Is Bright and Dark States of Light the Quantum Origin of Classical Interference?

Shan Gao
Research Center for Philosophy of Science and Technology,
Shanxi University, Taiyuan 030006, P. R. China
E-mail: gaoshan2017@sxu.edu.cn

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Abstract

Interference phenomena, such as those observed in Young's double-slit experiment, are foundational to quantum mechanics, yet their interpretation continues to spark debate. Villas-Boas et al. [Phys. Rev. Lett. 134, 133603 (2025)] propose a quantum-optical framework attributing non-detection in regions of destructive interference to photons occupying "perfectly dark" states, which they claim do not interact with a two-level atom sensor due to vanishing coupling in the Jaynes-Cummings Hamiltonian. We argue that this interpretation is fundamentally flawed. Dark states, such as the out-of-phase coherent state $|\alpha, -\alpha\rangle$, are readily detectable in alternative experimental setups, including dispersive coupling in cavity QED and photon-counting detectors like photomultiplier tubes or avalanche photodiodes, which are sensitive to the photon number operator. This detectability undermines the assertion that dark states are the intrinsic cause of non-detection in destructive interference regions. Instead, the quantum mechanical superposition principle, combined with the Born rule, fully accounts for interference patterns across all detection schemes, as evidenced by well-established experiments such as single-photon double-slit interference, Hong-Ou-Mandel two-photon interference, and cavity QED measurements. By overgeneralizing a detector-specific effect, the dark-state framework introduces an unnecessary and redundant construct, as the standard quantum mechanical formalism already provides a complete and experimentally validated explanation of interference phenomena.

1 Introduction

Interference phenomena, such as those observed in Young's double-slit experiment, are cornerstones of quantum mechanics, revealing the wave-like behavior of particles, including photons. In their Letter, Villas-Boas et al. [1] propose a quantum-optical framework that attributes non-detection in regions of destructive interference to photons residing in "perfectly dark" states, which do not interact with a two-level atom sensor. We argue that this claim is fundamentally flawed, as dark states are detectable in various experimental setups and theoretical models. Instead, non-detection is a detector-specific consequence of the quantum mechanical superposition principle and the Born rule, which together fully account for interference patterns across all detection schemes.

2 Critique of the Dark-State Framework

Villas-Boas et al. [1] propose a quantum-optical framework to reinterpret classical interference phenomena, classifying photonic states in a multi-mode system as bright states, which couple strongly to a two-level atom and correspond to constructive interference, and dark states, or photon-dark states (PDS), which satisfy $\hat{E}^{+}(\mathbf{r}, t)|\psi_0^N\rangle = 0$ and do not couple to the atom, associated with destructive interference. The electric field operator is defined as $\hat{E}^+(\mathbf{r},t) \propto \hat{a}_1 + \hat{a}_2 e^{i\theta}$, where $\hat{a}_i$ $(i = 1, 2)$ are photon annihilation operators for mode i. They claim that non-detection in regions of destructive interference results from photons residing in dark states.

Consider the out-of-phase coherent state $|\alpha, -\alpha\rangle$, identified as a PDS because it satisfies $\hat{E}^+(\mathbf{r},t)|\alpha, -\alpha\rangle = 0$ $(\theta = 0)$. In the Jaynes-Cummings (JC) Hamiltonian:

$$H_{\text{JC}} = \hbar\omega\sigma^+\sigma^- + \sum_i \hbar\omega_i \hat{a}_i^\dagger \hat{a}_i + \hbar g \sum_i (\sigma^+ \hat{a}_i + \sigma^- \hat{a}_i^\dagger), \tag{1}$$

where σ^+, σ^- are the raising and lowering operators for the two-level atom, and g is the coupling strength, the interaction term $\hbar g \sum_i (\sigma^+ \hat{a}_i + \sigma^- \hat{a}_i^\dagger)$ couples the atom to the field. For the PDS $|\alpha, -\alpha\rangle$, the interaction vanishes, leading to zero excitation probability via the Born rule and resulting in non-detection.

However, the claim that dark states cause non-detection is incorrect, as dark states are detectable with other interactions. For instance, a dispersive coupling in off-resonant cavity QED:

$$H_{\text{disp}} = \hbar\omega\sigma^+\sigma^- + \sum_i \hbar\omega_i \hat{a}_i^\dagger \hat{a}_i + \hbar\chi\sigma_z(\hat{a}_1^\dagger \hat{a}_1 + \hat{a}_2^\dagger \hat{a}_2), \tag{2}$$

where $\sigma_z = |e\rangle\langle e| - |g\rangle\langle g|$ is the Pauli Z operator for the atom, and χ is the dispersive coupling strength, allows detection of the PDS $|\alpha, -\alpha\rangle$. The photon number is:

$$\langle \alpha, -\alpha | \hat{a}_1^\dagger \hat{a}_1 + \hat{a}_2^\dagger \hat{a}_2 | \alpha, -\alpha \rangle = 2|\alpha|^2, \tag{3}$$

yielding an energy shift for the excited state $|e\rangle$:

$$\langle e, \alpha, -\alpha | H_{\text{disp}} | e, \alpha, -\alpha \rangle = \hbar\omega + 2\hbar\chi|\alpha|^2, \tag{4}$$

and for the ground state $|g\rangle$, $\langle g|\sigma_z|g\rangle = -1$, yielding $-2\hbar\chi|\alpha|^2$. The relative energy shift of $4\hbar\chi|\alpha|^2$ induces a phase evolution in a superposition state $\frac{1}{\sqrt{2}}(|g\rangle + |e\rangle)$:

$$|\psi(t)\rangle = \frac{1}{\sqrt{2}} \left(e^{i2\chi|\alpha|^2 t}|g\rangle + e^{-i2\chi|\alpha|^2 t}|e\rangle \right) |\alpha, -\alpha\rangle. \tag{5}$$

This phase $\phi = 4\chi|\alpha|^2 t$ is detectable via Ramsey interferometry.

Most photon detectors, such as photomultiplier tubes (PMTs) and avalanche photodiodes (APDs), are sensitive to the photon number operator $\hat{N} = \hat{a}_1^\dagger \hat{a}_1 + \hat{a}_2^\dagger \hat{a}_2$. Their Hamiltonian is:

$$H_{\text{det}} = \sum_i \hbar\omega_i \hat{a}_i^\dagger \hat{a}_i + \sum_j \hbar\omega_j \hat{b}_j^\dagger \hat{b}_j + \sum_{i,j} \hbar g_{ij} (\hat{a}_i \hat{b}_j^\dagger + \hat{a}_i^\dagger \hat{b}_j), \tag{6}$$

where $\hat{b}_j^\dagger$, $\hat{b}_j$ are the creation and annihilation operators for the detector's internal modes (e.g., electronic states in PMTs or APDs). A direct calculation shows the detection rate is proportional to $\langle \hat{N} \rangle = 2|\alpha|^2$. The Born rule ensures detection reflects the photon number, as confirmed in single-photon double-slit experiments [2], the Hong-Ou-Mandel effect [3], and cavity QED [4] (see also [5]).

3 Conclusion

Villas-Boas et al.'s dark-state framework correctly derives that states like $|\alpha, -\alpha\rangle$ are undetectable by a two-level atom in the JC Hamiltonian due to zero coupling. However, their claim that dark states cause non-detection is incorrect, as dark states are detectable in other detection schemes, such as dispersive coupling and photon-counting detectors. The overgeneralization of dark states as the cause constitutes a fatal flaw. Existing experiments, such as single-photon double-slit, Hong-Ou-Mandel, and cavity QED setups, confirm that the superposition principle, combined with the Born rule, fully explains interference patterns.

References

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