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The Angular Distribution of Photons in Orthopositronium Decay into Three Photons

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The three-photon decay of positronium is studied by using a positronium source, composed of ^{22}Na and silica aerogel and the triple fast coincidence method. The angular distribution of the photons in the large angle region is measured under symmetrical configuration of two photons with respect to the third photon in the final state. Combining with the data in the small angle region which has been published before, the complete curve of the angular distribution of photons is obtained. The experimental results are in good agreement with the theoretical predicted values.

The three photon decay of orthopositronium is a pure lepton-photon interaction process[1]. The three photons in the final state are coplanar according to the law of energy-momentum conservation. Under the symmetrical configuration with respect to the third photon (two photons are emitted both at α angle) as shown in Fig.1(a), the formula of the angular distribution of the photons in the final state is

$$P(x) = \frac{[2(1-x)^2+1]x}{2(1+x)}, \tag{1}$$

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where $x = \cos\alpha$, the maximum value of the angle α is 90°. When α are less than 60° the values of $P(x)$ are roughly constant from Eq.(1). From α = 60° to 90°, the values of $P(x)$ decrease rapidly. When α is equal to 90°, $P(x)$ is zero.

The angular distribution curve of the photons was measured for the first time in the paper [2], but the data was taken mainly in the region where α was less than 60°. In order to obtain the complete curve of the angular distribution of photons we have improved the experimental conditions on the basis of the work [2] by increasing the intensity of the source and enhancing the shields of the detectors, and have finished the measurements in the large angle region (from α = 60° to 90°). We have performed the measurements at α = 60°, 75° and 85° only because the angular distribution curve decreases very fast in the large angle region. In the present paper we report the measured results, combine them with the data in the small angle region, which have been published before and compare the results with the theoretical predicted values.

The experimental apparatus composed of the graduated ring, the supporting stands and the source supporter is shown in Fig.1(b). The plane of the ring is perpendicular to the ground. The inner diameter of the ring is 50 cm and the outer one 58 cm. The angular accuracy of the measurement is 0.5°. The positronium source composed of the Na positron source and the silica aerogel is located on the source supporter at the center of the graduated ring. The source is prepared by dropping 80 μCi ^{22}NaCl solution on a mylar foil. It is 8 mm in diameter and is sandwiched between the two silica aerogel pieces. In order to suppress the quenching effect of orthopositronium caused by oxygen the positronium source was placed in nitrogen atmosphere during the experiment.

The angular distribution of the photons are measured using three NaI(Tl) detectors D_1, D_2 and D_3 which have the same structure. Among them D_1 is fixed, D_2 and D_3 which are placed symmetrically with respect to the axis defined by the detector D_1 and the positronium source are able to be rotated around the center. D_2 and D_3 have the same angle α with respect to the axis. The size of the NaI(Tl) crystals of all detectors is ϕ 30 mm × 50 mm. The energy resolution of the NaI(Tl) detectors for 344 keV γ-rays is 12%. A cylindrical lead shield with a thickness of 1 cm is placed around the NaI(Tl) crystal. A 2.5 cm thick lead collimator is put at the top of the crystal. The collimator has a ϕ 30 mm × 9 mm rectangular hole by which the angle spread $\Delta\alpha$ = 3.4° is defined.

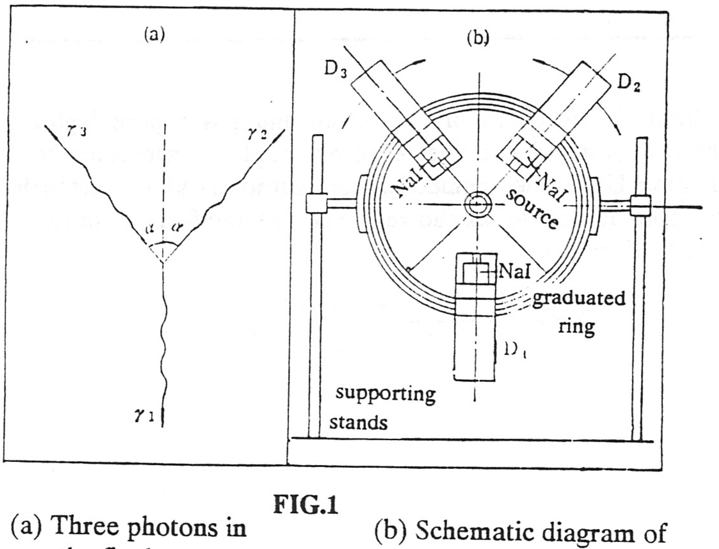

FIG.1

(a) Three photons in the final state.

(b) Schematic diagram of the experiment apparatus.

We select the three photon events by D_1, D_2 and D_3 triple fast coincidence together with the energy selection in the detector D_1. The output signals from the detectors D_1, D_2 and D_3 are sent to their own discriminator and shaper, then transmitted to the fast coincidence circuit with the time resolution of 10 ns. The linear output signals from the detector D_1 are analyzed by a single channel analyser with definite energy window. The energy window of the analyser should be correspondingly adjusted in the measurement at different angles. The pulses within the required energy region selected by the analyser are sent to a slow coincidence circuit together with the output pulses of the triple fast coincidence circuit. The time resolution of the slow coincidence circuit is 1 μs.

The efficiency of the detectors must be carefully calibrated because the energy of the photons accepted by the detectors varies with the angle α and the efficiency of the detectors varies with the energy of the photons in the angular distribution measurement. We have calibrated the energy linearity and the efficiency for each detector using the sources ^{241}Am, ^{152}Eu, ^{137}Cs and ^{54}Mn with given intensities. We then measure the angular distribution by means of the coincidence counts at different angles. We also use the three-fold fast coincidence signals to produce a gate pulse and record the output pulse spectrum of the detector D_1 using a multichannel analyser gated by the gate pulse as the monitor. The measurement indicates that the results obtained using the single channel analyser and the fast-slow coincidence method are in agreement within the experimental error with the results obtained from the analyses of the spectrum of the multichannel analyser gated by the fast coincidence signals. In order to measure the background we move the detector D_2 off the three-photon decay plane by about 60°. In this case the three detectors and the positronium source are not coplanar and the measured coincidence counts are background.

At first the backgrounds are subtracted from the coincidence counts at different angles. A correction for efficiency and geometry is then applied to the data. The relative values P_{exp} are obtained by means of normalization to the coincidence counts at α = 60°. We obtain P_{exp} = 0.86 ± 0.05 at α = 75° and P_{exp} = 0.52 ± 0.04 at α = 85°. The experimental errors arise from the errors of the efficiency curves of different detectors and the counting statistical errors.

We have performed the Monte Carlo simulation for real geometry (practically the positronium source is not a point source) according to the theoretical formula of the angular distribution and obtained the simulation values $P_{M \cdot C \cdot}$ by normalization at α = 60°. In Fig.2 the complete curve of the angular distribution is given from our measured results combining with the data in the small angle region which has been published before. The data from both experiments are normalized to the values at α = 60°. In the figure the circles are the experimental data and the histogram is the Monte Carlo values.

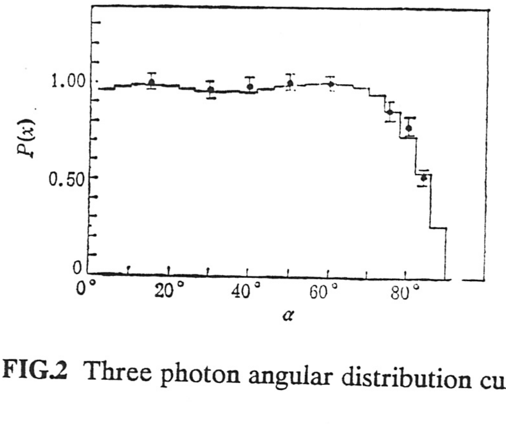

FIG.2 Three photon angular distribution curve.

The experimental results from both the small angle region and the large angle region indicate that the angular distribution of the photons from three photon decay of the positronium is in agreement with the theoretical predicted values.

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