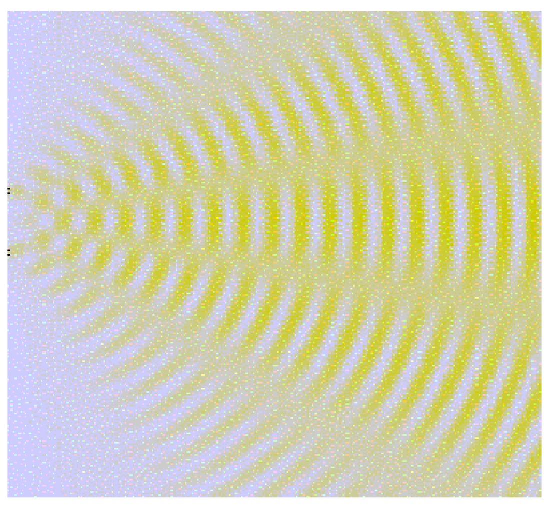

Updating the wave-particle duality

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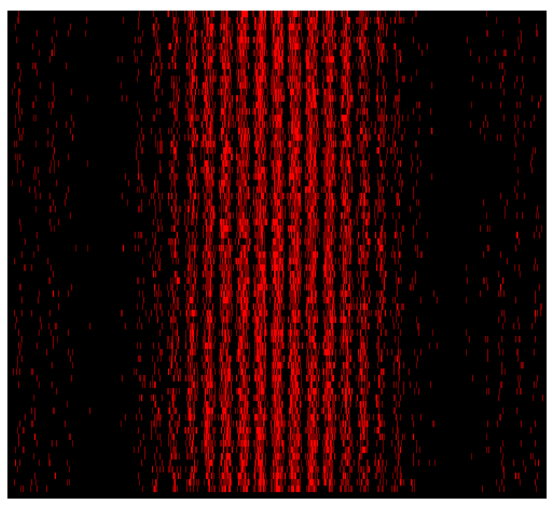


Introduction

The wave-particle-duality, the fundamental component of the new quantum formalism in Bohr's opinion, must be reformulated in order to incorporate the results of some experiments accomplished in the last decades of twentieth century.

The Bohr's *complementarity principle* stated the mutual exclusiveness and joint full completeness of the two (classical) descriptions of quantum systems; after Einstein-Podolsky-Rosen's paper, the *wave-particle duality*, or *wave-particle complementarity*, could be expressed by stating that it is impossible to build up an experimental arrangement in which we observe at the same time both corpuscular and wave aspects. In a two-slit experiment, they would correspond, respectively, to the which-way knowledge and the observation of an interference pattern. Bohr showed this mutual exclusivity in numerous examples[1], and linked it to the unavoidable disturbance inherent in any measurement event. In his opinion, the quantum mechanical indeterminism was a consequence of the wave-particle dualism, this is, of the *complementarity*, which was assumed as a fundamental principle rooted in an epistemological thesis: we do not have necessity of developing new concepts, as the account of experimental arrangements and the record of observations must always be expressed in common language supplemented with the terminology of classical physics [2].

Other authors, like Heisenberg, have pointed out that the use of classical concepts in quantum theory is ineludibly ambiguous, vague and unsystematic, and that the mathematical scheme give us the only way to achieve an unambiguous correlation with the experimental data[3]**.** Bloch was pleading for a *new language* since 1933[4], and Lévy-Leblond and Bunge, for instance, have proposed some neologisms (*quanton*,...).

In quantum mechanical formalism, the complementarity has a clear mathematical expression: two observables are complementary if precise knowledge of one of them implies that all possible outcomes of the other are equally probable; their extension to classical concepts (as wave and particle) is not concerned. In any case, the mathematical formalism of quantum mechanics does not establish the classical pictures as mutually incompatible.

Last findings and discussion

In 1991 Scully *et al* published[5] a variant of the two-slit experiment that incorporates two micromasers cavities and a laser beam to provide which-path information without net momentum transferred during the interaction[6]; the impossibility of knowing which slit an atom went through and still observe the interference fringes is preserved by the establishing of quantum correlations between the measuring apparatus and the system being observed. They claimed that *complementarity*, of which wave-particle duality would be a manifestation, is more fundamental than the *uncertainty principle*, but Busch *et al*[7] have stated that pretend to establish a hierarchy among uncertainty, complementarity and entaglement, all of them notions rooted in the linear structure of quantum mechanics and its non-conmmutative observables, is moot.

In 1996 B-G. Englert, following an approach originally due to Wooters and Zurek[8], derived[9], without making use of Heisenberg's uncertainty relation, an inequality that quantifies the mutual compatibility relation between fringe visibility and which-way information. The inequality, that they denominated as "interferometric duality", has the expression

$$D^2 + V^2 \leq 1 \ ,$$

where **D** stands for the distinguishability of the ways and **V** for the fringe visibility; both of them are mathematical expressions that can be measured to check experimentally the inequality[10]. The two extremes values in this expression would correspond to the Bohr's *wave-particle complementarity*, guarantied in the context of interference experiments in which an entaglement between the interfering states of the observed system and the states of the measuring apparatus happens[11]; the left values would correspond to intermediate particle-wave behaviours[12].

But there are interference experiments where the which-path information can be obtained without involving the mentioned entaglement, as the interference is not among the wavefunctions in the configuration space, allowing which-path precise knowing without affecting the observed interference pattern[13]. And, in addition to that, there are also other kinds of experiments in which both classical wave-like and particle-like behaviours are showed total and simultaneously on an individual system. For instance, in the Bose's double-prism experiment[14], tunnelling and perfect anticoincidence were observed in single photon states.

Conclusions and questions

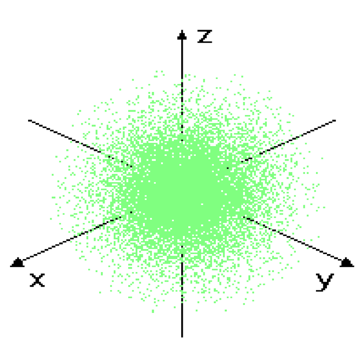
The *wave-particle duality* must be clearly formulated as an interpretative addition to quantum mechanics, to which it is possible to renounce if any pretension of visualize quantum phenomena in terms of classical concepts and intuitions is abandoned.

The meaning of the *wave-particle duality* must incorporate the simultaneous use of the two classical descriptions in the interpretation of experiments, loosing their original mutual exclusivity[15], which is incorporated as an extreme case in the new *interferometric duality*, a continuous quantum concept[16] that would possibly substitute it in the context of interference experiments where a description by using classical pictures is possible.

But there are interference quantum phenomena that can not be referred by using classical pictures and to which, consequently, the *interferometric duality* does not apply.

If we require *intuitive* understanding inside (orthodox) quantum mechanics:
a) In some experiments, classical pictures in term of particles and waves can help us, but the original Bohr's complementarity must be modified.
b) The classical descriptions must be developed only when the detection processes are completed, this is, for recorded phenomena (to avoid the *smoky dragon* of Wheeler).
c) In other experiments, including interference-type, this kind of (classical) *intuitive* understanding is not possible.

About non-classical *intuitive* understanding:
a) ¿Are non-classical forms of *intuition* possible? ¿Does make sense its very enunciation?
b) ¿What would be its connection to the classical?
c) ¿Can a mathematical formalism be prioritized on the natural language?



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