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# Experiment to test the incompleteness of quantum mechanics

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## Abstract

For almost 100 years, the incompleteness of quantum formalism and the probabilistic nature of measurement have been debated without any experiment being able to settle these questions. There exist contingent quantum interpretations that share the same mathematical formalism but have contradictory world views.

In double-slit interference experiments, standard quantum theory does not take particle size into account, which is not the case in de Broglie's double solution theory. We use the large size of Rydberg atoms to propose an experiment to test the incompleteness of the standard quantum formalism.

We present an interference experiment with asymmetric slits, a large slit that allows Rydberg atoms to pass through and a grating of small slits that do not. We show with numerical simulations that the transmission densities in the standard interpretation and in the double solution interpretation give very different results (one peak instead of two). Experimental implementation now seems possible and would be a crucial test between these two interpretations.

## Introduction

Since the late 1920s, the question of the completeness of quantum mechanics has divided its founding fathers [1]. The debates between Albert Einstein and Niels Bohr is certainly the most emblematic, and only ended with the death of both protagonists [2, 3, 4]. For Einstein, the indeterminacy of measurements stemmed from the lack of a "reality element" in quantum formalism, that would explain the statistical phenomenon of Born's rule and Heisenberg's inequalities; for him, Schrödinger's equation was merely a statistical vision of reality [5]. On the contrary, according to Bohr, the indeterminacy of measurements is fundamental and it would be futile, even absurd, to try to complete this formalism.

Einstein in no way disputed the predictions of the quantum formalism: the controversy concerned the interpretation of this formalism. Louis de Broglie proposed [6] in 1926 to complete the formalism by adding a second wave to the usual *statistical wave*. This second wave,  $u$ , which he calls the *matter wave* or *physical wave*, corresponds to the mass density of the extended corpuscle, its size is finite and its center of gravity  $X(t)$  is guided by the statistical wave. This theory, known as the *double solution theory* [7, 8, 9, 10, 11] is an ingenious way of completing the formalism, making it causal, without contradicting experimental measurements<sup>1</sup>. If we reduce the physical wave to its center of gravity  $X(t)$ , we obtain the *pilot wave theory*, presented by de Broglie, at the Solvay Congress in 1927, which for him was only a second-best solution. His work on the pilot wave was continued from 1951 onwards, notably by David Bohm [12], under the name de Broglie-Bohm (dBB) theory.

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<sup>1</sup>It should be specified that Schrödinger's statistical wave was usually referred to in the 20th century as the de Broglie matter wave. However, for de Broglie, the matter wave that he defined in 1926 is not the statistical wave but the  $u$ -wave corresponding to the spatial extension of the particle that concentrates its mass. The statistical wave was called the *pilot wave* by de Broglie in 1927. In the remainder of this article, we prefer to use the term *physical wave* (or *internal wave*) rather than *matter wave* to avoid confusion.

One of the most important historical moments in the debate on the completeness of quantum formalism was the EPR article of 1935 [13], which proposed a thought experiment by Einstein, Podolsky and Rosen to settle the question. Many years later, in the 1980s, Alain Aspect's team carried out modified EPR-type experiments that did not settle the question of completeness, but clearly demonstrated the non-locality of quantum entanglement [14]. These experiments, for which Aspect was awarded the Nobel Prize in 2022, launched what is now known as the second quantum revolution [15].

It should be noted that dBB theory and double solution theory are in complete agreement with the violation of Bell's inequalities, and they also make non-locality very explicit in their formalism. The non-local hidden variable that allows Bell's inequalities to be violated is the entangled statistical wave function of the two particles [16]. The problem of completeness therefore remains unresolved. Proponents of the Bohmian approach rightly argue that their approach is valid because it reproduces the same experimental results as standard theory [17]. Its opponents, on the other hand, see the fact that it provides no new results as a weakness: dBB's theory would be useless, even metaphysical, because it provides no new elements. It would be a debate of opinions or interpretations of two contingent theories [18, 19].

The aim of this article is to show that there is now a feasible thought experiment that can be used to decide between the two points of view, or at least to deepen our understanding of the problem. This experiment moves the debate from the realm of epistemology to that of physics, since it can be resolved by experiment.

It is a variant of the two-slit experiment carried out with sodium Rydberg atoms, in which one of the two slits is replaced by a grating of slits small enough not to let through the Rydberg atoms, but only the sodium ions. The interference patterns would be different depending on the interpretation considered.

## Proposed experiment: Interference of Rydberg atoms through a large slit and a grating of little slits.

The proposed experiment corresponds to the interference of a beam of Rydberg atoms through slits of different sizes (a large slit A and a grating B of small slits), cf. Fig 1.a.

The experiment is based on that of Serge Haroche and his team [20] who showed that the transmission of sodium atoms in a Rydberg state, through a grating of slits (of width  $2\mu m$ ) became zero when the principal quantum number  $n \geq 60$ . They showed that Rydberg atoms behave like 'hard spheres' of diameter  $d = ka_0n^2$ , with  $a_0 = 5.29 \times 10^{-11}m$  the Bohr radius and  $k = 9$  experimentally fixed. A Rydberg atom loses its valence electron when it comes into contact with the metallic edge of a slit and, in this case, we obtain a sodium  $Na^+$  ion after the slits <sup>2</sup>.

For our numerical simulations, we considered a wide slit A, with a width equal to  $l_A = 162\mu$ . The B grid has 100 slots of width  $l_B = 1.6\mu m$  and the distance between two small slots (centre to centre) is taken to be  $3.2\mu m$ . The other dimensions are given in Fig. 1.a.

The beam of Rydberg atoms corresponds to sodium atoms of mass  $m = 3.8 \times 10^{-29}kg$  with a velocity  $v_x = 150m/s$  along the  $(Ox)$  axis corresponding to a de Broglie wavelength  $\lambda_{dB} = 1.15 \times 10^{-10}m$ .

This experiment builds on an earlier proposal [21] that was similar but not very credible, as it involved using dBB trajectories corresponding to point particles to represent extended particles. This contradiction has been resolved by adopting the double solution instead of the dBB interpretation.

### Interference from unexcited sodium atoms

If the sodium atoms were unexcited, then they would pass through the small slits of B and we would obtain, 20cm after the slits, the interference figure (norm of the statistical wave function,  $|\psi(y)|^2$ ) with four peaks of Fig 1.b). This result is common to all interpretations of the quantum formalism.

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<sup>2</sup>Sodium ions can be deflected and not detected on the detection screen by adding a magnetic field after the slits.

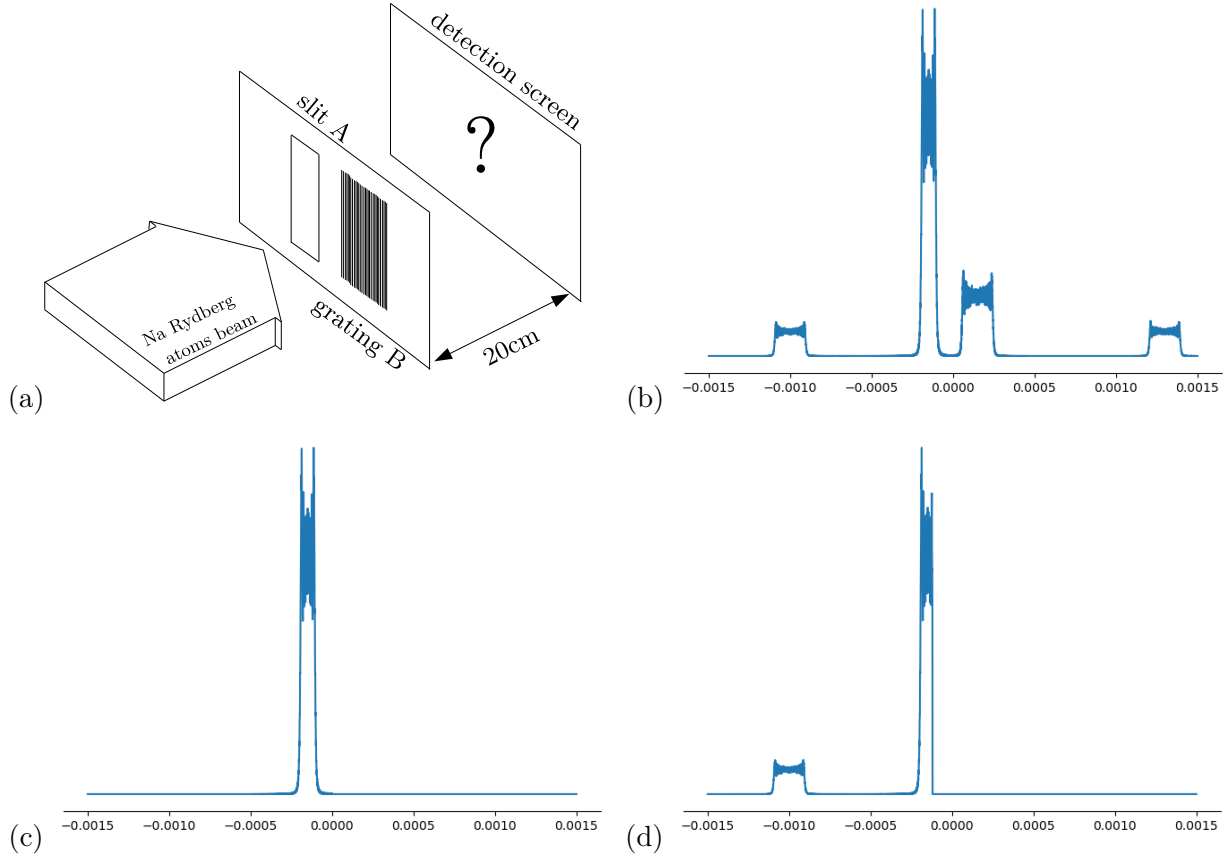


Figure 1: (a) Schematic drawing of the asymmetric slit experiment.

(b) The four peaks correspond to the norm of the statistical wave function (or external) of the unexcited sodium atoms on the detection screen.

(c) Single peak corresponding to the norm of the statistical wave function of the Rydberg atom beam on the detection screen in the standard interpretation.

(d) The two peaks corresponding to the norm of the statistical wave function of the Rydberg atom beam on the detection screen in the double solution theory.

Calculations of the time evolution of the  $\psi$  statistical wave are performed by numerically solving the time-dependent Schrödinger equation [22] using Feynman path integrals.

This statistical wave,  $\psi$ , initially emanating from the sodium source is large enough to pass through all the slits at the same time (the large one as well as the 100 small ones). After the slits, it recombines and forms interference. For the standard interpretation, this is the only existing wave, whereas for the double solution theory,  $\psi$  represents only the statistical or external wave, spreading out in space and able to divide into several parts. In this interpretation, a second wave exists at all times, the  $u$  physical wave (or internal wave). It represents the mass corpuscle, i.e. the atom's matter density. This wave is much more localised in space than the statistical wave, its size being of the order of the Bohr radius  $2a_0 \sim 10^{-10}m$  for a unexcited atom and  $ka_0n^2 \sim 10^{-6}m$  for a Rydberg atom ( $n = 60$  cf. Haroche experiment).

This physical wave does not spread out in space over time, unlike the statistical wave, and does not divide into several parts unless its nature changes (ionisation, chemical reaction, fission, fusion, etc.). Unlike the statistical wave, it can only pass through a single slit. The physical wave is measured by the measuring device when it hits the detection screen. The statistical wave is non-local and "drives" the center of gravity  $X(t)$  of the corpuscle, as in the dBB theory. It represents the hidden variable of the experiment, because it is never measured directly: it is the impacts that reveal it statistically. The  $u$  physical wave is local and has  $X(t)$  as its center of gravity.

## Standard interpretation

The standard interpretation considers only one wave function and therefore makes no distinction between the statistical wave function (or external wave) and the physical wave function (or internal wave). There is an identity between these two functions: if the wave function passes, the external and internal functions pass, and if the wave function does not pass, the internal and external wave functions do not pass. In this interpretation, the Rydberg atoms pass through the large slit A, and as Haroche's experiment shows, they do not pass through the slits in the B grating. In this case, the fact that the 100-slit grating exists or not does not change the results of the experiments. One can expect to have only one peak (Fig. 1.c) as if we were dealing with diffraction through the single slit A.

## Interpretation of the double solution

Consider Rydberg atoms emitted one by one. The  $\psi$  statistical wave of each atom passes through both the large A slit and the 100 small B grating slits. All the Rydberg atoms in a coherent source have the same statistical wave. However, according to the double solution theory, each atom's physical wave is different because it is located at a different position according to the initial  $|\psi(y)|^2$  distribution. Each physical wave follows a well-defined trajectory guided by the statistical wave. If the trajectory of the physical wave hits a slit in the B grating, it is *blocked* by the slit. Only the physical waves arriving at the wide slit A will pass through. The trajectory of the physical wave after the slits is guided by its statistical wave function, which is passed by the A slit and the 100 slits of the B grating. Its trajectory is therefore different from the one where there would only be slit A. The density obtained at 20cm from the slits has 2 peaks (Fig 1.d) and corresponds to that in Fig. 1.b truncated by half to the right.

There is therefore a significant difference between the numerical simulations of the histograms of the impacts of the Rydberg atoms according to the interpretations: a single peak for the standard interpretation (Fig 1.c) against two peaks for the double solution theory (Fig 1.d), these peaks also having well-defined positions. The main uncertainty on the experimental results should come from interactions with the edges of the slits, but this should only round off the shape of the two peaks.

Experimental implementation would therefore be possible as of yet, and would provide a crucial test between these two interpretations.

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