Chapter 12

You Can't Outwit the Weirdness

Wheeler's delayed choice interference experiment realised

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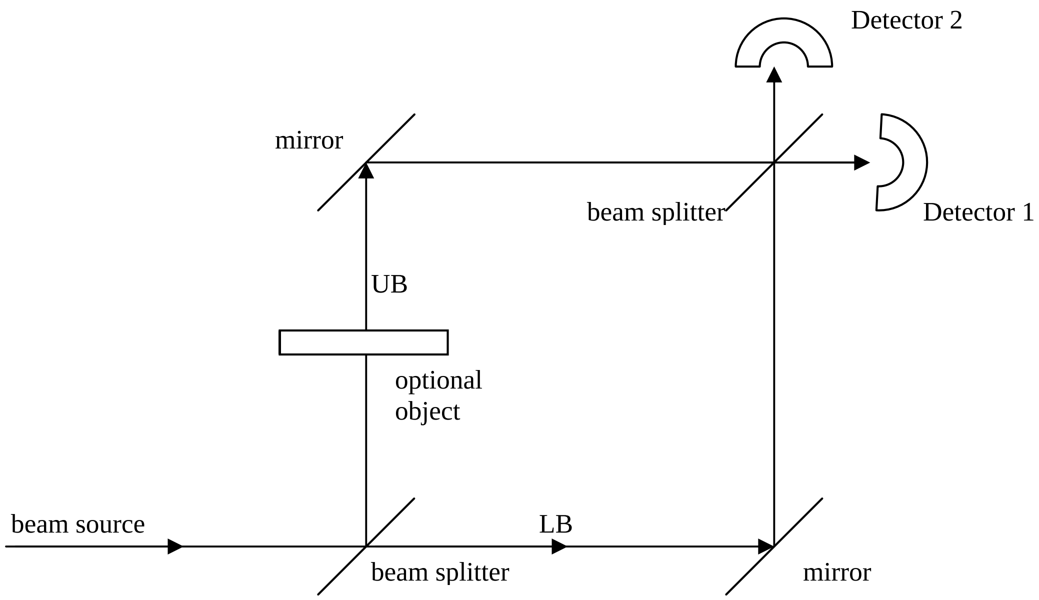
Consider a Mach-Zehnder interferometer (see Figure 1). The manifestation of interference in this device is that all output photons appear in detector 1, and none in detector 2. Why this happens is explained in Chapter 8. We know that if we measure which path the photon takes then interference is destroyed, and photons will be found by both detectors. In the case of a double slit experiment, the same destruction of the interference fringes occurs if a measurement is made to determine the path of the photon between the slits and the screen. Why this is inevitable is demonstrated in Chapters 4 and 8.

Wheeler posed the following *gedanken* experiment. Suppose that at some time after the photon has passed through the slits we choose at random whether to leave the screen or to snatch it away revealing a pair of telescopes, one focussed on each slit, thus observing whether the photon originated from the left or the right slit. Considering only those cases when the screen is left in place, the interference pattern will (one presumes) be found. But the remaining cases (when the screen is whipped away) have no interference pattern, just illuminated slits. But the photon is already committed regarding its behaviour when the decision to leave or remove the screen is taken, in the sense that it has already passed beyond the slits. The same quantum weirdness can be displayed by a Mach-Zehnder interferometer. Consider the final beam splitter (top right in Figure 1).

Figure 1 The Mach-Zehnder Interferometer

LB = Lower Beam; UB = Upper Beam



If the final beam splitter were omitted, detector 1 would measure only photons taking the path UB, and detector 2 would measure only photons taking path LB. Both would occur with equal frequency (assuming the first beam splitter is 50/50). There is no interference (rather trivially in this case since, in the absence of the final beam splitter, the two paths are never brought together in order to interfere).

But we can now consider leaving or removing the final beam splitter at random, and at a time after the photon has passed through the first beam splitter. To be more precise, we can ensure that the event defined by the photon passing through the first beam splitter cannot be causally influenced by the decision to retain or remove the final beam splitter. If quantum mechanics is correct, and if we confine attention to those randomly selected cases when the final beam splitter is retained, we shall find all the photons enter detector 1 and none into detector 2 (which is the manifestation of interference in this device).

This version of Wheeler's experiment, employing a Mach-Zehnder interferometer has actually been performed by Jacques et al (2007). The retention or removal of the final beam splitter was achieved electronically and the decision was made by a random number generator sufficiently quickly to be spacelike separated from the photon passing through the first beam splitter. Interference occurs unambiguously when the final beam splitter is activated, thus confirming the quantum mechanical expectation.

What does this result imply? The interpretation would seem to be that,

(i) For randomly selected cases which retain the final beam splitter, the photon must be regarded as "going both ways at once" in order to generate the observed interference pattern.

(ii) But the photon must therefore also "go both ways at once" for the remaining cases, when the final beam splitter is removed, since there is no causal link between this decision and the photons prior to the slits.

(iii) This suggests that the "collapse of the wavepacket", which leads to detection in one or other of the two detectors, does not occur until the photon encounters the detectors. Hence, when the final beam splitter is absent, detection of a photon in detector 1 does not quite mean that the photon took path UB. Prior to detection, either of detectors 1 or 2 might register the photon since the photon would have been in a superposition of both states. The counterfactual, that it might have taken path LB, only becomes a counterfactual after the detectors have detected a photon. Before that, both options were open. The outcome of the detection is truly indeterminate – there are no hidden variables which determine the 'actual path taken'.

References

V.Jacques, E.Wu, F.Grosshans, F.Treussart, P.Grangier, A.Aspect, and J.-F.Roch (2007) "Experimental Realization of Wheeler's Delayed Choice Gedanken Experiment", Science **315**: 966–968. arXiv: quant/ph-0610241.