Image Formation Using Quantum-Entangled Photons

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Quantum imaging techniques enable the construction of images which are either sharper or more noise-free than those that can be created by means of conventional imaging techniques. Here we describe our experimental and theoretical investigations of the process of coincidence imaging—or "ghost" imaging—with the goal of establishing any limitations to this method and of determining which features of the coincidence imaging process are quantum and which can be understood in terms of classical correlations.

The process of coincidence imaging using an entangled light source is illustrated in Fig. 1(a). A laser beam excites a second-order nonlinear optical crystal and, through the process of parametric downconversion, a pair of entangled photons is created. One of the photons illuminates an object and a non-imaging detector (a "bucket" detector) registers the scattering of the photon from this object. The other photon is directed onto an imaging device, a photodetector array. A coincidence circuit allows the output of the imaging detector to be recorded only in the presence of a trigger pulse from the bucket detector. In this manner, a sharp image of the object is obtained even though the photons that fall onto the imaging detector have never interacted with the object to be imaged.

There has recently been a spirited discussion[1,2] in the literature regarding the conditions under which coincidence imaging can occur and in particular regarding whether coincidence imaging is an intrinsically quantum process or whether it can be understood in terms of classical correlations.

Recently Gatti et al.[3] have argued theoretically that, for an object at a known distance from the apparatus, coincidence imaging can be performed using classical correlations but that quantum entanglement is required if one wants to obtain a sharp image of an object that might be either in the near or far field of the light source. We have performed an experiment to test this idea and find results[4] in agreement with these predictions.

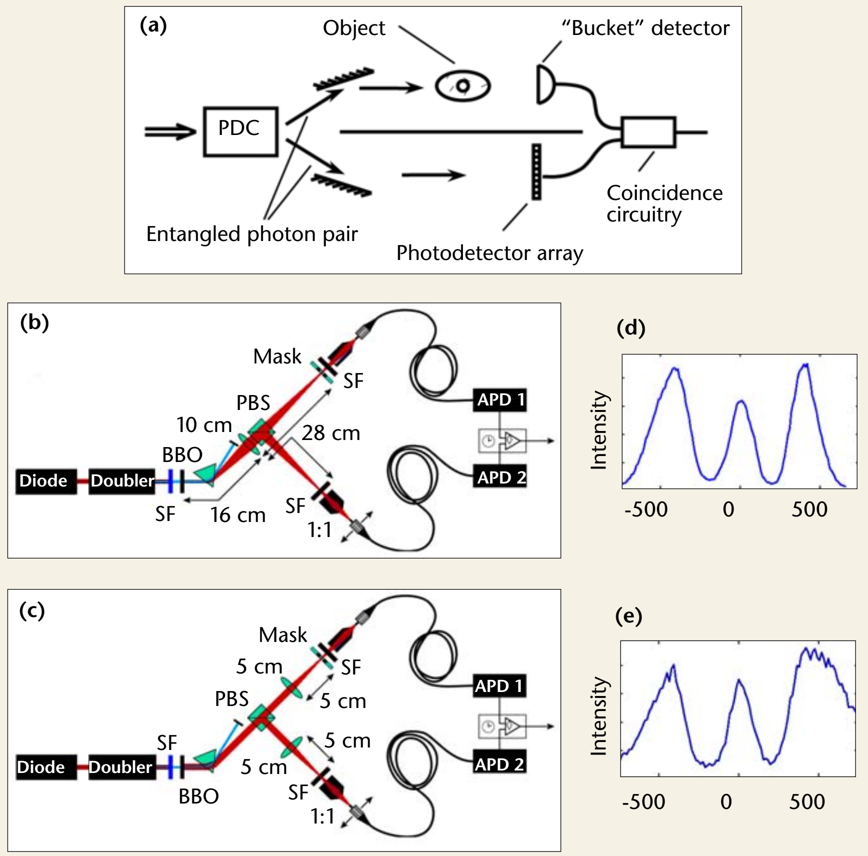

Figure 1. (a) Illustration of the process of coincidence imaging. Experimental setups (b, c) and measurements (d, e) showing coincidence images of a two-bar mask in both the near (b, d) and far (c, e) fields.

Our experiment and results are also shown in Fig. 1. In part (b) of the figure, an object in the form of a two-bar mask is imaged onto the plane of the parametric downconverter. In part (c), the object is placed in the far field of the downconverter. In both cases, a sharp image of the object is obtained by the coincidence circuit. We have also obtained results for the situation in which the parametric downconverter is replaced by a classically correlated source. In this case, we obtain sharp images for an object in either the near or far field but not in both. The results can be understood from the point of view that, in the quantum case, the observer can wait until the photon pair is emitted before deciding whether to measure the position or (transverse) momentum of one of the photons. The analogous quantity for the other photon is then precisely determined. We have also elucidated the relation between coincidence imaging and the Einstein-Podolsky-Rosen effect.[5]

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