Quantum entanglement effects in Geant4 for PET applications

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Background: In Positron Emission Tomography (PET), the images are degraded by scatter and random coincidences. However, two annihilation γ are predicted to be in a quantum entangled state. In this work, we explore the effect this phenomenon has on annihilation γ scattering and the potential to use this information in PET.

Material and Methods: The entanglement in linear polarisation of the annihilation γ modifies the double-Compton scattering cross-section as a function of the relative azimuthal scattering angle ($\Delta\phi$), producing a $\cos(2\Delta\phi)$ modulation with amplitude far in excess of that expected for non-entangled γ. A quantum entangled description of the scattering of annihilation γ is incorporated into Geant4 (QE-Geant4) [1]. It is validated against experimental data from a PET demonstrator made of LYSO detectors similar to those of the EXPLORER total-body PET scanner.

Through PET images reconstructed from a QE-Geant4 simulation of a preclinical scanner, a simple method is developed to remove the unwanted background, using the quantum entanglement information alone [1].

Results: QE-Geant4 $\Delta\phi$ distribution agrees very well with the experimental data. Lower amplitude of the $\cos(2\Delta\phi)$ distribution with the non-entangled Geant4 simulation is an entanglement witness.

The profiles of the scatter and random coincidences isolated in the PET images using the quantum entanglement information agree with the real backgrounds (*i.e.* the profiles of images reconstructed only with coincidences labeled as scatter or random during the simulations).

The results indicate that clinically relevant detectors allow access to quantum entanglement information. This offers independent, new information to quantify scatter and random backgrounds.

[1] D.P. Watts *et al.*, Nat. Commun., 12 (2021) 1-9.
[2] M.H.L Pryce and J.C. Ward, Nature, 160 (1947) 435.