Study of the angular correlation of photons in annihilation of orthopositronium

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An apparatus has been constructed for measurement of the angular correlation and energy spectrum of photons in the three-photon annihilation of positronium. Use of a finely ground powder of magnesium oxide placed in vacuum to stop the positrons permitted a three-photon annihilation probability of 20% to be obtained. The measured angular correlation and energy spectrum of the photons are in agreement with a quantum electrodynamics calculation within the statistical accuracy of the experiment, which amounts to 5%.

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A quantum electrodynamics calculation of the probability of three-photon annihilation of positronium was carried out by Ore and Powell,[1] but the theoretically predicted dependence of the probability on the kinematic variables was not investigated experimentally for a long time. Only in 1970 was the angular distribution of photons in 3γ annihilation measured by the method of detecting two photons by NaI(Tl) crystals with two-dimensional analyses of the pulse heights from the detectors.[2] Comparison of the experimental results with the predictions of the statistical theory and of quantum electrodynamics shows agreement with the quantum electrodynamics calculation with the exception of small but statistically significant deviations which are explained by the Compton scattering of the photons from the 3γ annihilation in the sample.

Kuz'menko *et al.*[3] attempted to measure the angular correlation by detection of three photons, but the low intensity of 3γ annihilation of the positron source used and, as a consequence, the poor statistics of the experiment did not permit the authors to draw any conclusions confirming or refuting the results of Mankamo and Jauho.[2] A theoretical study by Guzenko[4] showed that in the cross section for the three-photon annihilation of a positron there may be jumps comparable in magnitude with the cross section itself at points where one of the photons has an energy equal to $2m/3$ (m is the electron mass).

The present study is devoted to investigation of the angular correlation of photons in the 3γ annihilation of positrons for the purpose of checking the predictions of quantum electrodynamics.

KINEMATICS AND PROBABILITY OF THREE-PHOTON ANNIHILATION

When conservation of energy and momentum are taken into account the system of three photons arising in annihilation of an electron-positron pair at rest is described by five variables. If the direction of one of the photons is fixed and if we consider the independence of the annihilation process on rotation around this direction, the number of independent variables is reduced to two. In our work these are the angle θ_{12} between the directions of $\mathbf{k}_1$ and $\mathbf{k}_2$ and the angle α between the direction of $\mathbf{k}_3$ and the bisectrix of the angle θ_{12} ($\mathbf{k}_i$ is the momentum of the i-th photon). Positive direction of the angle α corresponds to a decrease of the angle between $\mathbf{k}_2$ and $\mathbf{k}_3$. The photon energies in these variables are described as follows:

$$k_1=m\frac{\sin(\theta_{12}/4+\alpha/2)}{\cos(\theta_{12}/4-\alpha/2)\sin(\theta_{12}/2)},$$
$$k_2=m\frac{\sin(\theta_{12}/4-\alpha/2)}{\cos(\theta_{12}/4+\alpha/2)\sin(\theta_{12}/2)}, \quad (1)$$
$$k_3=m\frac{\cos(\theta_{12}/2)}{\cos(\theta_{12}/4+\alpha/2)\cos(\theta_{12}/4-\alpha/2)}.$$

The probability of three-photon annihilation of the pair according to quantum electrodynamics is given in Refs. 1 and 5. In the variables chosen by us the probability of three-photon annihilation of the pair, integrated over the remaining variables, is written in the form

$$dw_{3\gamma}=\frac{(e^2)^6}{(2\pi)^3}m\frac{1}{2\sin^3(\theta_{12}/2)}\frac{\cos\alpha-\cos(\theta_{12}/2)}{\cos\alpha+\cos(\theta_{12}/2)}\left\{\sin^4\frac{\theta_{12}}{2}+\cos^4\left(\frac{\theta_{12}}{4}+\frac{\alpha}{2}\right)+\cos^4\left(\frac{\theta_{12}}{4}-\frac{\alpha}{2}\right)\right\}d\Omega_1\,d\Omega_2\,d\alpha. \quad (2)$$

EXPERIMENTAL METHOD

Positrons from a source (the isotope Na22), placed in a lead shield, passed through a collimator and hit a finely ground powder of magnesium oxide where they were stopped and annihilated. The ampoule with the positron source and the magnesium oxide was evacuated. Measurements showed that under these conditions 20% of the positrons underwent three-photon annihilation.

A diagram of the experiment is given in Fig. 1. Anni-

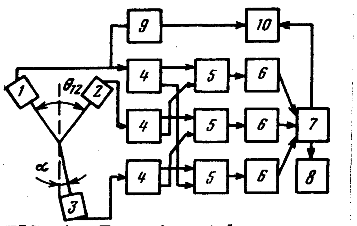

FIG. 1. Experimental arrangement: 1, 2, 3—γ detectors; 4—pulse shapers, 5—time-to-pulse-height convertors, 6—differential discriminators, 7—coincidence circuit, 8—scaler, 9—linear amplifier, 10—pulse-height analyzer.

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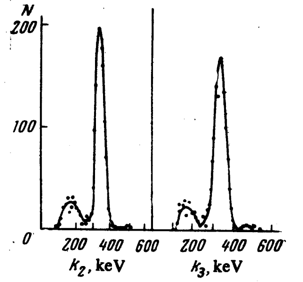

FIG. 2. Pulse-height spectra from the second and third detectors with control of the multichannel analyzer by the triple-coincidence pulse; $\theta_{12}=120°$, $\alpha=0$; N is the number of counts per channel.

hilation photons were detected by three scintillation detectors with NaI crystals of 40 mm diameter and 40 mm thickness, shielded by lead collimators with a window size 2×4 cm. The first and second detectors were placed at a distance of 27 cm, and the third detector at a distance of 18 cm from the radiation source, which resulted in a geometrical factor $\Delta\Omega/4\pi=0.87\times10^{-3}$ and an angular acceptance in the annihilation plane 4.2° for the first and second detectors and $\Delta\Omega/4\pi=1.97\times10^{-3}$ and 6.4° for the third detector.

Adjustment of the apparatus was carried out with detection of 3γ annihilation in a geometry in which the angles between the detectors were 120°. Pulse-height spectra were recorded from the second and third detectors by analyzers controlled by a gate pulse from triple coincidences. The measured spectra are given in Fig. 2, where it can be seen that, as should be the case in this geometry, photons with energy $2m/3=341$ keV are detected and there is a complete absence of background, which indicates the reliable separation of the 3γ annihilation process.

The triple-coincidence counting rate was measured as a function of the angle α for a constant angle between the first and second detectors $\theta_{12}=74°$.

EXPERIMENTAL RESULTS

The measured angular correlation is given in Fig. 3. The solid curve is the probability of three-photon annihilation calculated from quantum electrodynamics (Eq. (2)) and normalized to the experimental data. It is evident that the experimental results are satisfactorily described by the quantum electrodynamics calculation, and the deviations noted by Mankamo and Jauho[2] as well as the jumps in the cross section predicted by Guzenko[4] which should be observed at angles $\alpha=\pm8.8°$ are not observed.

The angular resolution of the experimental apparatus smooths out the jumps in the cross section, and therefore the experiment was changed somewhat in order to observe the behavior of the three-photon annihilation probability, by recording the energy of one of the pho-

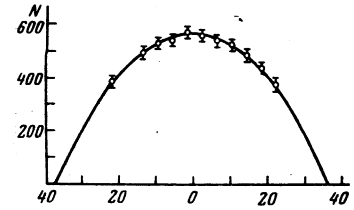

FIG. 3. Angular correlation at $\theta_{12}=74°$; the solid line is the quantum electrodynamics calculation; N is the number of counts.

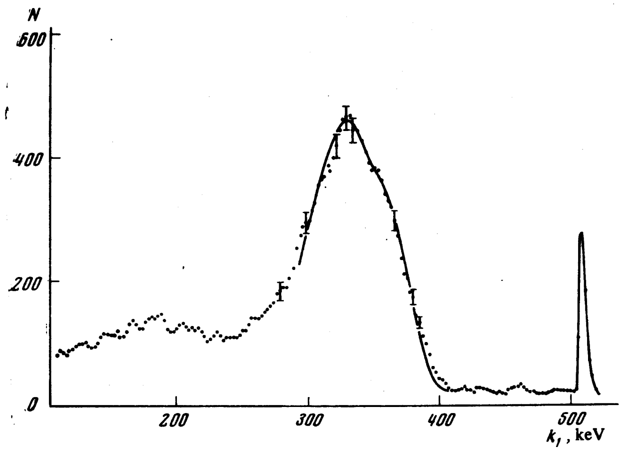

FIG. 4. Pulse-height spectrum with the germanium-lithium detector with control of the multichannel analyzer by the triple-coincidence pulse; $\theta_{12}=84°$. The solid line is the quantum electro-dynamics calculation; N is the number of counts per channel.

tons near the value $2m/3=341$ keV. For this purpose we used as the third detector an NaI crystal of diameter 60 mm and thickness 60 mm, shielded by a lead collimator with window size 4×4 cm, and the first detector was replaced by a germanium-lithium detector shielded by a collimator with window size 2×4 cm. All three detectors were placed at a distance of 18 cm from the radiation source. The angle between the first and second detectors was $\theta_{12}=84°$ and the angle α was 9°. The pulse-height spectrum from the germanium-lithium detector was recorded, the analyzer being turned on by triple-coincidence pulses. In this experiment the smoothing of the jump in the cross section is due only to the energy resolution of the germanium-lithium detector, which amounts to 3 keV for photons with energy 1330 keV, which corresponds to an angular resolution 0.5°.

The results of the measurements are shown in Fig. 4. The solid curve is the three-photon annihilation probability (Eq. (2)), calculated with allowance for the angle bins, γ-detector efficiency, and the contribution from the 511-keV background line, and normalized to the experimental data. In this experiment also we observe good agreement of the measured photon-energy spectrum and that calculated from quantum electrodynamics. The statistical accuracy of our experiment is completely sufficient to reveal the deviations observed by Mankamo and Jauho,[2] which reached 20%.

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[1]A. Ore and J. L. Powell, Phys. Rev. **75**, 1696 (1949).
[2]T. Mankamo and P. Jauho, Nucl. Phys. **A158**, 487 (1970).
[3]V. S. Kuz'menko, V. I. Noga, Yu. N. Ranyuk, and P. V. Sorokin, Voprosy atomnoĭ nauki i tekhniki (Problems of Atomic Science and Technology) No. 6(8), 32 (1973); Preprint, Khar'kov Physico-technical Institute, 73-31, 1970.
[4]S. Ya. Guzenko, Preprint Khar'kov Physico-technical Institute, 74-31, Khar'kov, 1974.
[5]A. I. Akhiezer and V. B. Berestetskiĭ, Kvantovaya élektrodinamika, Nauka, 1959, p. 372; English translation, Quantum Electrodynamics, Wiley, 1965.

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