Welcher-Weg Experiment[1]

The issue of the → wave-particle duality of light and matter is commonly illustrated by the → double-slit experiment, in which a quantum object of relatively well defined momentum (such as a photon, electron, neutron, atom, or molecule) is sent through a diaphragm containing two slits, after which it is detected at a capture screen. It is found that an interference pattern characteristic of wave behaviour emerges as a large number of similarly prepared quantum objects is detected on the screen. This is taken as evidence that it is impossible to ascertain through which slit an individual quantum object has passed; if that were known in every individual case and if the quantum objects behaved as free classical particles otherwise, an interference pattern would not arise.

The notion that a description of atomic objects in terms of definite classical particle trajectories is not in general admissible is prominent in Werner Heisenberg's seminal paper [1] of 1927 on the → uncertainty principle; there he notes: "I believe that one can fruitfully formulate the origin of the classical 'orbit' in this way: the 'orbit' comes into being only when we observe it." In the same year, in his famous Como lecture, Niels Bohr introduced the → complementarity principle, which entails that definite particle trajectories cannot be defined or observed for atomic objects because according to it their spatiotemporal and causal descriptions are mutually exclusive [2]. Bohr cited the uncertainty relation as a symbolic expression of complementarity but recognized that this relation also offered room for *approximately defined* simultaneous values of position and momentum. Still in the same year, at the 1927 Solvay conference, Albert Einstein questioned the impossibility of determining the path taken by an individual particle in a double-slit interference experiment [19]; he proposed an experimental scheme wherein he considered it possible to infer which slit the particle passed, without thereby destroying the interference pattern by measuring the recoil of the double-slitted diaphragm. This was the first instance of a *welcher-weg* or *which-way experiment.* As Bohr reported in his 1949 tribute to Einstein [3], he was able to demonstrate that Einstein's proposal was in conflict with the principles of quantum mechanics.

In subsequent years, different variants of such a *welcher-weg* experiment were considered as thought experiments illustrating the mutual exclusive options of either determining the path of a quantum object or observing its interference behaviour. Although Einstein's proposal of measuring the recoil of the double-slit system to infer the path was shown by Bohr to lead to an uncertainty of the slit location sufficient to blur the interference pattern, Feynman [20] later argued that any attempt to observe the path of an electron by shining light on it will lead to random momentum kicks on it in line with the uncertainty principle, thus washing out the interference.

A more rigorous quantum mechanical model and analysis of Einstein's which-way experiment was undertaken by Wootters and Żurek in 1979 [4]. The initial slit through which the photons are sent is suspended with a spring, and its

[1] In: *Compendium of Quantum Physics*, eds. F. Weinert, K. Hentschel and D. Greenberger, Springer-Verlag, to appear.

centre-of-mass motion is described quantum mechanically as that of particle subjected to a harmonic potential. This allows for a choice of measurements that can be performed on the slit once the photon has passed it and proceeds through the double-slit system towards the final screen. If an (approximate) measurement of the position of the slit is made, it is found that the photons impinging on the final screen build up an interference pattern; on the other hand, if the momentum of the initial slit is determined sufficiently precisely so as to allow the determination of the photon's path, the interference pattern does not develop. The fact that both choices are possible after the photon has passed the screen is due to the quantum correlations (entanglement) being built up between the photon and the initial screen; the experiment can thus be considered as an instance of Wheeler's *delayed-choice experiments* [5]. (For a recent experimental realization, see [6].)

Wootters and Żurek also gave an information-theoretic characterization of the trade-off between the quality of the path determination and the concurrent degradation of the interference contrast. They noted that even at 99% path certainty, the visibility of the interference pattern (crest to valley ratio) was still 1.5. In this way, they demonstrated that Bohr's strict complementarity is compatible with a notion of *graded* or *quantitative* complementarity (already hinted at by Bohr in 1927 [2]), according to which the exclusivity of the experimental options for path determination and interference observation are characterized more precisely and reconciled in a certain sense. This conclusion has subsequently been corroborated by demonstrations of the the joint *approximate* measurability of noncommuting observables, such as complementary path and interference observables in Mach-Zehnder interferometry. (Examples and references can be found in the review [21].) In the 1980s, the discovery of novel information-theoretic uncertainty relations (e.g., [7, 9, 8]) and a related Mach-Zehnder interferometric which-way experiment performed with laser light [8] boosted interest in the investigation of quantitative wave-particle duality.

In the Wootters-Żurek model, the path information is obtained by effecting a momentum exchange between the photon and the initial slit screen. In 1991, Scully, Englert and Walther proposed a radically new variant of which-way experiment [10]: an atom passes through a double-slit system, and its two possible paths are then directed through two microwave cavities in which path information is stored in the entanglement being produced between internal degrees of freedom of the atom and the cavity field. In this experiment, the interaction is too weak to lead to any significant momentum transfer which cannot thus account for the destruction of the interference pattern. As shown in [10], the interference pattern can be restored if a suitable observable of the probe system not commuting with the path indication observable is measured. Since the counterfactual path information is *erased*, this phenomenon is referred to as *quantum erasure*; it was first described by Scully and Drühl in 1982 [11], and an experimental realization incorporating the delayed-choice feature was reported in [12].

The first realization of a *welcher-weg* experiment with individual atoms similar to the proposal of Scully, Englert and Walther was obtained by Dürr, Nonn and Rempe in 1998 [13]. It is shown there that neither mechanical momentum transfers nor the position-momentum uncertainty relation are relevant for the explanation of the destruction of interference. Nevertheless duality relations have been found that describe a quantitative trade-off between the quality of path determination and interference visibility [14, 15, 16] which have been shown to be instances of appropriate uncertainty relations [21].

A neutron-interferometric double resonance experiment involving neutrons and photons allowing simultaneous observation of interference and individual energy losses have also been used to test Einstein's related 'Einweg' assumption, in discussions with Bohr, that particles take single definite paths despite these paths being unknown to experimenters [17, 22].

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