon(k)$ is conveniently measured using radioactive sources of known activity.

At 510 kev, the slow-annihilation radiation from spectrometer focused positrons for calibration. For higher energies, standard sources must be used. Source holders were constructed which allowed these sources to be placed a few millimeters from the exposed face of the anthracene crystal, thus duplicating almost exactly the conditions of the actual experiment. Thus, absorption and scattering of the gamma rays by the apparatus were accounted for exactly.

The discrimination level in the gamma-ray channel was set to suppress all counts due to 510 kev "slow" annihilation radiation in order to reduce the number of spurious and accidental coincidences. With this setting, the counter-efficiency was calibrated for four gamma-ray energies between 0.9 and 2.8 Mev by using sources of Co^{60}, Na^{24}, and Y^{88}. The strength of the Co^{60} and Na^{24} sources was determined by coincidence counting and, for Co^{60}, by comparison with a Bureau of Standards calibrated source. The Y^{88} was compared with a Co^{60} standard on a brass-wall G-M counter which has a known energy dependence of the efficiency.[10] The efficiency of the gamma counter for other energies was determined by interpolation (Fig. 3). The proper setting of the bias level in the gamma channel was verified before and after each run by checking the counting rate obtained with a standard Co^{60} source.

The variation in efficiency of the counter as a function of counter angle was slight: amounting at most to five percent at the lowest energies, not measurable at the highest and was neglected in the integrals over gamma energy.

D. RESULTS

Spurious coincidences with the beta pulse in the window could arise from several processes. A positron backscattered out of the anthracene, being annihilated in the baffles near the beta counter, could yield such a coincidence as could a low-energy β^+ arriving at the beta counter having been scattered by the baffles. A β^+ could also be annihilated in such a place that the tow counters see the annihilation radiation in coincidence.

[10] E. Bleuler and G. S. Goldsmith, *Experimental Nucleonics* (Rinehart Publishing Company, New York, 1952), p. 182.

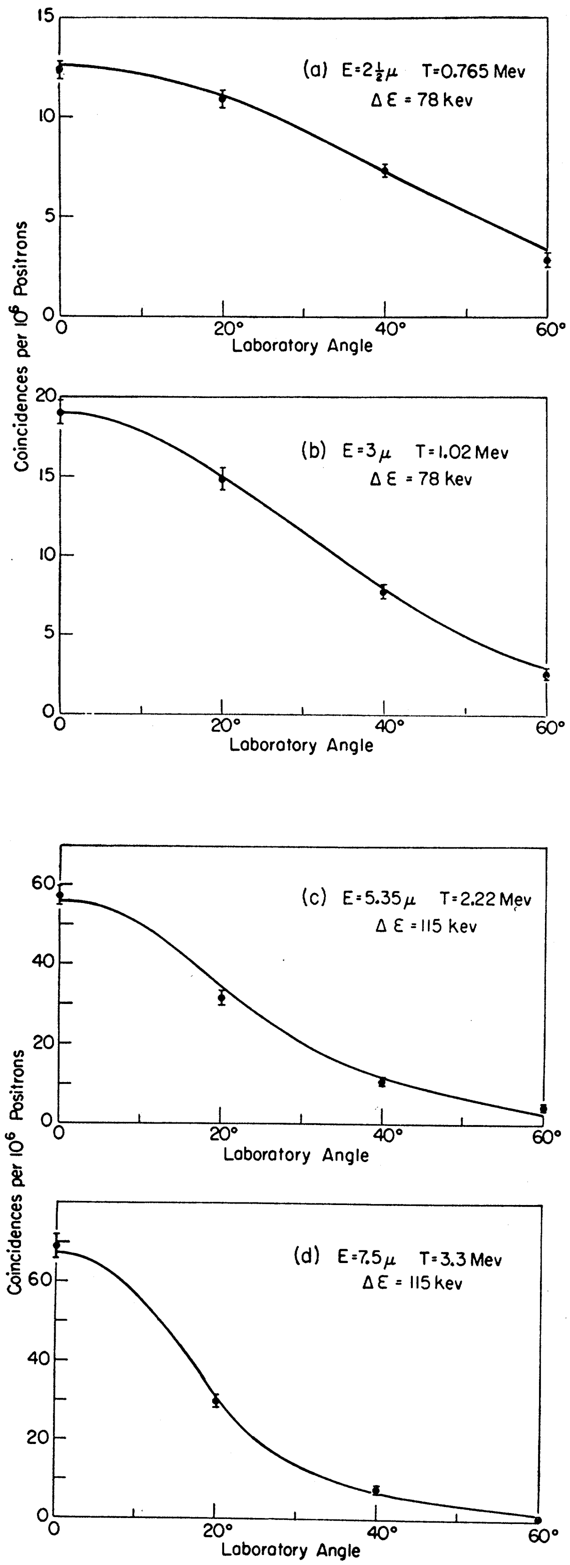

FIG. 4. Observed coincidence rates for positron kinetic energies $T=0.765$ Mev, 1.02 Mev, 2.22 Mev, and 3.3 Mev. Solid lines are the theoretical expectation using Born approximation [Eq. (11)].

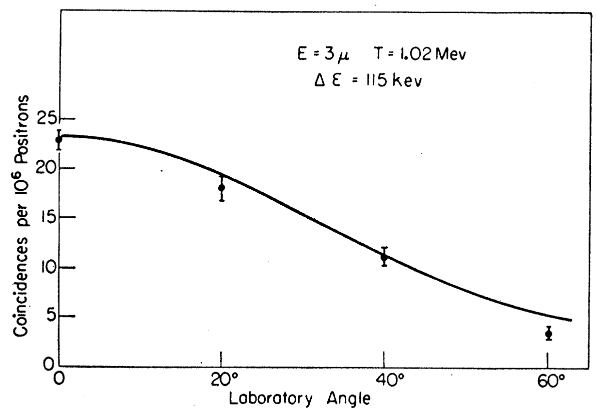

FIG. 5. Another measurement of the coincidence rate for $T=1.02$ Mev [like Fig. 4(b)], but using a larger energy interval ΔE. Solid curve is again the theoretical expectation.

The geometrical arrangement makes the latter process extremely unlikely. The low gamma-counting efficiency for slow annihilation radiation makes these processes negligible in comparison with the desired effect.

An event in which a hard gamma ray from the source is Compton scattered in or near the beta counter may result in a beta pulse of the height selected and the scattered quantum may be counted in the gamma counter. This process cannot be distinguished from fast annihilation.

The contribution of this process was estimated by measuring the coincidence rates, with beta pulses in the window, at gamma-counter angles 0°, 20°, 40°, 60° with both positron sources, with the spectrometer current at zero. This background coincidence rate was used to correct the annihilation-in-flight data. The maximum correction was ~5%, for 0.765-Mev positrons, gamma-counter angle 0°. The corrections to the data at 2.2 and 3.3 Mev, with Ga^{66}, were negligible.

The number of small pulses in the beta counter per incident particle due to events other than annihilation was measured for 1.02-Mev negatrons using a Sr^{91}-Y^{91} source. For the pulse-height window used in the annihilation experiment at this energy, there were 8.2 pulses per 10^3 incident electrons.

This result gives an estimate of the background positron counting rate in the window and should be compared with the number of fast annihilations under the same experimental conditions, which is about 2.5 per 10^3 incident positrons. Actually, the background counting rate with a positron source is somewhat higher

TABLE II. Mean energy loss and scattering angle.

E(Mev)	Window (kev)	ΔE(kev)	ΔE_s(kev)	$\pi^{\frac{1}{2}}\alpha$
3.3	75–190	115	131	17.3°
2.2	75–190	115	131	22.9°
1.02	75–190	115	131	40.2°
1.02	60–138	78	100	35.4°
0.765	60–138	78	100	43.5°

because of effects due to annihilation gamma rays. Of course, none of these background counts should cause true coincidences, but they will contribute an accidental coincidence rate.

On the other hand, bremsstrahlung produced by positrons in the anthracene might cause coincidences indistinguishable from annihilation in flight. The probability of this process[5] should be about the same for positive and negative electrons, too small to be detected in our experiment. This was verified by means of electrons from a Sr^{91}-Y^{91} source.

Annihilation-in-flight coincidence measurements were made for the positron kinetic energies 0.765, 1.02, 2.2, and 3.3 Mev and, at each energy, at the gamma-counter angles 0°, 20°, 40°, and 60° with the spectrometer axis. Depending on the coincidence counting rate in the clamped discriminator channel (which ranged from 25 to less than $\frac{1}{2}$ counts per min) data were taken in separate runs lasting from 20 min to 3 hr. The spectrometer current remained quite constant once the unit had reached a stable temperature. The total number of coincidences from all similar runs corrected for background counts was divided by the total number of incident positrons (Table I). These values can be compared directly with the theoretical expressions [Eq. (11)]. This comparison is made in Figs. 4 and 5 and in Table I. The experimental error indicated is the standard deviation of the total number of counts. Table II lists the windows, ΔE, ΔE_s, and $\pi^{\frac{1}{2}}\alpha$ for the four positron energies. The slightly lower accuracies at gamma-counter angle 60° were due to the low counting rates.

The data are, within the experimental error (estimated to be ±5%), in good agreement with the theoretical expression, both as to angular distribution and absolute value.

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Measurements of Contact Resistance between Normal and Superconducting Metals*†

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The contact resistance between crossed wires of Pb and Sn, Pb and Cu, Sn and Cu, Sn and In separated by their natural oxide layers has been measured at constant temperatures as a function of current direction and magnitude. Plots of these measurements in the case of a normal and a superconducting element show the resistance at low currents to be constant and to increase suddenly above a critical current. The low current resistance generally decreased with decreasing temperature. Calculation of the radius of the current-bearing area gives radii of atomic dimensions and shows that in some cases part of the barrier resistance disappears. Furthermore, four contacts showed an immeasurably small resistance at a temperature where only one of the contact members was superconducting. These measurements and earlier ones by others suggest a schematic representation of the resistance as a function of current and temperature. No significant rectification between normal conductors and superconductors was observed.

I. INTRODUCTION

EXPERIMENTS have been performed by Meissner and Holm[1] on the contact resistance between two superconductors separated by the thin oxide films of both elements. They found that the resistance attributable to the barrier itself remained essentially constant with temperature as long as the metals were in the normal conducting state. However, at a temperature below the critical temperature of the metal, in the case of identical contact members, the total resistance disappeared. In the case of lead-tin contacts, this temperature was below the critical temperature of tin. The temperature at which this took place was found to agree with Silsbee's hypothesis, namely that the quenching of superconductivity was due to the magnetic field created by the current. It was felt that the barrier penetration was a quantum mechanical tunnel effect which apparently became resistanceless when both contact members were superconducting.

Further experiments were performed by Dietrich[2] on contacts between tantalum elements separated by barriers up to 120 A thick of CeO_2 and TiO_2. Barriers up to 40 A thick were found to have an immeasurably small resistance at a sufficiently low temperature and current. However, in these experiments Silsbee's

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[1] W. Meissner and R. Holm, Z. Physik 74, 715 (1932).

[2] F. Dietrich, Z. Physik 133, 499 (1952).