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Wheeler's delayed-choice gedanken experiment with a single atom

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The wave–particle dual nature of light and matter and the fact that the choice of measurement determines which one of these two seemingly incompatible behaviours we observe are examples of the counterintuitive features of quantum mechanics. They are illustrated by Wheeler's famous 'delayed-choice' experiment[1], recently demonstrated in a single-photon experiment[2]. Here, we use a single ultracold metastable helium atom in a Mach–Zehnder interferometer to create an atomic analogue of Wheeler's original proposal. Our experiment confirms Bohr's view that it does not make sense to ascribe the wave or particle behaviour to a massive particle before the measurement takes place[1]. This result is encouraging for current work towards entanglement and Bell's theorem tests in macroscopic systems of massive particles[3].

The question of whether light behaves like a particle or wave had a long and strongly contested history until the advent of quantum mechanics, where it was accepted that it could indeed exhibit either behaviour. Conversely, it was de Broglie's hypothesis of matter waves[4] that deviated from the preceding view of massive bodies exclusively as particles, which was confirmed by the electron diffraction experiments of Davisson and Germer[5]. Even more bizarrely, the way in which an experiment is performed seems to induce one of these behaviours to the exclusion of the other. The question of whether a single photon in an interferometer passes through either one arm (as a particle) or both simultaneously (as a wave) led to Wheeler devising his famous gedanken experiment, which supposed that the decision of whether to attempt to measure particle or wave behaviour is made after the photon enters the interferometer. By removing the second beamsplitter of the interferometer (Fig. 1a), which-way information is revealed[6], which precludes an interference measurement, while inserting the beamsplitter destroys information about the path taken by the photon and re-establishes a wave interference dependent on the phase difference ϕ between the arms.

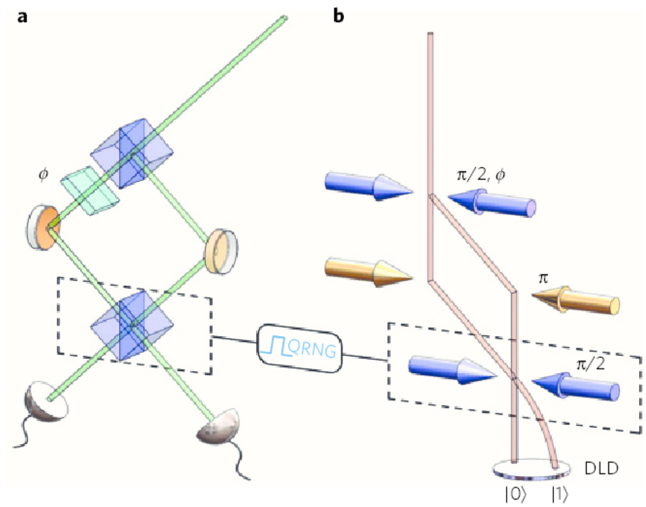

Figure 1 | Schematics of Wheeler's delayed-choice experiments. a, Optical version of Wheeler's delayed-choice experiment. **b**, Atomic version of Wheeler's experiment, where the physical beamsplitters and mirrors are now replaced with optical Bragg pulses. A quantum random number generator (QRNG) is used to decide whether the last beamsplitting pulse is either implemented or not. The random number is triggered and chosen after the π-pulse (mirror pulse), thereby ensuring that the atom has no prior knowledge of how it will be detected when it enters the interferometer.

Although many experiments have shown particle–wave duality with photons[7], including delayed-choice schemes[8–10], delayed-choice quantum eraser experiments[11] and entanglement swapping using delayed choice[12], only recently has the complete scheme proposed by Wheeler been realized experimentally[2]. By simultaneously ensuring that only a single photon is present in the interferometer at once, and that the decision of interferometer configuration is relativistically separated from the photon's entry to the interferometer, it was unambiguously shown that Wheeler's supposition that such a choice affects the 'past history' of the photon was correct.

Recent advances in the trapping and cooling of atoms has led to the ability to readily observe wavelike phenomena with particles that have mass, such as the interference between two Bose–Einstein condensates[13]. However, progress towards demonstrating Wheeler's experiment with massive particles, such as a delayed-choice Stern–Gerlach interferometer with metastable hydrogen[14] or a spin interferometer with neutrons[15], have been limited. Importantly, these experiments used beams containing more than one particle in the apparatus at any one time, rendering a meaningful test of Wheeler's ideas impossible, at least at the quantum level. Nonetheless, they demonstrate an advantage of using massive particles over photons, the relatively slow velocity (compared to light) of the atoms through the interferometer allows an increased time for making the delayed choice.

Here, we report the first realization of Wheelers famous delayed-choice gedanken experiment with single massive particles. The only successful demonstration of Wheeler's ideas so far has been achieved with single photons[2]. Here we use atoms, which is an important distinction, since atoms have many internal degrees of freedom. This allows coupling to the external environment through, for example, the atom's sensitivity to magnetic and electric fields. Moreover, an atom has significant mass, which allows strong coupling to gravitational fields. These interactions of the atom with its environment are required for the appearance of decoherence; thus, in this sense an atom can be thought of as a more classical particle than a photon. As such, our experiment tests Wheeler's ideas in a regime in which it has never been tested.

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