Interaction Free Measurement: Seeing in the Dark

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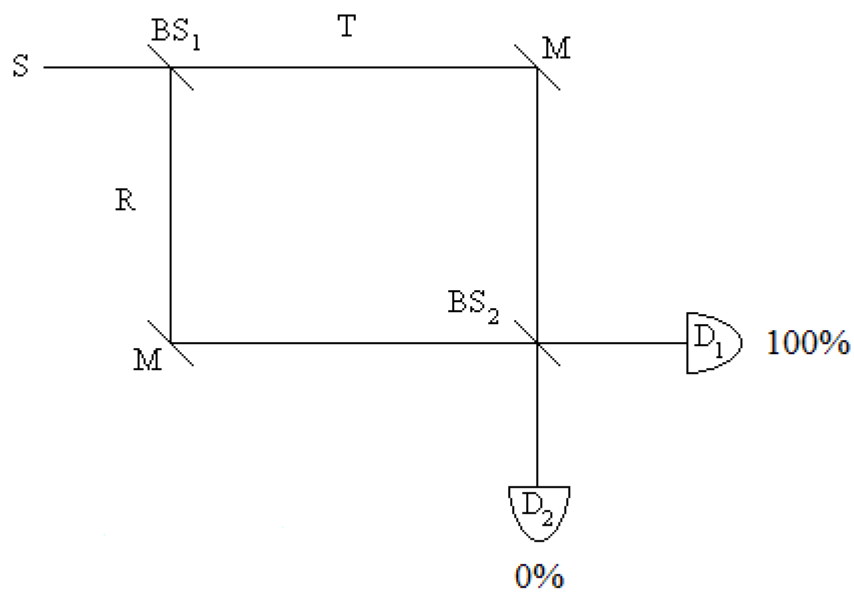
The illustration of the concept of interaction-free measurement requires the use of an interferometer. A simple illustration employs a Mach-Zehnder interferometer (MZI) like the one shown here.



This equal-arm MZI consists of two 50-50 beam splitters (BS_1, BS_2), two mirrors (M) and two detectors (D_1, D_2). A source emits a photon which interacts with BS_1 producing the following superposition. (By convention a 90 degree (i) phase shift is assigned to reflection.

$$S = \frac{1}{\sqrt{2}} \cdot (T + i \cdot R) \qquad \mathbf{1}$$

The transmitted and reflected branches are united at BS_2 by the mirrors, where they evolve into the following superpositions in the basis of the detectors.

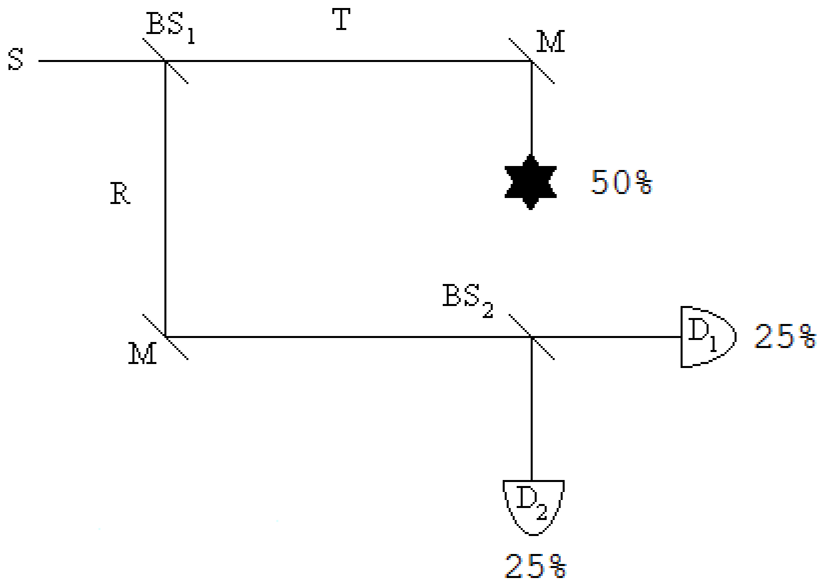
$$T = \frac{1}{\sqrt{2}} \cdot (i \cdot D_1 + D_2) \qquad \mathbf{2} \qquad\qquad R = \frac{1}{\sqrt{2}} \cdot (D_1 + i \cdot D_2) \qquad \mathbf{3}$$

Substitution of **2** and **3** into **1** reveals that the output photon is always registered at D_1. There are two paths to each detector and constructive interference occurs at D_1 and destructive interference at D_2.

$$S = \frac{1}{\sqrt{2}} \cdot (T + i \cdot R) \left| \begin{array}{l} \text{substitute}, T = \frac{1}{\sqrt{2}} \cdot (i \cdot D_1 + D_2) \\ \text{substitute}, R = \frac{1}{\sqrt{2}} \cdot (D_1 + i \cdot D_2) \end{array} \right. \rightarrow S = D_1 \cdot i$$

Probability at D_1: $(|i|)^2 = 1$

The MZI provides a rudimentary method of determining whether an obstruction is present in its upper arm without actually interacting with it. As we shall see, it is not an efficient method, but it does clearly illustrate the principle involved which then can be used in a more elaborate and sophisticated interferometer to yield better results.



In the presence of the obstruction equation **2** becomes $T = \gamma_{Absorbed}$. This leads to the following result at the detectors.

$$S = \frac{1}{\sqrt{2}}\cdot(T + i\cdot R) \quad \begin{vmatrix} \text{substitute}, T = \gamma_{Absorbed} \\ \text{substitute}, R = \frac{1}{\sqrt{2}}\cdot(D_1 + i\cdot D_2) \end{vmatrix} \rightarrow S = \frac{\sqrt{2}\cdot\gamma_{Absorbed}}{2} - \frac{D_2}{2} + \frac{D_1\cdot i}{2}$$

Quantum mechanics predicts that for a large number of experiments 50% of the photons will be absorbed by the obstruction, 25% will be detected at D_1 and 25% will be detect at D_2. This later result is the signature of interaction-free measurement. Even if the photon is not absorbed, the mere presence of the obstruction causes the probability of detection at D_2 to go from zero to 25%. The photon's arrival at D_2 signals the presence of an obstruction in the upper arm of the MZI, and the obstruction is detected without an interaction.

Of course, 25% is not great efficiency, so this is "a proof of principle" example. However, with a little ingenuity the probability of interaction-free detection can be increased dramatically. To see how this can be accomplished read "Quantum Seeing in the Dark" by Kwiat, Weinfurter and Zeilinger in the November 1996 issue of *Scientific American*.