Measurement of correlation between polarization of annihilation photons emitted in e^+e^- system to detect entanglement at MeV range

D. Kumar[1,2,3]*, N. Krawczyk[1,2,3], S. Sharma[1,2,3] on behalf of the J-PET collaboration
[1]Faculty of Physics, Astronomy, and Applied Computer Science, Jagiellonian University, Poland.
[2]Total-Body Jagiellonian-PET Laboratory, Jagiellonian University, Kraków, Poland
[3]Center for Theranostics, Jagiellonian University, Cracow, Poland
*e-mail: d.kumar@doctoral.uj.edu.pl

Introduction and Motivation

Quantum electrodynamics predicts that photons originating from the decays of e^+e^- annihilations are entangled and have mutually orthogonal polarization [1]. Since the polarization of the photons is orthogonal to each other, correlation can occur in subsequent interactions. Compton scattering of photons can be used as a polarization analyser to measure such correlations [2]. To measure the correlation between the scattered photon due to entanglement, the two photons must be detected before and after the scattering [3].

Methodology

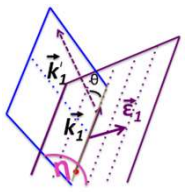
Klein–Nishina differential cross section

$$\frac{d\sigma(E,\theta,\eta)}{d\Omega} = \frac{r_0^2}{2}\left(\frac{E'}{E}\right)^2\left(\frac{E}{E'}+\frac{E'}{E}-2\sin^2\theta\cos^2\eta\right)$$

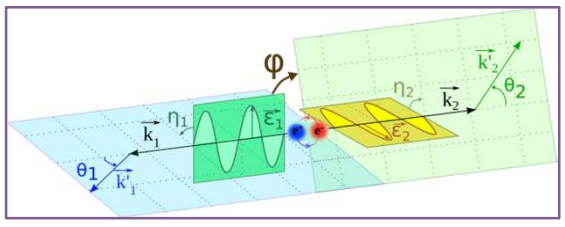
$$E'(E,\theta) = \frac{E}{1+\frac{E}{m_e c^2}(1-\cos\theta)}$$

- An incident photon is mostly scattered **perpendicular** to the polarization direction of the incident photon.
- Polarization of a photon can be defined as

$$\epsilon = k \times k'$$

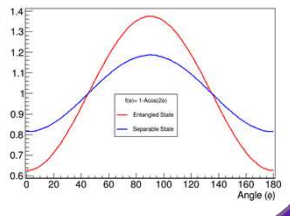


- For 2 annihilation photons, double Compton Scattering differential cross section



$$\frac{d^2\sigma_{double}}{d\Omega_1\Omega_2} = \frac{r_0^4}{16}\left[\frac{\{(1-cos\theta_1)^3+2\}\{(1-cos\theta_2)^3+2\}}{(2-cos\theta_1)^3(2-cos\theta_2)^3} - \frac{sin^2\theta_1 sin^2\theta_2}{(2-cos\theta_1)^2(2-cos\theta_2)^2}\cos(2\phi)\right]$$

$$f(\theta,\phi) = 1 - A(\theta)\cos(2\phi)$$

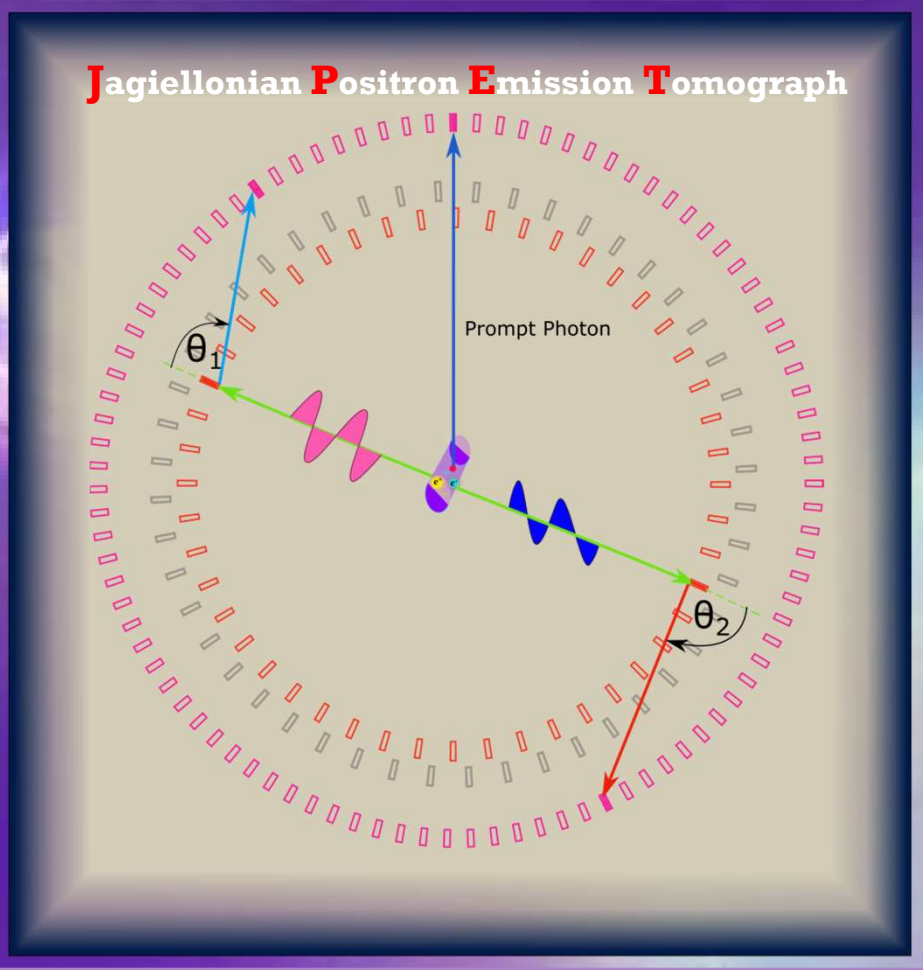


$A = 0.48$ for entangled state

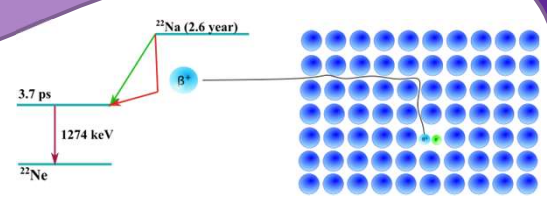
$A = 0.23$ for separable state

J-PET

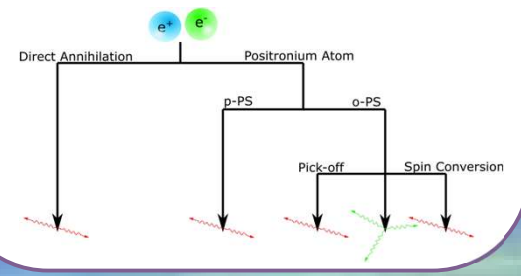
- A potential detector to perform entanglement studies in MeV range [4,5,6].
- 192 plastic scintillators : 50 x1.9 x 0.7 cm^3
- 3 cylindrical layers : 42.50 cm, 46.75 cm and 57.5 cm.
- Angular Resolution ~ 1^0



Positronium formation



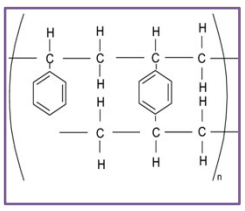
Positron annihilation channels



Experimental Details

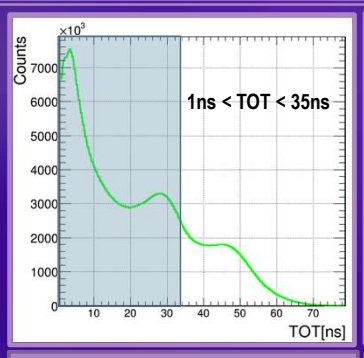
Source : ^{22}Na (1 MBq)

Chamber Material : XAD-4

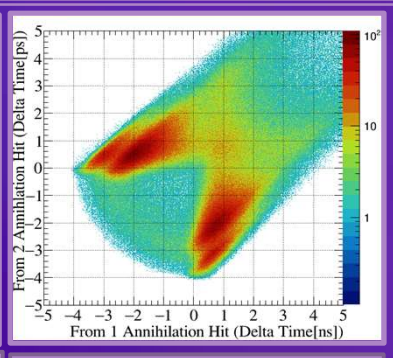


An experiment was performed using a plastic chamber by placing a source in its centre surrounded by the XAD-4 material. XAD-4 is a material with high porosity (~90% of empty volume)

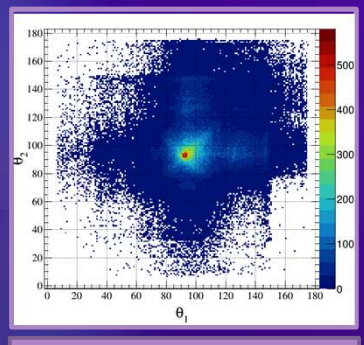
Preliminary Results



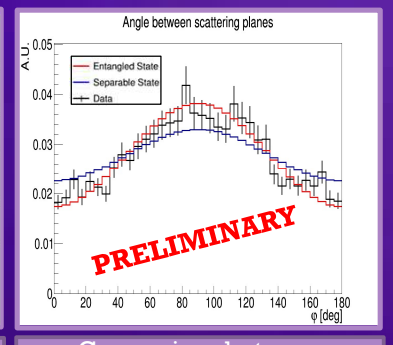
Time Over Threshold (TOT) as a measure of Energy Deposition



Scatter Test **(S) = Δt – d/c** Assignment of the scatter hit to primary hit



Correlation between the scattering angles $(\theta_1 - 100)^2 + (\theta_2 - 100)^2 = 30^2$



Comparison between experimental data and theoretical predictions

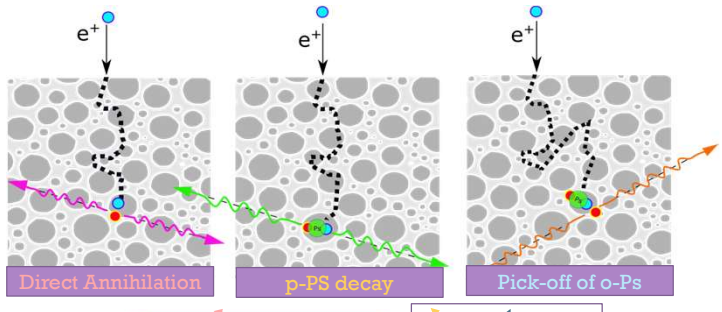
Summary

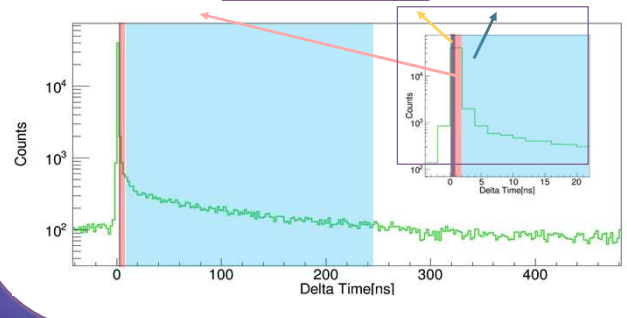
J-PET is a unique detector, which can be used to perform the measurement of the correlation of polarization of annihilation photons emitted in e^+e^- system in full phase space.

- It is theoretically predicted that the annihilation photons originating from e^+e^- system are entangled and their polarization directions are orthogonal to each other.
- Orthogonality in the polarization of photons leads to an enhanced correlation in the scattering plane of both photons.
- Theoretically, the maximum visibility of the correlation is at scattering angle of ~ 82^0
- In this work, we present preliminary results for experimentally measured polarization correlation and compared the result with the theoretical predictions.

Future Prospective

- Use the positronium lifetime spectra to distinguish the influence of different positron annihilation channels on the polarization correlation of emitted back-to-back photons.





References

[1] Snyder, H. S., Pasternack, S. & Hornbostel, J Phys. Rev.73, 440 (1948)
[2] O. Klein, Y. Nishina, Y. Z. Physik 52, 853 (1929)
[3] P. Moskal et al., Acta Phys. Polon. B 47, 509 (2016)
[4] S. Niedzwiecki et al., Acta Phys. Polon. B48 (2017) 1567
[5] P. Moskal et al., Nature Communications 12. 5658 (2021)
[6] P. Moskal et al., Science Advances, Vol 7, Issue 42, Page No. 4394 (2021)
[7] P. Moskal et al. Eur. Phys. J. C 78, 970 (2018).

Acknowledgement

We acknowledge support by the TEAM POIR.04.04.00-00-4204/17 program, the NCN grant no. 2021/42/A/ST2/00423, 2019/35/B/ST2/03562 and the SciMat and qLife Priority Research Areas budget under the program Excellence Initiative - Research University at the Jagiellonian University.