

Experimental Observation of Electron-Photon Entanglement

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Entanglement [1] is a phenomenon which lies at the heart of quantum mechanics and provides key advantages to quantum optics experiments and applications, which are nevertheless limited by the nature of the particles used. The control of free electrons has revolutionised classical imaging techniques through the introduction of the transmission electron microscope (TEM), a powerhouse of atomic-resolution imaging and analysis. However, until recent experimental developments [2],[3], evidence of entanglement in the TEM has remained elusive. Here, we demonstrate the presence of entanglement in position and momentum between an electron and the coherent cathodoluminescence (CL) photon that it emits upon passage through a thin membrane sample [2].

We implement coincidence (ghost) imaging in a TEM [4], using a single photon counter and a spatially-resolved Timepix3 electron camera to study single electron-photon pair correlations [5]. With our setup, we are able to form an image of an object placed outside the TEM, in either the image plane or momentum plane of the photon path. From our coincidence images, we derive the joint uncertainty in both position and momentum spaces. The product of these two joint uncertainties violates the classical uncertainty bound [6] by more than 20 standard deviations: $\Delta x_-^2 \Delta k_+^2 \leq 0.321 \pm 0.027 < 1$ [2], thereby demonstrating the presence of entanglement between the electron-photon pair, in the continuous variables of position and momentum. Further prospects enable the use of the same setup to test electron-photon correlations against stricter entanglement bounds or in discrete variables (e.g. [7]). This demonstration provides a pathway for the introduction of electron-photon pairs into quantum imaging techniques to exploit the unique and complementary properties of these two particles.

References

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