Entangling the spatial properties of laser beams

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We have experimentally demonstrated entanglement of the spatial properties (position and momentum) of two laser beams [1]. We have achieved spatially entangled beams by combining a TEM_{00} reference beam with a squeezed TEM_{10} beam, and then entangling this beam with another TEM_{10} squeezed beam. For each entangled beam, a measurement can be made on the TEM_{10} component in order to find the beam position (real part) or the transverse beam momentum (imaginary part).

A direct measurement of the correlations between the two beams allows a calculation of the degree of inseparability. The two beams are entangled if these correlations are stronger than can be attained by classical means. The EPR (Einstein, Podolsky and Rosen) entanglement is measured by making predictions on what will be measured on one beam, based on a measurement of the other beam, and this is quantified by the degree of EPR paradox. An inseparability measurement of 0.51 and a degree of EPR paradox of 0.62 have been achieved, showing a genuine proof of the entanglement of position and momentum of two laser beams. The technology developed here can be used to make high precision optical measurements, or as a resource for new quantum information applications, particularly those that require multi-mode entanglement.

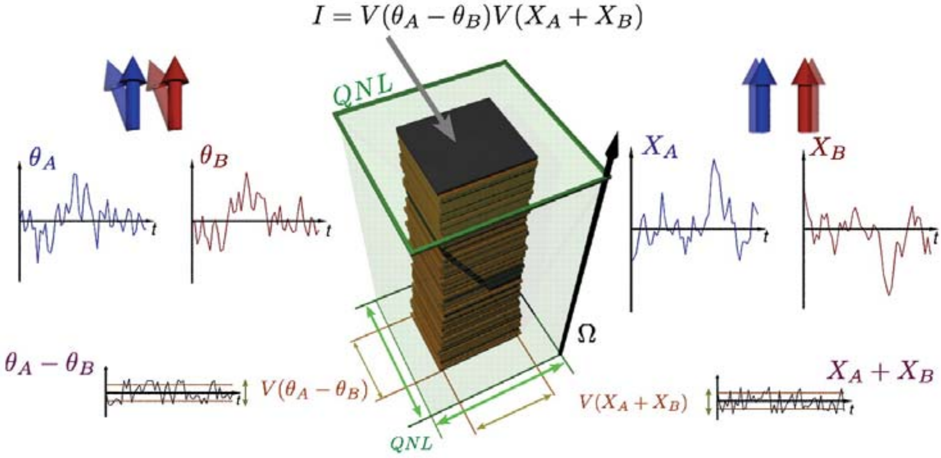

Fig. 1: No laser beam can have a fixed position or momentum. Spatial entanglement manifests itself as a strong quantum correlation between the position and direction of two beams, A (blue) and B (red). On the left, this illustration shows the fluctuating directions θ_A and θ_B of two beams, which are correlated, and on the right, the positions X_A and X_B, which are anti-correlated. For perfectly entangled beams the differences (θ_A-θ_B) and (X_A+X_B) would both be zero. Real entangled beams have a small residual differential movement. The variances $V(X_A + X_B)$ and $V(\theta_A - \theta_B)$ are calibrated against their respective quantum noise limit (QNL), which corresponds to the differential movement of two laser beams with independent quantum noise. A good measure of entanglement is the Inseparability, which for a symmetric system is the product $I = V(X_A + X_B)V(\theta_A - \theta_B)$. This is shown as the area of the filled rectangles in the centre of this figure. Each slice of the tower represents one measurement and the comparison of the area with the QNL (the green box) shows directly the degree of inseparability.

References

[1] K. Wagner et al., Science **321**, no. 5888, pp. 541 - 543 (2008).