An experiment to throw more light on light

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We propose an experiment in which "single photon states" are incident on a combination of two prisms placed opposite each other. When the gap between the prisms is larger than the wave length, the incident "photon states" suffer total internal reflection inside the first prism (registered by counter 1). When the gap is shorter than the wavelength, there is a possibility of their tunneling across the gap (registered by counter 2). The two counters 1 and 2 clicking in perfect anticoincidence would show simultaneously sharp particle and wave characteristics, highlighting inadequacy of the complementarity principle in its usual form. Other possibilities of the outcome are not favoured by the formalism of quantum optics.

It is becoming increasingly clear from recent experiments that the last word has not been said about the wave–particle nature of light. For instance, a very striking feature is the observed difference [1] between a weak pulsed source producing thermal light and a source producing "single photon states" from atomic radiative cascades. The former has no nonclassical effect (even when the average energy per light pulse is much less than that of one photon) whereas the latter produces perfect anticorrelation for detections on both sides of the beam splitter, which is interpreted as an evidence of "single particle behaviour of light pulses" (implying that such light pulses "should not be described as wave packets divided on a beam splitter but rather as single photons that cannot be detected simultaneously on both sides of the beam splitter" [1]). The usual notion of wave–particle duality for a single photon has nevertheless been vindicated in a complementary experiment [1] with "single photon states" showing interference between two channels of a beam splitter ("a photon interferes with itself").

In this note we propose an experiment that would provide further insight into the wave–particle nature of "single photon states". The classical analogue of this experiment was performed by Bose [2] in 1897 as reported in Sommerfeld's "Optics" [3]. Bose took two asphalt prisms and placed them opposite each other with a large air gap between them (fig. 1). When microwaves with $\lambda = 20$ cm were incident on the first prism, they were found to be totally internally reflected by it. As he decreased the air gap and made it of the order of several centimeters, Bose found that the waves could tunnel through the gap. This was a striking confirmation of the wave nature of microwaves. Similar experiments can be done with visible light. Feynman [4] has given a detailed explanation of this effect based on the theory of classical electrodynamics.

The question that arises is: What would happen if

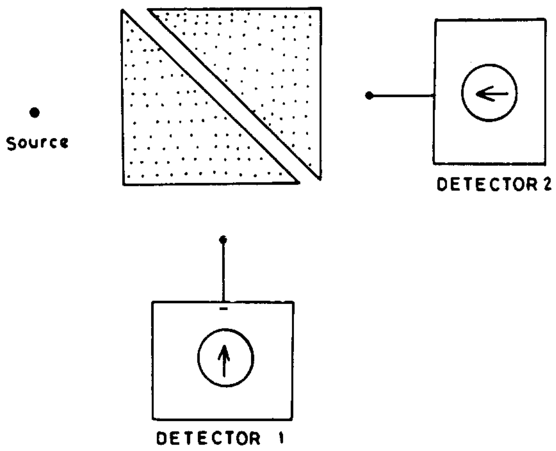

Fig. 1.

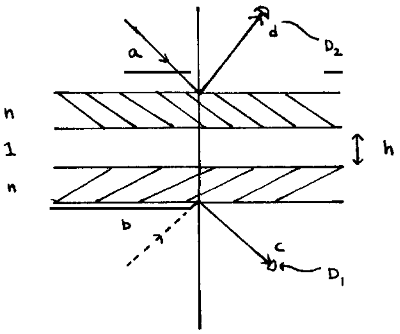

Fig. 2.

this experiment is performed with "single photon states"? There are the following possibilities of the outcome:

(a) The "tunneling" phenomenon *occurs* and the two counters (1 and 2) click in perfect *anticoincidence.*

(b) The "tunneling" *occurs* and the two counters (1 and 2) click in *coincidence.*

(c) The "tunneling" does *not* occur and *only* counter 1 clicks.

We now argue that possibility (a) is the one favoured by quantum optics. The experimental arrangement can be modelled by the scheme shown in fig. 2. In classical electrodynamics the field amplitudes a, c, d obey the relations

$$d=\gamma a, \quad c=\alpha a\,, \tag{1}$$

where γ and α are respectively the reflection and transmission amplitudes. For certain angles of incidence, the total internal reflection occurs and the waves in the region 1 are evanescent. If the thickness (h/λ) is large enough, then by the time the fields reach the surface of the second prism, the amplitude has decayed to almost zero and no transmission or tunneling takes place. In quantum theory, the quantities d, c, and a are to be treated as annihilation operators. Moreover, in order to maintain the commutation relations, we have to add the vacuum field b at the open port. Thus eq. (1) is to be modified to

$$c=\alpha a+\beta b, \quad d=\gamma a+\delta b\,, \tag{2}$$

and one has the commutation relations

$$[a,a^\dagger]=[b,b^\dagger]=1, \quad [a,b^\dagger]=0\,,$$
$$[c,c^\dagger]=[d,d^\dagger]=1\,. \tag{3}$$

Note that $|\alpha|^2+|\gamma|^2=1$, since the prisms are supposed to be lossless. Moreover, β is related to γ through, at most, a phase factor. The probability $p_d(1)$ $(p_c(1))$ of detecting a photon at the detector D_1 (D_2) is given by

$$p_d(1)=\mathrm{Tr}\{p|1\rangle_{d\,d}\langle 1|\}\,, \tag{4}$$

where $|1\rangle_d$ is the single photon state associated with the mode d. Assuming the input states as $|1\rangle_a|0\rangle_b$, these probabilities can be calculated as

$$p_d(1)=|\gamma|^2, \quad p_c(1)=|\alpha|^2\,. \tag{5}$$

Note that the results (5) are the same as one would get on the basis of classical electrodynamics. Thus tunneling would occur as long as it occurs in classical theory and therefore the possibility (c) is ruled out. In order to see the quantum features let us find out if the detectors click in coincidence or anticoincidence. We thus need to know the joint probability $p_{cd}(1,1)$ of detecting one photon at D_1 and one photon at D_2,

$$p_{cd}(1,1)=\mathrm{Tr}\{p|1\rangle_c|1\rangle_{d\,d}\langle 1|_c\langle 1|\}\,. \tag{6}$$

Using (2), (6) reduces to

$$p_{cd}(1,1)=0\,, \tag{7}$$

which implies that the two detectors *click in anticoincidence.* We thus show that the *possibility (a) is the one* obtained by quantum optical considerations. The quantum optical considerations can lead to the possibility (b) if (i) the incident field contains more than one photon, i.e. the probability that the incident field has more than one photon is nonzero, and (ii) the medium adds a noise photon, say, from thermal fluctuations.

Possibility (a) implies that "a single photon state" displays both particle *and* wave characteristics in this experiment because transmission through "tunneling" is essentially a wave phenomenon (as is evident from the fact that it should disappear when the gap between the prisms is made *larger* than the wavelength), whereas perfect anticoincidence definitely implies particle-like propagation (as pointed out in ref. [1], any description using the wave picture during propagation would predict a *non-zero minimum* rate of coincidences). In some "Welcher Weg" experiments carried out to probe the nature of wave–particle dualism, variable degrees of sharpness of wave- and particle-like behaviour have been observed. This goes beyond the usual discussions of the complementarity principle in showing that it is possible to obtain partial "particle knowledge" and partial "wave knowledge" from the same experimental arrangement in terms of "which path" information and the corresponding contrast of the interference pattern [5]. What distinguishes the experiment proposed here from such "Welcher Weg" experiments is that tunneling (wave-like propagation), rather than interference, in conjuction with perfect anticoincidence (particle-like propagation), rather than "which path" information, implies *simultaneously sharp* particle- *and* wave-like properties. In fact, in the proposed experiment one can *label* each photon registered in one of the two detectors as coming either after tunneling through the gap or after internal reflection from the first prism (analogous to "which path" information) and *at the same time* the ratio of the numbers of transmitted and internally reflected photons displays a wave-like property. This is irreconcilable with the usual formulation of the complementarity principle (implying *mutual exclusiveness* between complete "particle knowledge" and complete "wave knowledge") but it consistent with both the Einstein–de Broglie version of wave–particle duality [6] [#1] and the viewpoint advocated by Heisenberg [7] who wrote in 1959 "... the concept of complementarity introduced by Bohr into the interpretation of quantum theory has encouraged the physicists to use an ambiguous language, to use the classical concepts in a somewhat vague manner in conformity with the principle of uncertainty ... When this vague and unsystematic use of the language leads into difficulties, the physicist has to withdraw into the mathematical scheme and its unambiguous correlation with the experimental facts".

If this experiment is repeated with sources of light that do not produce single photon states, there is no reason to expect perfect anticoincidence. This shows that the *simultaneously sharp* particle- *and* wave-like propagation is characteristic only of "single photon states" generated by "quantum" sources. This fundamental difference between light emitted by "quantum" and other sources cannot be observed in other "Welcher Weg" experiments in which the type of source (and hence the type of light emitted) plays no role.

Possibility (b) would definitely be incompatible with quantum optics, but could be explained in terms of stochastic optics (classical wave plus real zero point field) [8].

Possibility (c) is neither favoured by quantum optics nor by stochastic optics.

It is evident, therefore, that possibility (a) is the crucial one in confronting the complementarity principle. Similar experiments with electrons or neutrons one at a time would also be interesting. Experiments of this type would have considerable heuristic value and it would be worthwhile to explore the possibility of doing them with the help of the technology available today.

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[#1] According to the Einstein–de Broglie formulation, a microphysical entity such as a photon or an electron is actually a localized particle associated with an objectively real wave $\phi(x, y, z, t)$, propagating in space and time, and proportional to the quantum mechanical wave function $\psi(x, y, z, t)$.

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