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Experimental observation of polarization correlation of entangled photons from positronium atom using J-PET detector

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Quantum entanglement is one of the fundamental correlations between particles that has not yet been confirmed with high-energy photons. Quantum electrodynamics (QED) predicts that annihilation photons produced by the decay of the singlet state of positronium (Ps) atoms are entangled in their polarization. Since these photons have an energy of 511 keV, there is no polarizer to measure the polarization of these photons. However, the direction of the scattering photons when interacting with an electron via the Compton process depends strongly on the polarization of the photon. Therefore, Compton scattering can be used as a polarization analyser. The polarization direction of the photon can be defined as the cross product of the momentum vector of the incident and scattered photon. By measuring the polarization of annihilation photons originating from Ps decays, their polarization correlation can be determined. Measuring this correlation will for the first time, will answer the open question of studying quantum entanglement in high-energy photons. Moreover, it also have potential applications in PET imaging, where the quality of image reconstruction directly depends on the selection of pure annihilation photons, which can be separated based on the strength of the polarization correlation. In this paper, we report on the method for determining the polarization correlation of annihilation photons using the J-PET detector.

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1. Introduction

Quantum entanglement, a captivating phenomenon in the field of quantum physics, remains a cornerstone of fundamental particle correlations that continues to be explored and unraveled. While entanglement has been extensively studied in various low-energy systems, the confirmation of this phenomenon with high-energy photons has been an ongoing challenge.Quantum electrodynamics (QED) predicts that when a singlet state of positronium atom (Ps) decays, the produced annihilation photons exhibit entanglement in their polarization due to conservation of angular momentum and parity [1]. The combined wave function for maximally entangled two photons can be given by

$$\psi = \frac{1}{\sqrt{2}}(|H\rangle_1 |V\rangle_2 - |V\rangle_1 |H\rangle_2). \tag{1}$$

where H and V represent linear horizontal and vertical polarization of first or second photon. However, since these photons possess an energy of 511 keV, traditional polarizers cannot be employed to directly measure their polarization and observe the polarization correlation. As suggested by Wheeler, Compton scattering can be used to test the predicted entanglement of photons [2]. Photons upon interacting with the electron predominately scatter normal to the polarization plane of the photons. Therefore, by measuring the angle between the scattering plane of the two annihilation photons, polarization correlation between them can be estimated. The double differential cross section for the scattering of two linearly polarized photons by θ_1 and θ_2 at the respective azimuthal angles ϕ_1 and ϕ_2 can be expressed as:

$$\frac{d^2\sigma(\theta,\phi)}{d\Omega_1 d\Omega_2} = \frac{r_e^4}{16}\left[A(\theta_1,\theta_2) - B(\theta_1,\theta_2)cos(2(\Delta\phi))\right] \tag{2}$$

where

$$A(\theta_1,\theta_2) = \frac{\{(1-cos\theta_1)^3+2\}\{(1-cos\theta_2)^3+2\}}{(2-cos\theta_1)^3(2-cos\theta_2)^3}$$

$$B(\theta_1,\theta_2) = \frac{sin^2\theta_1 sin^2\theta_2}{(2-cos\theta_1)^2(2-cos\theta_2)^2}$$

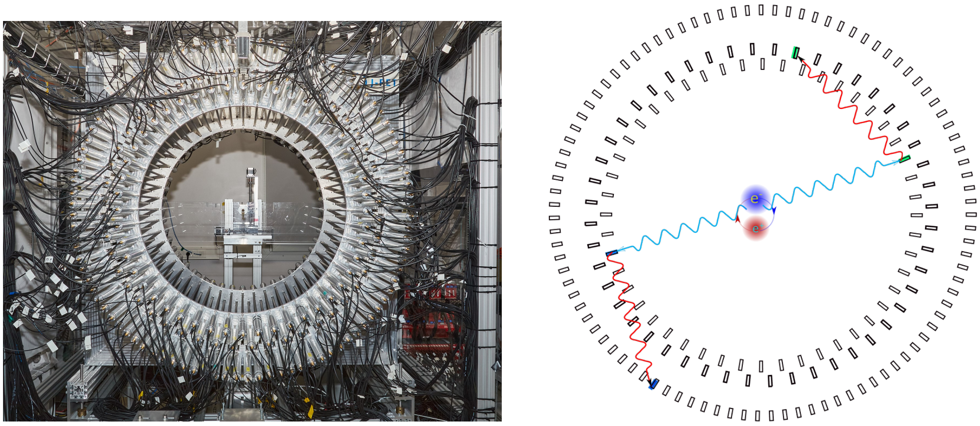
θ_1 and θ_2 are the scattering angles, $\Delta\phi$ is the relative azimuthal angle $(\phi_1 - \phi_2)$ for two photons and r_e is the electron radius [3][4]. The double differential cross-section given by equation 2 is modulated by $cos(2(\Delta\phi))$ term, resulting in the correlation ratio R, which is defined as

$$R(\Delta\phi) = \frac{P(\Delta\phi = \pm 90^\circ)}{P(\Delta\phi = 0)} \tag{3}$$

For maximally entangled photons, R has the maximum value of 2.85 at $\theta_1 = \theta_2 = 81.7^\circ$ [5]. To investigate polarization correlation in Ps atoms, the experiment utilized the J-PET (Jagiellonian-PET) detector [6]. The primary objective of this experiment is to observe and confirm the polarization correlation of entangled photons originating from the decays of Ps atom by measuring the angle between the scattering planes of the annihilation photons. For the determination of scattering plane, momenta direction of annihilation photons before and after the scattering have to be estimated [7].

2. The J-PET detector

The Jagiellonian Positron Emission Tomograph (J-PET) is a PET scanner built from plastic scintillators, consisting of 192 half-meter-long strips with photomultiplier readouts at both ends. Compared to crystal-based detectors, plastic scintillators are several times cheaper and could be considered as a more economical alternative to crystals in future PET scanners [8–10]. The scintillators are arranged in concentric cylindrical layers with diameters of 85 cm, 93.5 cm and 115 cm respectively, where dimension of each strip is $50 \times 1.9 \times 0.7$ cm^3. The geometry of this device and the use of plastics as a detection module enables it to use as a Compton scatterer to measure the photons' polarization and thus study correlation between the polarization of two back-to-back annihilation photons [6, 11]. For the Ps production, ^{22}Na source surrounded by XAD4 is used and placed in the small annihilation chamber. The chamber was positioned in the center of the J-PET detector. The pressure of 10^{-3} Pa was maintained inside the chamber.



(a) (b)

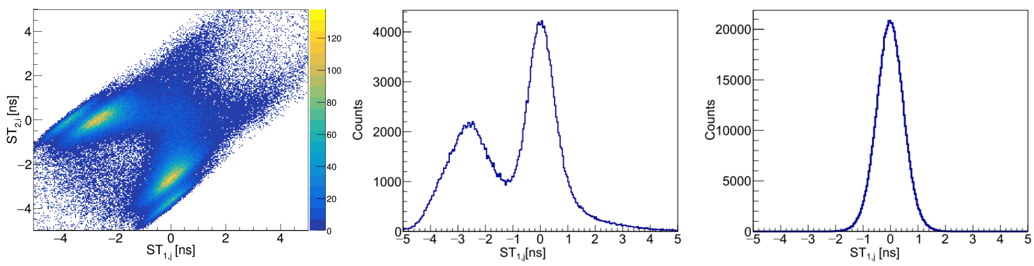
Figure 1: (a) The 3-layer J-PET detector in the laboratory. (b) Cross section of the J-PET detector overlapping with event of interest. Electron and positron annihilate in the centre of the detector emitting annihilation photons(Blue lines) and their subsequent scattered photons(Red lines)

3. Analysis

J-PET allows the investigation of the polarisation correlation of photons originating from Ps atoms by analysing 4-hits (photons registered in the detector) consisting of two annihilation photons and their respective secondary Compton scattering on an event-by-event basis. The Time over Threshold (TOT) method is used to identify the annihilation and the scattered hits [12]. The selection of two annihilation photon is further refined using the geometrical cuts on the reconstructed annihilation point in accordance with the dimensions of source chamber used in the experimental setup where positron annihilates into two photons. For the assignment of a scatter candidate to its parent annihilation photons, a Scatter Test is performed based on the mathematical definition:

$$ST_{i,j} = (t_i - t_j) - r_{ij}/c \tag{4}$$

where $ST_{i,j}$ is the scatter test for i^{th} annihilation photon with j^{th} scattered photon candidate. $t_{i/j}$ is the hit time information of annihilation/scattered photon and r_{ij} is the distance between the hit position of the annihilation and scattered photon. In the ideal case i.e, for scattered photon that belongs to its parent annihilation photon (defined as a 'true scatter'), the value of ST must be equal to zero. But due to detector effects it will be smeared around zero as shown in figure 2c.Three different methods for assignment of a scatter photon to its parent annihilation photon using ST are studied using Monte Carlo simulations of the experimental setup to get the maximum purity of the events. When a scattered hit is assigned to its parent annihilation hit it is termed as 'true scatter' and for all other possible cases it is termed as 'false scatter'.



(a) **(b)** **(c)**

Figure 2: (a) Two dimensional distribution of Scatter Test (ST) where on the X-axis is the value of ST for the first annihilation hit with all the scatter hits while on the y axis is the value of ST for second annihilation with all the possible scatter hits. (b) Scatter test for one of the annihilation photons with all ('true scatter' as well as 'false scatter') the scatter photons. (c) Scatter Test for one of the annihilation photons with its subsequent scatter photon ('true scatter').

3.0.1 First Method (M1)

In this method, the value of ST is calculated for scattered hit candidate with both annihilation hits i.e $ST_{1,j}$ and $ST_{2,j}$ is calculated for j=1. As the Scatter Test distribution for the 'true scatter' lies between -1 < ST < 1 (fig. 2(c)), therefore for the annihilation hit the $-1 < ST < 1$ condition is met, the scatter hit is assigned to that annihilation hit. If the condition is true for both the annihilation hits then the scatter is assigned to annihilation with smaller ST value. Same procedure is repeated for the second scatter hit. And if both annihilation hits have assigned scatter hit, then the event is saved for further investigation. With this approach, 68% of the events survived where 39% events are with correct assignment of scatter to their parent annihilation photons.

3.0.2 Second Method (M2)

This method utilize the condition $ST_{1,j} = ST_{2,j}$ on the 2D ST plot (in Fig. 2) shown on left side of Fig. 3. All the scatter hits under the line $ST_{1,j} = ST_{2,j}$ (the region shown in green) are assigned to $1st$ annihilation while those above this line (red region) are assigned to the $2nd$ annihilation hit. If both the annihilation hits have an assigned scatter hit then the event is saved for further analysis. Although all scatter hits were assigned to some annihilation hits but still 51% of the events were rejected and the saved events had around 52% purity.

3.0.3 Third method (M3)

For the third method the two dimensional Scatter Test plot Fig.2a is used for the assignment of the scatter hits to its annihilation hits. The two high density regions in the distribution are

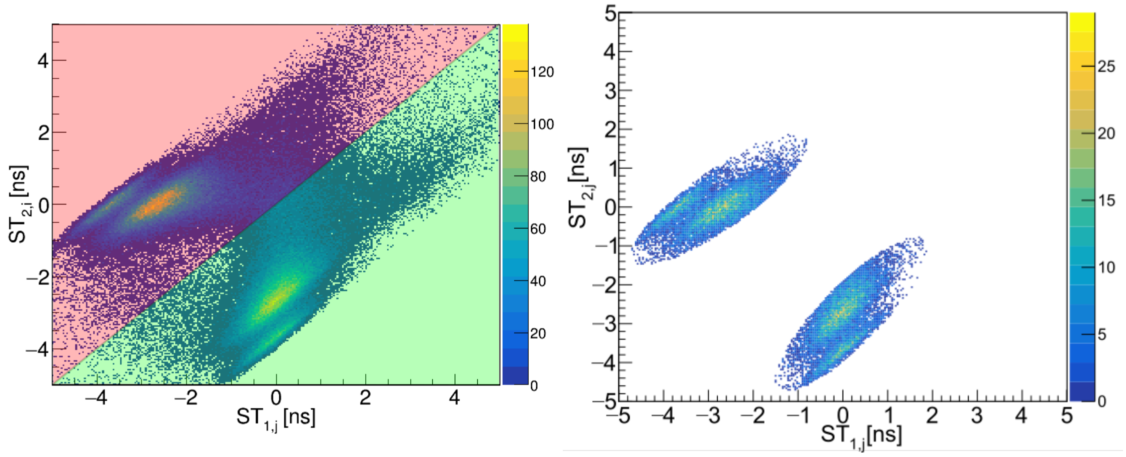


Figure 3: 2D Scatter test plots showing (left) M2 and (right) M3.

chosen using elliptical cut as shown in Fig.3 where these regions correspond to the two annihilation photons. As each point in plot is a scatter hit, all the hits in the lower ellipse were assigned to 1^{st} annihilation photon and all the hits that belong to upper ellipse were assigned to 2^{nd} annihilation photon. Finally, if the both the annihilation hit have an assigned scattered photon then the event was saved for further analysis. As a small region is selected so only 24% of the events survived after this method resulting in around 71% of the "true scatter" for both annihilation hits.

4. Conclusion

The measurement of polarization correlation of the photons from the Ps atom is very important to test the entanglement of the photons but can also be used to improve the image quality in PET imaging. To measure the polarization correlation, the identification of scattered photons and their assignment to its parent annihilation photon is crucial. J-PET detector is the only detector that can not only serve as a PET scanner but is also able to correctly recognize and identify the scattered photon due to its unique design. Table 1 shows comparison of three discussed methods in terms of efficiency and purity. Among the methods discussed, method M3 is very promising with a high purity of 71% but has a very low efficiency. It also needs to improved in terms of purity. It was also observed that these method not only serves as assignment method but also improve the Signal to Noise Ratio of the events.

Method	Efficiency	Purity
M1	68	39
M2	49	52
M3	24	71

Table 1: Comparison of the three methods in terms of efficiency and purity of events, where efficiency is the percentage of 4 hit events that survive the method while purity is the percentage of true scatter events for each method.

Although high purity is very essential from the prospective of testing the entanglement of photon but for this technique to find any practical application in PET imaging high efficiency is also desired. New methods have to developed to achieve better purity for testing entanglement.

Acknowledgments

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