INTERACTION-FREE MEASUREMENT OF A QUANTUM OBJECT: ON THE BREEDING OF "SCHRÖDINGER CATS"

Paul G. Kwiat, Harald Weinfurter, Anton Zeilinger

Institut für Experimentalphysik, Universität Innsbruck
Technikerstraße 25, A-6020 Innsbruck, Austria

The possibility of an "interaction-free" determination of the presence of an object was first discussed by Renninger and by Dicke,[1] who examined the effect on a quantum system due to the *non*-observation of a particular result (e.g., the non-scattering of a photon). Elitzur and Vaidman extended these ideas, so that the presence of an object modified the interference of a photon, even though the photon and object need not have interacted.[2] In the best case, their method works only 50% of the time. We have recently reported a different technique,[3] based on the quantum Zeno effect,[4] which allows the fraction of interaction-free measurements (IFMs) to be arbitrarily close to 1. As a result, one even has the possibility to employ multi-photon pulses for the interrogation. When the object being observed is in a quantum superposition state, one can prepare superpositions and entanglements of these macroscopic states of light.

There are many ways to perform interaction-free measurements.[3] For example, consider the scheme shown in Fig. 1. A vertically-polarized photon is directed into the system at time T = 0, and removed after N cycles (by a fast switch, not shown). Its polarization is rotated each cycle by $\Delta\theta = \pi/2N$, e.g., with an optically active material, or a waveplate. In the absence of any absorbing/scattering object, the polarization-Michelson interferometer does not alter the polarization of the light (since the horizontal and vertical components are recombined with the same phase relationship with which they entered); the final polarization of the light after N cycles is thus horizontal. In the object's presence, however, at each cycle the *non*-absorption of the photon by the object (with probability $cos^2\Delta\theta$) "collapses" the photon wavefunction back into a vertically-polarized state, and the process repeats. After all N cycles, the total probability for the photon to be absorbed by the object is $1 - \eta$, where $\eta = cos^{2N}\Delta\theta$ is the probability that the photon is still vertically-polarized; in the presence of the opaque object, there is *no* chance that the photon is found to be horizontally-polarized. Hence, the action of the IFM on the state of the photon may be written as

$$|V\rangle_{photon} \xrightarrow{\text{no object}} |H\rangle_{photon} \; ; \quad |V\rangle_{photon} \xrightarrow{\text{object}} \sqrt{1-\eta}|0\rangle_{photon} + \sqrt{\eta}|V\rangle_{photon} \; .$$

In the limit of $\eta \to 1$ ($N \to \infty$), the probability of absorbing the photon vanishes.

The above method also works when the interrogation is performed with multi-photon states. In the absence of the object, the stepwise evolution of the polarization from V to H occurs independent of the state of light used. With the object in, the probability of absorbing

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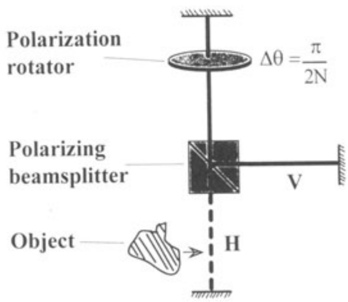

Figure 1: Interaction-free measurement scheme.

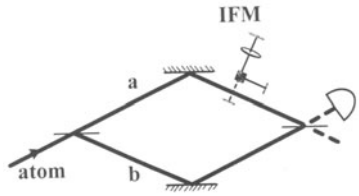

Figure 2: Using IFM to examine a quantum object.

one of n photons equals $1-\eta^n$, which can be made arbitrarily small for η sufficiently close to 1. Thus the presence of a single object may be used to control the polarization of a multi-photon input state, e.g., a number state, a coherent state, a squeezed state, etc.

We now investigate the effect of an object in a superposition state of being "there" or "not there". Consider an atom having just passed an adjustable "beamsplitter" (Fig. 2), so that the state of the atom is given by $|\psi\rangle_{atom} = \alpha|a\rangle_{atom} + \beta|b\rangle_{atom}$. Coupling path a to an IFM device[5] initially in state $|V\rangle_a$ gives:

$$\alpha\sqrt{1-\eta}|0\rangle_a|e\rangle_{atom} + \alpha\sqrt{\eta}|V\rangle_a|a\rangle_{atom} + \beta|H\rangle_a|b\rangle_{atom} \quad ,$$

where the first term represents the possibility that the atom was excited by the photon into the long-lived state $|e\rangle_{atom}$. For $\eta \to 1$, this becomes $\alpha|V\rangle_a|a\rangle_{atom} + \beta|H\rangle_a|b\rangle_{atom}$, an entangled state. Similarly, using a multi-photon input state $|V,V,V,...\rangle_a$ yields in this limit $\alpha|V,V,V,...\rangle_a|a\rangle_{atom} + \beta|H,H,H,...\rangle_a|b\rangle_{atom}$. Now we recombine the atom beams a and b on a 50-50 beamsplitter, and correlate with a measurement of $(|a\rangle_{atom} + |b\rangle_{atom})/\sqrt{2}$, giving $|\psi\rangle_{light} = \alpha|V,V,V,...\rangle_a + \beta|H,H,H,...\rangle_a$, a "Schrödinger cat". Via the IFM process we have managed to transfer the superposition from a single atom to a macroscopic state of light.

A straightforward extension will produce macroscopic *entangled* states of light. We need merely use a second IFM apparatus to look at the b path of the atom; its initial state $|V,V,...\rangle_b$ can in general be quite different from the initial state of the IFM in path a, with different photon number, statistics, etc. After the evolution, and projecting out the symmetric state of the atom, one obtains $|\psi\rangle_{light} = \alpha|V,V,V,...\rangle_a|H,H,...\rangle_b + \beta|H,H,H,...\rangle_a|V,V,...\rangle_b$, an entangled state of the multi-photon pulses. Clearly, these schemes can be generalized further and allow one to realize a wide class of interesting states of light.

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