



Repositorio Institucional de la Universidad Autónoma de Madrid

<https://repositorio.uam.es>

Esta es la **versión de autor** del artículo publicado en:

This is an **author produced version** of a paper published in:

Nature Photonics 9 (2015): 76-77

DOI: <http://dx.doi.org/10.1038/nphoton.2014.325>

Copyright: © 2015 Nature Publishing Group

El acceso a la versión del editor puede requerir la suscripción del recurso

Access to the published version may require subscription

Thought experiments made real

Fernando Martín

For centuries, the question of the wave-particle duality of light has been the subject of intense debate. In 1672, Isaac Newton concluded that light was made of particles, or corpuscles as he used to call them. Only six years later, Christian Huygens proposed that light consisted of waves. Newton's point of view was widely accepted by the scientific community, mostly because of the high recognition of his many scientific contributions. This was so until 1803, when Thomas Young reported his famous double-slit experiment. Young used a point light source to illuminate a panel containing two narrow, parallel slits and found that the light passing through these slits and impinging on a screen exhibited interference patterns similar to those experienced by known waves. This observation was taken as the final proof that light was made of waves. This view held until 1923, when Arthur Compton showed that scattering of light could only be understood if one recovered the corpuscular nature of light. The subsequent birth of Quantum Mechanics settled down the controversy by establishing that not only photons but also any massive particle behaves both as a wave and a particle. As a consequence of this wave-particle duality, a coherent beam of particles passing through closely spaced slits should also lead to interference fringes similar to those observed in the original Young's experiment with photons.

Young's double-slit experiment with massive particles is nowadays viewed as the simplest demonstration of wave-particle duality. Interference patterns similar to those found by Young have been reported by using beams of electrons, neutrons, and even heavier particles like fullerenes moving through carefully designed slits. The challenge in these experiments is twofold: to ensure (i) that coherence of the particle beam is high enough and (ii) that the slits are close enough to each other, i.e., the distance between slits is comparable to the wavelength associated to the particle beam. Both conditions are necessary to ensure that the quantum particle is delocalized over a spatial region larger than the space between slits. The latter is a consequence of Heisenberg's uncertainty principle, which states that the precision with which the momentum and the position of a particle can be known are inversely proportional to each other.

The question of whether it is possible to determine through which slit the particle passes while preserving the interference patterns has been the object of passionate scientific and philosophical discussions and has been discussed in textbooks (e.g., Feynman's lectures in physics¹) to illustrate the weirdness of Quantum Mechanics. One of the most famous discussions involved Albert Einstein and Niels Böhr, when the former was challenging the complementarity principle of Quantum Mechanics, which states that complementary observables, as position and momentum, cannot be measured accurately at the same time². According to this principle, the determination of which slit the particle passes through inevitably destroys the wave aspects and implies the disappearance of the interference. Einstein disagreed with this point of view and argued that it would be possible to obtain detailed information on position and momentum by using the universally accepted laws of conservation of energy and momentum. To prove it, he suggested a "gedanken" experiment, the so called «Einstein-Böhr recoiling

double-slit gedanken experiment», in which one of the two slits in Young's experiment is allowed to move. Measuring the momentum transfer between the particle and the moving slit would allow one to identify which slit the particle passed through on its way to the screen. And this without destroying the interference pattern because, according to Einstein, determination of the direction of the recoil of the screen after the particle has passed through should not alter the successive development of the process. Unfortunately, the weight of a massive, macroscopic slit makes this kind of measurement impossible, which explains why the above two contradictory interpretations could never be checked on a real recoiling double-slit interference experiment. Writing in *Nature Photonics*, Xiao-Jing Liu and collaborators at the SOLEIL Synchrotron in France report the first experimental realization of the Einstein-Böhr "gedanken" experiment by using a molecular double slit³.

In the last decade, several experimental and theoretical works have shown that electrons escaping from diatomic molecules, as e.g. in ionization by ion impact⁴ or photoionization^{5,6}, experience interference effects that could be interpreted as those observed in typical double-slit experiments. This phenomenon, based on an early prediction by Howard Cohen and Ugo Fano⁷, is only possible when electrons are ejected simultaneously from both atomic centers, as in the case of emission from delocalized molecular orbitals, and their kinetic energy is such that their associated wavelength is comparable to the interatomic distance. This is illustrated in the top panel of figure 1. Elaborate first-principles theoretical calculations in combination with accurate vibrationally resolved photoelectron spectroscopy measurements have unambiguously shown that this is indeed the case for the simplest H_2 molecule and other diatomic molecules⁸. Evidence of similar interferences has been found in photoionization of more complex molecules⁹ and in photo double ionization of the H_2 molecule¹⁰. As molecular double slits are extremely light in comparison with macroscopic slits, this earlier work showed that measuring the particle-slit momentum transfer was no longer out of reach, thus paving the way for an experimental realization of Einstein-Böhr "gedanken" experiment.

The recoiling double slit that Xiao-Jing Liu et al. have used is molecular oxygen, O_2 , in which each oxygen atom plays the role of a slit. In their experiment, the neutral molecule is excited with soft x-ray synchrotron radiation into a repulsive electronic state that ultimately leads to dissociation of the molecule. In its way towards dissociation, the electronically excited O_2 molecule can decay to the various electronic states of O_2^+ by ejection of an outer electron and the filling of the hole by a valence electron (Auger decay). By using state-of-the-art electron-ion coincidence techniques, which allow one to determine the full momentum of all charged particles produced in individual photo-excitation events, the momentum exchange between the emitted (Auger) electron and the molecular or the atomic ions has been measured. Since the Auger electron is ejected in the field of the two nuclei, double slit interference effects are thus possible.

By measuring the recoil momentum of the molecular or atomic ions, the two scenarios represented in figure 1 have been reproduced. In the first one (top panel), the Auger electron is ejected soon after the excitation, i.e., before the molecule has had time to start dissociating. In this case, the recoil momentum is

imprinted on both atoms (equivalent to having coupled slits), thus preventing one to determine from which atom the electron was ejected. As a consequence, the measured Auger-electron spectrum exhibits the usual double slit interferences. In the second scenario (bottom panel), the Auger electron is ejected later, when the molecule has begun to dissociate, and transfers the recoil momentum to only one of the two oxygen atoms (equivalent to having independently moving slits). The key point is that, in electron-ion coincidence experiments as this one, the momentum transfer to the atom moving in the direction of the ejected electron is different from that to the atom moving in the opposite direction, as a consequence of the opposite Doppler shifts. It is precisely the measurement of this asymmetry in momentum transfer what allows one to provide which-way information on the process, i.e., to determine which slit the electron passed through, as envisioned by Einstein and Böhr. In this second scenario, the experimental results of Xiao-Jing Liu et al. show that the Auger-electron spectra do not exhibit any trace of the interference pattern, as predicted by quantum mechanics and against Einstein's expectations.

Apart from being the first realization in a laboratory of the famous "gedanken" experiment proposed in the early days of quantum mechanics, the work of Xiao-Jing Liu et al. paves the way towards a better understanding of the quantum world and eventually to control it. For example, by recording the emission of the Auger electron as a function of the momentum transferred to the atomic fragments, which depends on the internuclear distance at which Auger decay occurs, one could study the transition from a fully coherent regime to a fully incoherent one, and shed light on how to design strategies to favor one over the other. In this respect, the use of the Doppler effect as a maker for path identification seems a very promising idea that should be further exploited in the future.

Finally, it is worth stressing an aspect that concerns all molecular double-slit experiments but is absent in the macroscopic world: the quantum nature of the slits. Although the atomic nuclei are much heavier than the ejected electron and, therefore, behave more "classically", strictly speaking the slit separation when the Auger decay takes place cannot be known with absolute precision. However, the interference pattern survives when the decay occurs before the molecule starts to dissociate. In other words, the non locality of the momentum transfer from the ejected electron to the remaining molecular ion does not destroy the coherence between paths. Further experimental and theoretical work would be desirable in order to understand this peculiarity of molecular double slits.

Fernando Martín is at the Departamento de Química and Condensed Matter Physics Center of Universidad Autónoma de Madrid, 28049 Madrid, Spain, and the Instituto Madrileño de Estudios Avanzados en Nanociencia, Ciudad Universitaria de Cantoblanco, 28049 Madrid, Spain.

email: fernando.martin@uam.es

References

- [1] Feynman, R. P., Leighton R. B. & Sands, M., in “*Feynman Lectures on Physics, vol. 3: Quantum Mechanics*”. Basic Books. New Millenium Edition. 2011.
- [2] Böhr, N., in “*Quantum Theory and Measurement*”. Eds. Wheeler, J. A. & Zurek, W. H., p. 9–49 (Princeton Univ. Press, 1983).
- [3] Liu, X.-J. et al. *Nature Photonics*, this issue.
- [4] Stolterfoht, N. et al. *Phys. Rev. Lett.* 87, 023201(2001).
- [5] Rolles, D. et al. *Nature* 437, 711–715 (2005).
- [6] Fernández J., Fojón O., Palacios A. & Martín F. *Phys. Rev. Lett.* 98, 043005 (2007)
- [7] Cohen, H. D. & Fano, U. *Phys. Rev.* 150, 30–33 (1966).
- [8] Canton, S. E. et al. *Proc. Natl. Acad. Sci. USA* 108, 7302–7306 (2011).
- [9] Argenti, L. et al. *New J. Phys.* 14, 033012 (2012).
- [10] Akoury D. et al. *Science* 318, 949–952 (2007).

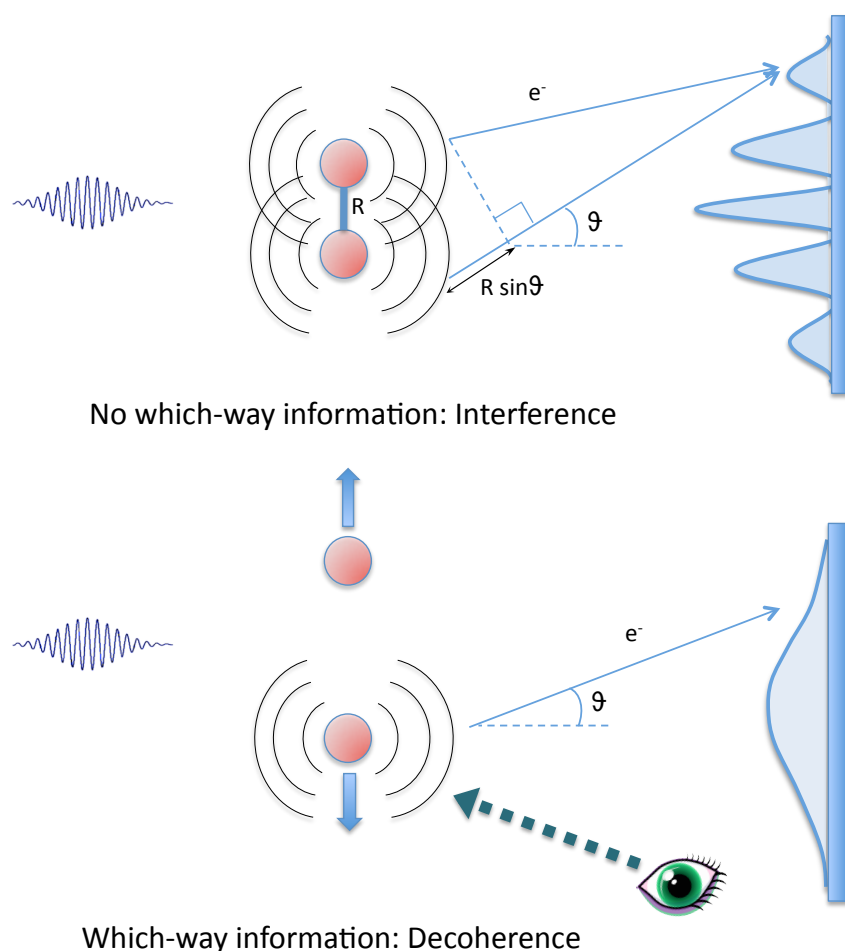


FIGURE 1. Top panel: Molecular version of Young's double-slit experiment. A pulse of light (left) impinges on a diatomic molecule, leading to coherent electron ejection (e^-) from the two atomic centers (the "two slits", red circles) in the form of waves (black lines). These waves reach a screen (right) where the intensity of the electron signal is recorded. Constructive interferences between electron waves generated by the two atomic centers are obtained at observation angles θ satisfying $n \lambda = 2 R \sin \theta$, where R is the internuclear distance, λ is the electron wavelength, and n is an integer number. No information about the path followed by the electron can be obtained from this experiment. **Bottom panel: Molecular version of Einstein-Böhr gedanken experiment.** Same as above, except that, in this case, the two atomic centers separate in opposite directions (thick vertical arrows) as a result of dissociation. An observer (green eye) measures the momentum of the atomic fragment from which the electron wave is emitted. As a result of this measurement, which provides information about the path followed by the electron, interference patterns are no longer observed in the screen.