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Investigating quantum entanglement of high-energy photons from positron annihilation in a porous medium

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Abstract. Quantum electrodynamics (QED) predicts that photons from positronium decay are maximally entangled. However, experimental verification of this entanglement in high-energy photons has remained elusive due to competing decay processes and interactions with the surrounding medium. The J-PET detector is a multi-modules detector based on plastic scintillators that has the potential to measure such correlation in the whole phase space. Photons interact with plastic mainly via Compton scattering, which makes J-PET particularly suitable for this type of study. Moreover, by incorporating the positron lifetime as an additional parameter, to differentiate between various decay processes and examine how the polarization correlation changes as a function of lifetime. Such studies provide new insights into quantum entanglement at high energy regimes and hold potential to enhance positron emission tomography (PET) imaging techniques. Recent results demonstrate the J-PET detector's capability to measure the polarization correlation of photons emitted from positron annihilation in a porous medium. In this paper, we present a review of past research in this field, highlighting the need for further investigation of polarization correlation of annihilation photons.

1 Introduction

Positronium (Ps) is an exotic atom composed of an electron and its antiparticle, the positron. These two particles, interact via electromagnetic force, form a short-lived, purely leptonic system uniquely suited for probing fundamental physics. Ps is a valuable tool for testing the predictions of QED, the theory that describes the light−matter interaction [1]. Ps can be used to test the accuracy of QED with high precision by studying the decay rates, discrete symmetries, and to search for evidence of exotic particles like mirror matter [2, 3]. The ground state of Ps, can exist in two spin configurations: singlet ($^1S_0$; para-positronium) and triplet ($^3S_1$; ortho-positronium). The annihilation modes of these spin states follow charge conjugation parity conservation. A particularly fascinating property of para-positronium (p-Ps) is that the photons emitted from its decay exhibits quantum entanglement [4, 5, 6]. The two-photon state disintegration of p-Ps can be written as

$$\psi = \frac{1}{\sqrt{2}}(|X\rangle_1 |Y\rangle_2 - |Y\rangle_1 |X\rangle_2) \quad (1)$$

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where $|X\rangle_1 |Y\rangle_2$ describes a photon moving in the +z direction with linear polarization along x-axis, and a photon moving in the –z direction with polarization along the y axis; while $|Y\rangle_1 |X\rangle_2$ denotes the opposite. Equation (1) implies that two photons are maximally entangled in their polarization and their polarization are perpendicular to each other. As the polarizer for γ rays does not exist, the polarization of such high-energy photons can be analyzed indirectly through Compton scattering [7]. In Compton scattering, the scattered photon's trajectory provide information about the linear polarization of the incident photon as it is preferentially scattered in directions perpendicular to the polarization plane [8, 9]. Consequently, if two photons are initially polarized at right angles to each other, their scattered photons are expected to emerge in mutually perpendicular directions [10]. This method has a major disadvantage that it doesn't provide event-by-event correlation between the polarization but only a statistical one. For an entangled pair of photons, the joint probability of scattering at scattering angles of θ_1 and θ_2 is given by:

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

where, $\Delta\phi$ is the relative azimuthal angle $(\phi_1 - \phi_2)$ for two photons and r_e is the electron radius [4, 11]. Experimental observations are strongly influenced by the ratio B/A. When B/A is small, the modulation introduced by cosine term become less pronounced, which leads to a lower detectability of the variation in the observed pattern. Since B/A depends on the scattering angles, the visibility of the pattern depends directly upon θ_1 and θ_2, and become maximum at $\theta_1 = \theta_2$ =81.7°. As proposed in reference [12] , the asymmetric ratio R, can be used to determine whether the annihilation photons are entangled, separable or uncorrelated. The asymmetric ratio R, defined as

$$R(\Delta\phi) = \frac{P(\Delta\phi = \pm 90°)}{P(\Delta\phi = 0)} = \frac{1 + B/A}{1 - B/A} \tag{3}$$

The upper limit for the asymmetry ratio R, in the case of separable states is 1.63 [12, 13]. For entangled photons, R has a maximum value of 2.85 at $\theta_1 = \theta_2 = 81.7°$. The value of R depends on the scattering angles θ_1 and θ_2 with the value of R being lower for smaller and larger angles, as shown in Fig. 1 (a).

2 Status of the experimental studies

One of the first experiment were carried out in 1948 by R.C. Hanna with a ^{64}Cu positron source packed in aluminium tube, and the annihilation photons were allowed to scatter at an angle of 90° angle using metallic scatterers. Analysis of these results showed a polarization correlation ratio of $R = 1.51 \pm 0.10$, which was far below the theoretically predicted value of $R = 1.86$ [14] after taking into account the properties of the detector system. To extend this work, Wu and Shaknov (1950) conducted a similar experiment with a ^{64}Cu source, encapsulated in an 8 mm sealed aluminium capsule. Using two anthracene crystal detectors and an aluminium scatterer oriented at an angle of 82°, they found $R = 2.04 \pm 0.08$, which is close to the theoretical value $R = 2.0$ [15]. In 1975, Kasday et al. used a 10 mCi ^{64}Cu source placed in a brass holder. The annihilation occurred both within the source and the surrounding holder material. Their measurements of $R = 2.04 \pm 0.02$ agreed with the theoretical calculations ($R = 1.9 \pm 0.2$) [16].

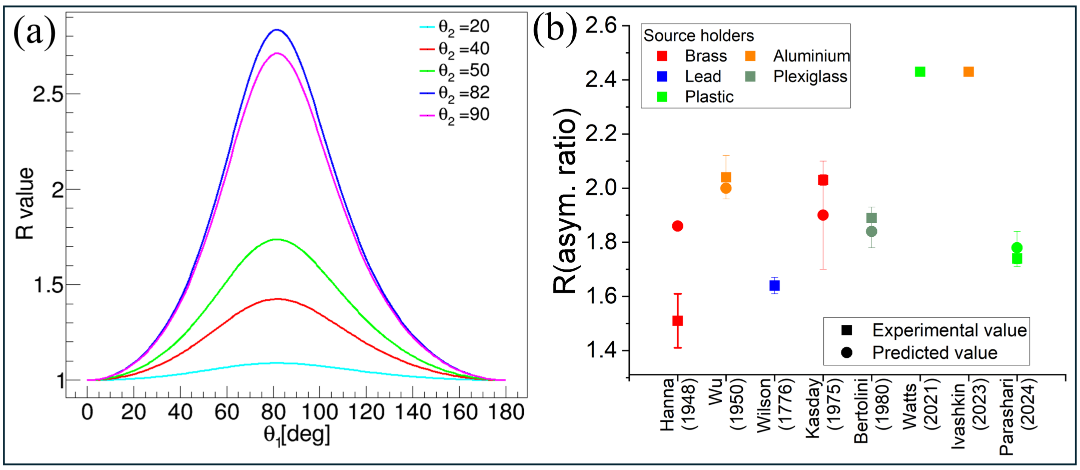

Figure 1: Plot (a) illustrates how the R-value varies with scattering angle θ_1 and θ_2.Plot (b) compares the experimental results (square boxes) and simulated values taking into account properties of the particular detector system (circular point), for different materials of positron source holder (colour coded). The values of R may be influenced by the properties of the source holder material, and detector configuration.

Wilson et al. (1976) expanded this work by measuring the relative plane of polarization as a function of distance. They used an irradiated ^{64}Cu source inside a lead holder, NE104 plastic as a scatterer and NaI detectors placed at scattering angle around 82°. They obtained R value of 1.64 ± 0.03 at a source-scatterer distance of 0.6 m [17]. Importantly, the value of R remain relatively constant across varying distances between source and scatterer. In 1980, Bertolini et al. used HPGe detectors and ^{64}Cu source irradiated with thermal neutrons, placed in plexiglas capsule with a copper lining. The copper lining was used as a stopper for positrons. They measured $R = 1.89 \pm 0.04$, which is quite close to the theoretical value $R = 1.84 \pm 0.06$ [18]. The specification of above-mentioned studies are included in the following table 1.

Experiment	**Source**	**Source Holder**	**Scatterer**	**Exp. Results(R)**
R.C. Hanna (1948)	^{64}Cu	Brass	Metallic scatterers	1.51 ± 0.10
Wu and Shakov (1950)	^{64}Cu	Aluminium capsule	Aluminium	2.04 ± 0.08
Wilson et al. (1976)	^{64}Cu	Lead	NE-104 plastic	1.64 ± 0.03
Kasday et al.(1975)	^{64}Cu	Brass	Plastic	2.03 ± 0.02
Bertolini et al.(1980)	^{64}Cu	Plexiglass	HPGe	1.89±0.04
Watts et al. (2021)	^{22}Na	Plastic	CZT	1.85±0.04
Ivashkin et al.(2023)	^{22}Na	Aluminium	Plastic	2.43 ± 0.018
Parashari et al.(2024)	^{22}Na	Plastic	GAGG:Ce	1.74 ± 0.03

Table 1: Summary of polarization correlation measurements (R value) from various experiments. The table includes details of the source, source holder, and scatterer used in each experimental setup.

These studies were mainly aimed at verifying or disproving quantum entanglement. As the underlying principles of quantum entanglement become more accepted, interest in the correlation of photon polarization study waned. The study of quantum entanglement in e^+e^- annihilation gained renewed interest due to its potential application in PET imaging [19]. The feasibility to incorporate polarization correlation information into PET imaging became realistic, with the development of the first PET scanner based on plastic scintillators [2, 20, 21, 22]. The unique properties of plastic scintillators, in which photons interact predominantly via Compton scattering, facilitate the measurement of polarization correlations and pave the way for novel imaging techniques with improved diagnostic capabilities [20, 21]. This renewed interest has inspired experimental groups around the world to measure polarization correlation with both existing and optimized setups. In 2021, Watts et al., performed a table top experiment with ^{22}Na source to measure these correlations and reported $R = 1.85 \pm 0.04$, which is consistent with the simulations [23]. Ivashkin et al. (2023) used a 50 MBq sodium source produced through proton irradiation of aluminium and obtained $R = 2.435 \pm 0.018$, showing good agreement with the simulated data as well as theoretical prediction for maximal entanglement [24]. More recently, Parashari et al. (2024) used GAGG:Ce crystals and measured the photon correlations with $R = 1.74 \pm 0.03$. The obtained value of R from simulation using their setup was $R = 1.78 \pm 0.06$ [25]. All these systematic studies indicate that, apart from experimental limitations and appropriate normalization with respect to the available phase space, one of the crucial factors that might be influencing the strength of the polarization correlation, as represented by the R values in Fig. 1 (b), is the medium in which Ps atoms are formed.

The J-PET detector is a PET scanner consisting entirely of plastic scintillators [26, 27]. It consists of 192 detection modules arranged in 3 concentric layers [28]. The cylindrical geometry of the J-PET and the trigger-less data acquisition allow the simultaneous registration of the annihilation photons and their respective scatterings, which enables the measurement of the polarization correlation in annihilation photons [21]. We have investigated the behaviour of this correlation using an annihilation chamber consisting of a ^{22}Na source confined between porous material [29]. In addition, J-PET has another unique feature: the ability to measure and to image positron lifetimes [27, 30, 31]. The measurement of Positron lifetime can be used to distinguish between different annihilation processes. By combining positron lifetime measurements with the analysis of the polarization correlation of photons, J-PET uniquely enables the study of the degree of entanglement associated with different annihilation mechanisms.

3 Discussion

The results and experimental setups from various studies are summarized in Table 1, and the corresponding R-values are shown in Fig. 1 (b). Notably, most of the prior experiments used metallic media for positron annihilation, where Ps formation is very rare [32]. Therefore, the measured polarization correlations likely arise from the direct annihilation of positrons. However, to use the information about the polarization of annihilation photons in PET imaging, it is crucial to understand the behaviour of their quantum correlations, potentially impacted by tissue environment. Biological tissue, which consists mainly of hydrocarbons and amino acids, provides a very different environment for positron interactions.

These media including bio-medical system enable additional processes such as the formation of p-Ps, pick-off annihilation and the conversion of ortho-Ps to para-Ps as the origin of annihilation photons [33, 34]. Recent J-PET results have shown a correlation between the degree of quantum entanglement and the type of material in which electron-positron annihilation takes place. This confirms the entanglement loss due to the mixing of contributions from additive processes within a porous medium [29].

4 Conclusion

The study of quantum entanglement in annihilation photons originating in the decays of Ps atoms has been a topic of intense investigation due to its direct implications in fundamental physics and PET imaging [35, 36]. The J-PET detector, with its unique ability to measure the polarization correlation using Compton scattering, offers platform for quantum PET research. Furthermore, the simultaneous measurement of positron lifetime allows further investigation of quantum correlation, which may be influenced by the annihilation medium. In a recent experiment with a porous medium, we observed non-maximal entanglement. However, to further quantitatively investigate the primary factors affecting the polarization correlation in annihilation photons, a systematic study with different media in a controlled experimental environment is necessary. This will deepen our understanding, enabling the application of this information to in-vivo medical imaging.

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