Identifying entanglement using quantum "ghost" interference and imaging

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Abstract: We report a quantum interference and imaging experiment which shows quantitatively that entangled two-photon violate the EPR inequality. This measurement provides a direct way to distinguish quantum entanglement from classical correlation in continuous variables.

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We report an experiment which exploits quantum interference-imaging effects to verify if entangled two-photon states violate the EPR inequality:

$$\Delta(\mathbf{k}_1 + \mathbf{k}_2)\Delta(\mathbf{r}_1 - \mathbf{r}_2) > 1. \tag{1}$$

Since this inequality holds for any pair of classically correlated photons, it represents a standard to distinguish quantum entanglement from classical correlation in continuous variables. The experiment reported here represents the first direct verification of Eq. (1) with systems of two-photons.

A schematic of the experimental setup is shown in Fig. 1. This setup allows to measure both 'ghost' interference-diffraction and 'ghost' image patterns of the double-slit [2, 3]. The results are shown in Fig. 2. The single counts on both D_1, D_2 and D_3, which are scanned in the transverse direction, show no features at all. It is, however, possible to observe a 'ghost' interference-diffraction pattern when counting coincidences between D_1 and D_2 and to observe a 'ghost' image pattern in coincidences between D_1 and D_3 [2, 3].

The continuous line in Fig. 2(a) is a fitting of the experimental data, realized using the visibility V of the interference pattern as the fitting parameter. From this we find: $\Delta(k_{x_s} + k_{x_i}) = 2.5 \pm 0.6$ mm^{-1}. By studying the 'ghost' image (Fig. 2(b)) we obtain: $\Delta(x_s - x_i) = 0.11 \pm 0.02$ mm. The product of the uncertainties evaluated from the two sets of measurements gives:

$$\Delta(k_{x_s} + k_{x_i})\Delta(x_s - x_i) = 0.3 \pm 0.1 < 1. \tag{2}$$

The non-classicality condition introduced in Eq. (1) is then violated by entangled two-photons emitted by SPDC.

In summary, we proved quantitatively that entanglement implies almost perfect momentum-momentum and position-position correlations, stronger than any classical correlation. Classical correlation cannot exhibit such behavior, due to the uncertainty principle. Our measurement provides a direct way to distinguish between quantum entanglement and classical correlation in momentum and/or position variables, for systems of two photons. This is a quite different approach with respect to Bell's inequality and may represent an extension of Bell's inequality, in optics. An important practical consequence is that only the non-local correlation implicit in entangled systems allows to 'overcome' the usual diffraction limit and to obtain super-resolved images, as proposed and demonstrated in Ref. [4, 5].

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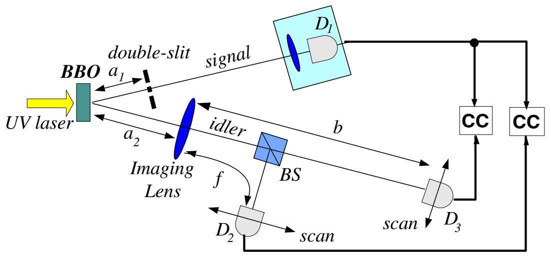

Fig. 1. Schematic of the experimental setup for observing the two-photon 'ghost' interference and 'ghost' image.

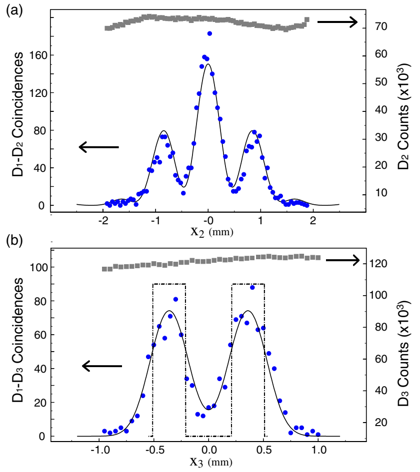

Fig. 2. Experimental data. (a) 'Ghost' interference-diffraction pattern. (b) 'Ghost' image pattern.