N92-22055

PROPOSAL FOR A QND WHICH-PATH MEASUREMENT USING PHOTONS*

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A scheme is proposed for experimentally realizing the famous two-slit gedänken experiment using photons. As elegantly discussed for electrons by Feynman, a particle's quantum pathways interfere to produce fringes in the probability density for the particle to be found at a particular location. If the path taken by the particle is experimentally determined, the complementarity principle says that the fringes must disappear. To carry out this experiment with photons is difficult because normally the act of determining a photon's location destroys it.

We propose to overcome this difficulty by putting a type-II optical parametric amplifier (OPA) in each arm of a Mach-Zehnder interferometer, and observing fringes at the output, as shown in Fig.1. An OPA responds to an input photon by increasing its probability to produce a pair of photons, one having (vertical) polarization orthogonal to the (horizontal) polarization of the input photon. A polarizing beam splitter is used to eject only those photons with polarization orthogonal to the input, the detection of which allows partial inference about the path taken by the input photon without destroying it. The measurement is thus of the quantum nondemolition (QND) type.

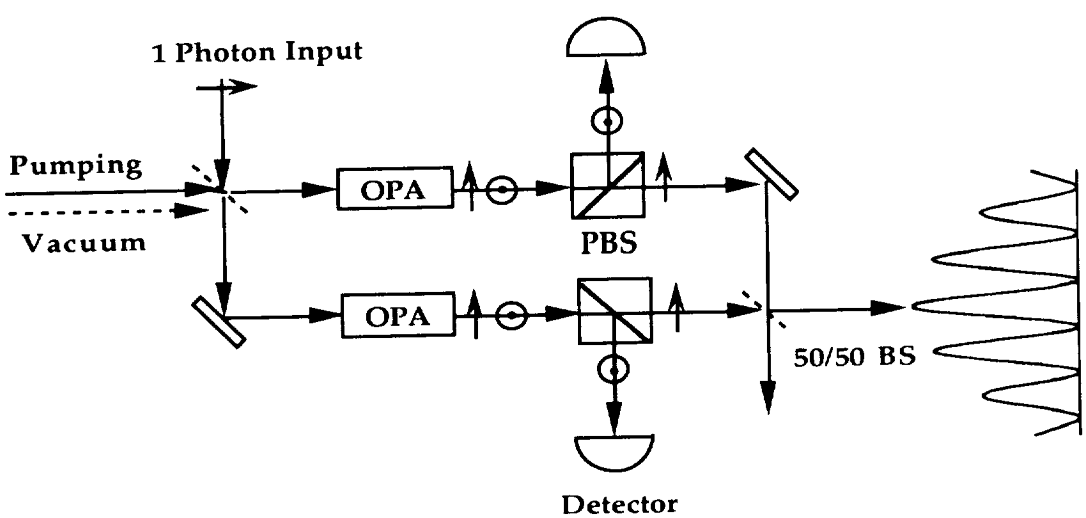

Fig.1 Apparatus for which-path measurement.

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The price paid for this inference is at least one noise photon in the interferometer, which degrades the fringe visibility, in accordance with the complementarity principle. Information theory is used to show that the visibility is connected to the amount of information available to be collected, regardless of whether or not anyone looks at it. In this sense information should perhaps be regarded as a physical quantity, rather than a subjective concept.

The calculation treats the signal (horizontal polarization) and idler (vertical polarization) modes of the OPA quantum mechanically and the pump mode as a given classical field. The one-photon input state is transformed on the 50/50 beam splitter by a unitary transformation (Ref.1), and then is acted upon by a factorized two-mode squeezing operator (Ref.2) for each OPA crystal. From the resulting probabilities for mode occupation, Bayes theorem is used to infer the probabilities P(upper | n_v,m_v) and P(lower | n_v,m_v) for each path (upper or lower) that the input photon may have taken. This inference is possible because the probability distributions for numbers of generated idler photons, n_v,m_v, depend on the number of photons (0 or 1) entering each OPA.

Information gain is defined in the following way knowing the prior probabilities (1/2,1/2) and the final probabilities inferred from Bayes theorem: $\Delta I = I_{prior} - I_{final}$, where $I_{prior} = 1$ bit is the initially missing information, and the final information after the measurement is

$$I_{final} = P(upper|n_v,m_v)\log_2 P(upper|n_v,m_v) + P(lower|n_v,m_v)\log_2 P(lower|n_v,m_v).$$

For a given sub-ensemble of trials in which n_v (m_v) idler photons are generated in the upper (lower) arm, the fringe visibility is found to be

$$V_{n_v,m_v} = 2(m_v+1)(n_v+1)/[(m_v+n_v+1)(m_v+n_v+2)].$$

The sub-ensemble fringe visibility and information gain are plotted in Fig.2 for different values of n_v and m_v. When $n_v=m_v$ the information gain is zero, and the visibility approaches unity for small n_v and m_v. For larger values of n_v and m_v the noise in the OPA degrades the visibility even though no information is imparted. For $n_v=0$ and $m_v >>1$, the information increases and the visibility decreases, in accordance with the complementarity principle. See related discussions (Refs.3-5) .

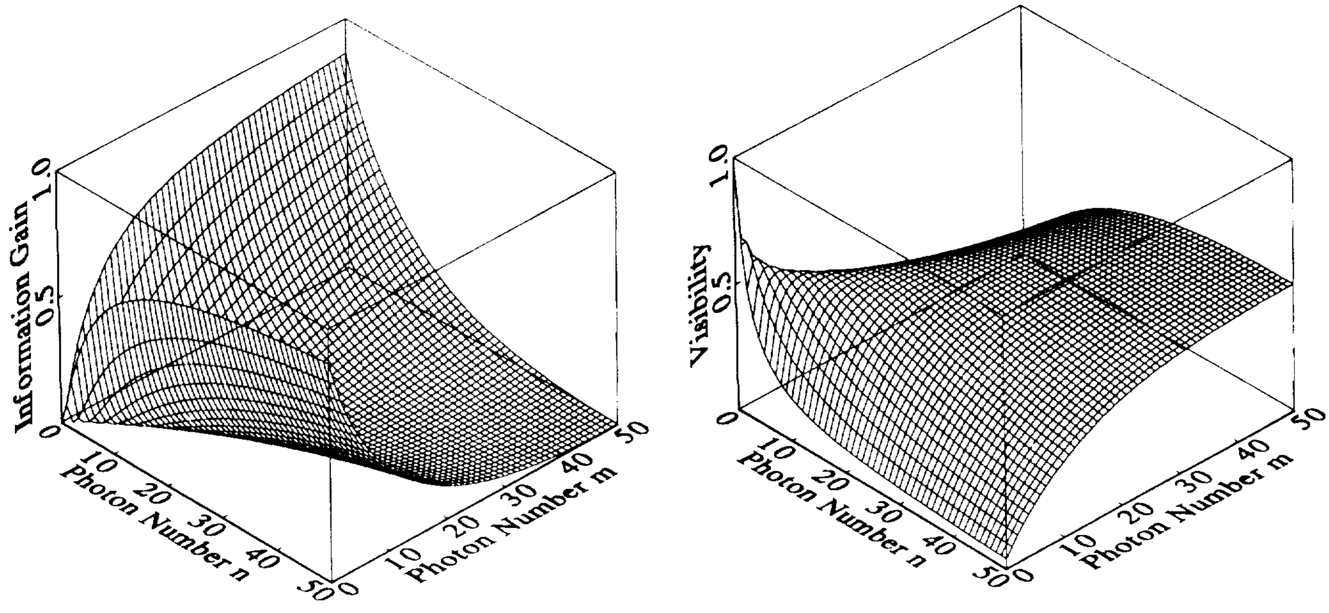

Fig.2 Information gain and fringe visibility versus measured photon numbers.

Thus, partial measurements of the photon path can be made, but noise is added, degrading the visibility, and thereby enforcing the complementarity principle. If n_v and m_v are not measured, and the total ensemble is used to calculate visibility, it can be shown that there is still an inverse relation between average information gain and visibility. Thus, it is not necessary to collect the information, only that it be "out there" available to be collected. This suggests that information has an objective, rather than a subjective, physical reality. It should be considered whether information plays an unrecognized role in physical processes, and as such should be incorporated in a more explicit, dynamical way into the theory of quantum mechanics.

* Research supported by the National Science Foundation.

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