Whole Photon or Nothing

Paul Dirac was one of the pioneers of quantum theory and his textbook of 1930, *The Principles of Quantum Mechanics*, an exposition in concise and measured prose and which became the early standard work on quantum mechanics, stated a much-repeated principle of detection early in its pages [446, pp. 8-9]:

> *The result of such a determination must be either the whole photon or nothing at all. Thus, the photon must change suddenly from being partly in one beam and partly in the other to being entirely in one of the beams. So long as the photon is partly in one beam and partly in the other, interference can occur when the two beams are superposed, but this possibility disappears when the photon is forced entirely into one of the beams by an observation.*
>
> *…the wave function gives information about the probability of one photon being in a particular place and not the probable number of photons in that place. The importance of the distinction can be made clear in the following way. Suppose we have a beam of light consisting of a large number of photons split up into two components of equal intensity. On the assumption that the intensity of a beam is connected with the probable number of photons in it, we should have half the total number of photons going into each component. If the two components are now made to interfere, we should require a photon in one component to be able to interfere with one in the other. Sometimes these two photons would have to annihilate one another and other times they would have to produce four photons. This would contradict the conservation of energy.*
>
> *The new theory, which connects the wave function with probabilities for one photon, gets over the difficulty by making each photon go partly into each of the two components. Each photon then interferes only with itself. Interference between two different photons never occurs.*
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The feature that "each photon then interferes only with itself" is essential to the orthodox interpretation of quantum mechanics and to understanding quantum measurement. It essentially means that self-interference can occur only if two components of the wave packet can overlap, which requires that the optical path length not exceed the coherence length. Note that Dirac's statement applies only to situations where interference is revealed by measuring single photons and not to experiments where correlations between different photons are detected. The latter corresponds to the case of destructive interference of photons originating from separate, independent sources [447] [23].

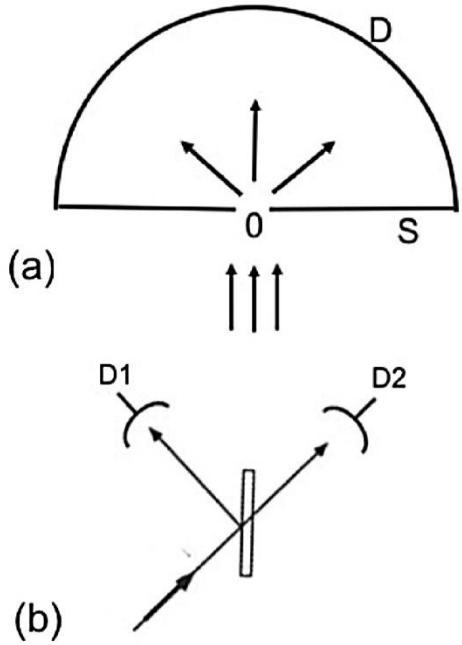

Figure 5.15: (a) Einstein's 1927 thought experiment from the 5th Solvay Conference: photons are diffracted through hole in screen S to detecting hemisphere D; (b) Simplified version with beam splitter and two detectors.

At the time that Dirac made these statements, experiments had not yet confirmed all of these claims regarding "the whole photon or nothing at all" and "each photon then interferes only with itself." If a photon enters a beam splitter, as in Figure 5.155(b), with the resulting "click" of either detector D1 or D2, is the decision to either reflect or transmit made at the beam splitter or at the detectors? If a beam splitter is indeed a unitary device, as discussed in Chapter 2, shouldn't the stochastic clicking occur at the detectors and not at the beam splitter? And what are the implications of these possibilities? The status of these questions was raised as early as the landmark 5th Solvay Conference in 1927, at which Dirac was the youngest participant. Among the twenty-nine attendees were such luminaries as Einstein, Bohr, Planck, Lorentz, Marie Curie, Schrödinger, Pauli, Heisenberg, Compton, de Broglie, and Born. During the General Discussion, Einstein proposed a thought-experiment of particles impinging on a small slit in a screen being diffracted onto a hemispherical detector (such as a photographic film), Figure 5.15.

Einstein then discussed two interpretations of this scenario [4, pp. 400-401]:

> *Interpretation I. The de Broglie-Schrödinger waves do not correspond to a single electron, but to a cloud of electrons extended*

> *in space. The theory does not give any information about the individual processes, but only about the ensemble of an infinity of elementary processes.*
> *Interpretation II. The theory has the pretension to be a complete theory of individual processes. Each particle directed towards the screen, as far as can be determined by its position and speed, is described by a packet of de Broglie-Schrödinger waves of short wavelength and small angular width. This wave packet is diffracted and, after diffraction, partly reaches the film D in a state of resolution.*
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> G. Bacciagaluppi and A. Valentini, Quantum Theory at the Crossroads: Reconsidering the 1927 Solvay Conference, Cambridge University Press, 2013.

He argued that by Interpretation I, $|\psi|^2$ represents the probability of a particular particle being at a given point of the detector whereas with Interpretation II, $|\psi|^2$ gives the probability that at a given instant the same particle is present at a given point. He says,

> *Here, the theory refers to an individual process and claims to describe everything that is governed by laws.*
>
> G. Bacciagaluppi and A. Valentini, Quantum Theory at the Crossroads: Reconsidering the 1927 Solvay Conference, Cambridge University Press, 2013.

In other words, Interpretation I does not specify the individual trajectories of the particles and so is incomplete, but with interpretation II, the theory claims to be complete. Einstein also objects that II would allow the same elementary process to produce an action at two or more places across the detector, resulting in

> *an entirely peculiar mechanism of action at a distance, which prevents the wave continuously from producing an action in two places on the screen.*
>
> G. Bacciagaluppi and A. Valentini, Quantum Theory at the Crossroads: Reconsidering the 1927 Solvay Conference, Cambridge University Press, 2013.

Such action at a distance would be viewed by Einstein as conflicting with his theory of relativity as he would also later object in his 1935 Einstein-Podolsky-Rosen (EPR) paper. Einstein is also recognizing here the “whole photon or nothing at all” aspect required by quantum mechanics and later emphasized by Dirac in his 1930 book. These points were also made by Heisenberg in his 1929 University of Chicago lectures [429, p. 39] where he discusses Einstein’s 1927 example in terms of a photon impinging on a semi-transparent mirror or *beam splitter*, Figure 5.15(b).

> *…one other idealized experiment (due to Einstein) may be considered. We imagine a photon which is represented by a wave packet built up out of Maxwell waves. It will thus have a certain spatial extension and also a certain range of frequency. By reflection*

at a semi-transparent mirror, it is possible to decompose it into two parts, a reflected and a transmitted packet. There is then a definite probability for finding the photon either in one part or in the other part of the divided wave packet. After a sufficient time, the two parts will be separated by any distance desired; now if an experiment yields the result that the photon is, say, in the reflected part of the packet, then the probability of finding the photon in the other part of the packet immediately becomes zero. The experiment at the position of the reflected packet thus exerts a kind of action (reduction of the wave packet) at the distant point occupied by the transmitted packet, and one sees that this action is propagated with a velocity greater than that of light.

However, Heisenberg finds the nonlocality requirement of "reduction of the wave packet" due to the "whole photon or nothing" property does not conflict with relativity, claiming

it is also obvious that this kind of action can never be utilized for the transmission of signals so that it is not in conflict with the postulates of the theory of relativity.

This may be the earliest statement of the *peaceful coexistence* of quantum theory and relativity, to use Abner Shimony's persistent phrase [448].