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Quantum Entangled PET Imaging

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The effect of quantum entanglement was first discussed more than 80 years ago [1,2]. Particles that are quantum entangled are described by a common wavefunction which leads to enhanced correlations between the particle interactions, even when separated over macroscopic distances. The two photons resulting from positron annihilation are predicted to be in such an entangled state. Their entanglement in linear polarisation modifies the double-Compton scattering cross-section as a function of the relative azimuthal scattering angle of the photons ($\Delta\phi$), resulting in a $\cos(2\Delta\phi)$ modulation having an amplitude far in excess of that expected for non-entangled photons. Previous experimental measurements have shown enhancement consistent with the entangled predictions, albeit for restricted scattering kinematics and using conventional detectors (e.g. NaI [3]). The recent advances in CZT detector technology allowed us to overcome many of the past difficulties and obtain experimental demonstration of quantum entanglement in MeV range with large acceptance. One of the most exciting applications of quantum entanglement is in Positron Emission Tomography (PET), a technique widely used for medical research and clinical diagnosis. It utilises the back-to-back emission of annihilation photons to image metabolic processes inside of the body. PET images are obtained with significant in-patient scattering and random backgrounds, which reduce image resolution and contrast. Both of those problems are mitigated using scintillator detectors with timing resolution of a few hundreds of nanoseconds, thus making solid state detectors largely impractical for such purpose. Using quantum entanglement principles could open new ways to use CZT detectors in PET.
To investigate the potential benefits of quantum entanglement, it was incorporated into the GEANT4 code using polarized Klein-Nishina formula [4,5]. The simulation was verified against experimental data from a CZT PET demonstrator developed by Kromek, shown in Figure 1. The detector system is comprised of a pair of 10 mm thick 800 µm pixel pitch CZT detectors connected to the main controlling unit. Events with two interactions in each detector were selected and analysed, Using the excellent energy and 3D position resolution which are among the strongest advantages of CZT detectors allowed reconstruction of photon trajectories along with their scattering angles. In Figure 2 we show the experimental data from the CZT system (black data points) exhibiting the clear modulations predicted by quantum mechanics. The prediction from the QE-GEANT4 simulation including entanglement (blue line) is clearly essential to reproduce the experimental data.
In addition to the experimental demonstration of quantum entanglement, we present simulated GEANT4 imaging studies of the efficacy of exploiting the implicit quantum entanglement between true PET photon coincidences. PET images of a NEMA_NU4 phantom using a simulated array of CZT detectors were obtained. 2D PET images were reconstructed from the data using simple filtered back projection (FBP) methods. A simple procedure to use the new information from the entanglement enabled spatially resolved determination of the contribution of both scatter and random coincidences to the image. The ability to extract such information purely from the data offers new opportunities for PET imaging methodologies.

The results indicate that use of CZT detector systems would allow access to previously inaccessible quantum entanglement information in PET. This offers independent, new information to quantify random and scatter backgrounds. In future work, we plan to incorporate this information into more advanced image reconstruction techniques and optimise the design of new imaging systems. The work presented has been accepted for publication at Nature Communications [6].

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