VECTOR-LIGHT QUANTUM COMPLEMENTARITY

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The principle of complementarity, declaring that quantum objects share mutually exclusive characteristics, has had a major significance for the foundations of physics and a profound impact on the interpretation of the fundamental nature of reality [1]. The arguably most recognized manifestation of complementarity in physics is the wave–particle duality, which restricts the coexistence of wave and particle qualities of quantum systems [2]. In two-way interferometry, such as the famous double-slit (or double-pinhole) experiment, the duality is expressed via the relations [3–5]

$$P^2 + V^2 \leq 1, \quad D^2 + V^2 \leq 1, \tag{1}$$

in which P is the path predictability, representing the *a priori* ‘which-path information’ (WPI), D is the path distinguishability, quantifying the available WPI stored in the system, and V is the intensity visibility. For photons, however, interference does not necessarily appear solely as intensity fringes, but also, or exclusively, as polarization modulation [6–8], a feature that the conventional relations in Eq. (1) do not account for.

In this work, by studying polarization modulation in double-pinhole photon interference, we derive two general complementarity relations that cover genuine vectorial quantum-light fields of arbitrary state [9]. The complementarity relations are shown to reflect two different, fundamental aspects of wave–particle duality of the photon, having no correspondence within the usual scalar quantum treatment. In particular, we demonstrate that, contrary to scalar light, the *a priori* WPI of single-photon vector light does not couple to the intensity visibility, but to a generalized visibility, which also characterizes the variation of the polarization state. Moreover, it is shown that for general quantum light such complementarity is not a manifestation of quantum-state purity, but instead of complete coherence. Our work thus provides deeper insights into foundational quantum physics.

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