Delayed choices in atom Stern-Gerlach interferometry

B. J. Lawson-Daku, R. Asimov, O. Gorceix, Ch. Miniatura, J. Robert, and J. Baudon
Laboratoire de Physique des Lasers, CNRS URA 282, Université Paris–Nord, Avenue J. B. Clément, 93430-Villetaneuse, France
(Received 19 December 1995; revised manuscript received 1 May 1996)

Delayed-choice experiments have been performed using an atomic Stern-Gerlach interferometer operating with a low-intensity beam of metastable hydrogen atoms. By use of a fast-commutable analyzer, it is possible to modify the operating mode of the interferometer while the atom has already entered the device. Various types of delayed-choice experiments have been carried out to check the standard interpretation of quantum-mechanics. Within the experimental accuracy, our results do not show any discrepancy between permanent and delayed-choice operating modes of the interferometer. [S1050-2947(96)00712-3]

PACS number(s): 03.75.Dg, 03.65.−w

I. INTRODUCTION

In their paper on delayed-random-choice quantum-mechanical experiments [1], Alley, Jacubowicz, and Wickes mentioned the following sentence written by Niels Bohr [2]: ''[...] it obviously can make no difference as regards observable effects obtainable by a definite experimental arrangement, whether our plans of constructing or handling the instrument are fixed beforehand or whether we prefer to postpone the completion of our planning until a later moment when the particle is already on its way from one instrument to another.'' In this context Wheeler [3] and von Weizsäcker [4] asked whether the result of an interference experiment is modified if the observation of either the path followed by the photon or the interference pattern is decided after the photon has entered the interferometer, e.g., has passed the slits in a Young interferometer. So far some of the gedanken experiments proposed by Wheeler have been realized with photons, in space and time domains [5,6] or using a random-delayed choice [1]. In these experiments two-path interferometers are used (Mach-Zehnder interferometers) and the delayed decision concerns the second (recombining) beam splitter, which may or may not be activated, using a Pockels cell as a polarization rotator. When this second beam splitter is activated, after the photon has passed the first beam splitter, the two paths are indistinguishable and interferences are observed. By contrast, when the second beam splitter is not activated, the interferences disappear (test of the wave-particle duality). The general conclusion of all these experiments is that the so-called Copenhagen interpretation of quantum mechanics is valid.

One of the main difficulties in such experiments is obviously the high velocity of light that requires the use of short pulses and fast electronics at the nanosecond scale. Another difficulty is that one particle only should be present at any time in the interferometer. This implies not solely low flux (hence low signals) but also a special statistics of the photons such that the second-order correlation function at zero $g^{(2)}(0)$ should be as small as possible. This point is discussed in detail in Ref. [5], where different photon sources are compared: a low-pressure discharge lamp [$g^{(2)}(0)=2$], laser [$g^{(2)}(0)=1$], and resonant fluorescence light from a dilute atomic beam or from a single trapped ion [$g^{(2)}(0)=0$, i.e., antibunched photons [7,8]]. This is of particular importance in *random* choice experiments, such as that of Baldzuhn, Mohler, and Martienssen [9], which use photon pairs produced by parametric fluorescence: one of the photons serves as a trigger and the other one traverses a Mach-Zehnder ring interferometer.

To our knowledge no such delayed-choice experiment has been made up to now with neutrons (for which experiments have already been proposed by Zeilinger [10]) or atoms, in spite of the fact that various interferometric techniques have been developed in recent years [11]. Compared to photons, atoms (and neutrons) have the great advantage of their low velocity needing characteristic times in the microsecond range rather than in the nanosecond one. For low intensities the time delay between two successive atoms is a random variable distributed according to a Poisson law [12], as in the case of a laser beam. In the present paper, several delayed-choice experiments carried out using a Stern-Gerlach interferometer operating with a beam of metastable hydrogen atoms H* ($2s_{1/2}$) are reported. In the weak magnetic fields used here ($\lesssim$0.5 G), H* atoms behave as spin-1 particles, which gives three possible paths corresponding to the magnetic numbers $M_F=-1,0,+1$. This enables us to realize delayed-choices other than the simple observation, or lack thereof, of the interferences. Nevertheless, all these experiments are of the type of those proposed by Wheeler and are obviously in the context to which Niels Bohr's remark refers.

II. EXPERIMENT

A. General principle

The Stern-Gerlach interferometer is based upon the atomic spin polarization. Its optical counterpart (with two polarization states instead of three) is the interference produced by a birefringent crystal plate cut parallel to the optical axis [Fig. 1(a)]. A light beam, linearly polarized in direction $\hat{\mathbf{P}}$, traverses the plate whose polarization eigenvectors are $\hat{\mathbf{e}}_1$, $\hat{\mathbf{e}}_2$.

Each polarization component propagates through the plate at its own phase velocity, which finally produces two phase-shifted amplitudes on the two orthogonal states $\hat{\mathbf{e}}_1$, $\hat{\mathbf{e}}_2$. In order to observe the interference effect it is necessary to project the final polarization state onto the linear polarization $\hat{\mathbf{A}}$ of an analyzer. It is well known that the highest contrast is obtained when $\hat{\mathbf{P}}$ makes an angle of 45° with $\hat{\mathbf{e}}_1$ and $\hat{\mathbf{e}}_2$, $\hat{\mathbf{A}}$

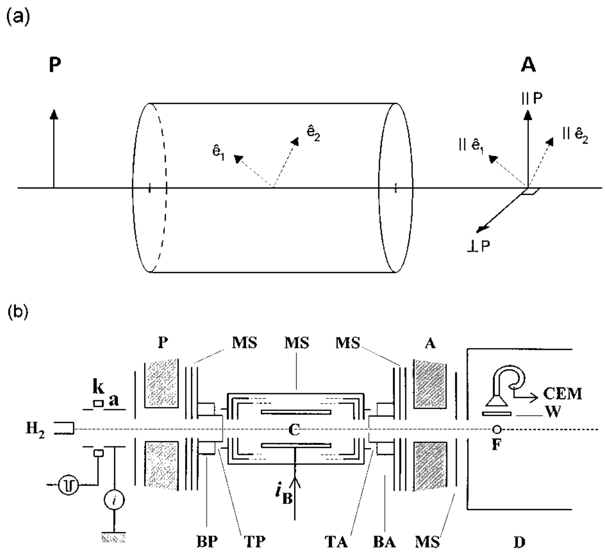

FIG. 1. (a) Optical interferences with a crystal plate. $\hat{\mathbf{P}}$, polarizer; $\hat{\mathbf{e}}_{1,2}$, polarization eigenvectors of the plate; $\hat{\mathbf{A}}$, analyzer. (b) Experimental setup: k_a, electron gun; P, polarizer; A, analyzer (P and A are two 600 G vertical magnetic fields); MS, magnetic shieldings; C, pair of coils producing the magnetic-field profile $\mathbf{B}(z)$ (phase object); D, detector; F, static electric field; W, MgF_2 window; CEM, channel electron multiplier. The additional coils BA and TA are shown in more detail in Fig. 2(a) (coils BP and TP are symmetrical to BA and TA, respectively).

being either parallel or perpendicular to $\hat{\mathbf{P}}$. It is also easy to see that by rotating $\hat{\mathbf{A}}$ after the photon has passed the plate, it is possible to decide whether one observes an interference pattern ($\hat{\mathbf{A}} \| \hat{\mathbf{P}}$), the complementary pattern ($\hat{\mathbf{A}} \perp \hat{\mathbf{P}}$), or no interference at all ($\hat{\mathbf{A}} \| \hat{\mathbf{e}}_{1,2}$).

B. Source and detector

The static realization of such a device for H* atoms [see Fig. 1(b)] has been already described elsewhere in detail [13]. The H* atoms are produced by a 120-eV electron bombardment of a thermal beam of H_2 molecules. The dominant part of the atomic velocity distribution is roughly Maxwellian and is centered around 10 km/s. Many species are produced by the electron bombardment, but the detector is specific of H* ($2s$) atoms. It consists of a static electric field localized within a 1-mm-wide region that induces the $2s$-$2p$ transition. The Lyman-α photon resulting from the subsequent $2p$-$1s$ transition is detected through a MgF_2 window by a channel electron multiplier. The overall detection efficiency is about 6%. The fact that only a relatively small fraction of the atoms are detected does not affect the interference patterns obtained in a single-atom mode.

C. Polarizer, analyzer, and phase object

The atoms are spin polarized by passing them through a transverse 600-G magnetic field (Lamb-Retherford method [14]). Once past the polarizer, the atomic beam consists of two equal and uncorrelated populations of metastable Zeeman levels $2s_{1/2}$, $F=1$, $M_F=+1$ and 0. This atomic beam is then partially polarized. In fact, however, as the hyperfine energy splitting between levels $2s_{1/2}$, $F=0$ (depopulated) and $2s_{1/2}$, $F=1$ is large enough to prevent any further repopulation of the former level, our partial polarization is similar, while complementary, to a total polarization of the $2s_{1/2}$, $F=1$, $M_F=-1$ level (up to a constant background).

The two pole pieces of the polarizing electromagnet are disymmetrized with respect to the longitudinal z axis (distances 3 and 5 mm). The polarizer is followed by a triple magnetic shielding consisting of two soft-iron foils and one μ-metal foil separated by 0.5-mm gaps, with 4-mm holes centered on the z axis. Under such conditions the fringe field behind the shielding is approximately *longitudinal* (parallel to the atomic velocity when the transverse 600-G field is directed upward), with a magnitude of 14 G at the center of the last diaphragm. Placed 8 mm downstream is a 10-cm-long cylindrical triple μ-metal shielding, within which the residual field (due to outer sources) is less than 2 mG. In addition, this shielding will contain a controlled low transverse magnetic-field profile $\mathbf{B}(z)$ (the phase object of the interferometer). Let us assume for a moment that it is empty. It is followed by another three-foil shielding and, 8 mm downstream, by a second electromagnet (the analyzer), these elements being exactly symmetrical to those of the entrance part.

In the evolution of the spin of an atom moving in an inhomogeneous static magnetic field, two parameters are of special importance: the local Larmor frequency ω_L (1.4 MHz/G) and the local angular velocity Ω of the field ''seen'' by the moving atom. Within the region extending from the polarizer to the entrance of the central cylindrical shielding, ω_L is everywhere larger than 6 MHz, whereas Ω is lower than 0.1 MHz. Under such conditions ($\omega_L \gg \Omega$) the projection of the spin along the *field direction* is constant (adiabatic evolution): any Zeeman state M_F prepared by the polarizer remains unchanged provided that it is referred to the local direction of the field. Alternatively, the field within the central shielding is so small that the spin rotation angle is at most 10°: it is now the spin direction referred to as the z axis that remains almost unchanged.

The interference patterns are obtained by scanning the magnitude of the transverse field profile $B(z)$ ($B\equiv 0$ corresponds to the central fringe). When $B \not\equiv 0$, at the entrance of the cylindrical shielding, the direction of the field rotates in space by an angle of 90° over a distance of 4 mm. As the field magnitude in this ''transition region'' is always less than 0.5 G, the ratio ω_L/Ω is less than 0.5%, which leads to a ''diabatic'' evolution: the incoming (longitudinal) spin state is abruptly projected onto the quantization axis $\hat{\mathbf{B}}$ of the phase object. This is equivalent, in the optical counterpart, to the diabatic passage from the basis set $\{\hat{\mathbf{P}}, \hat{\mathbf{P}}'\}$, where $\hat{\mathbf{P}}'$ is orthogonal to $\hat{\mathbf{P}}$, to $\{\hat{\mathbf{e}}_1, \hat{\mathbf{e}}_2\}$. A similar evolution is obtained at the output of the phase object. It is equivalent to the diabatic passage from $\{\hat{\mathbf{e}}_1, \hat{\mathbf{e}}_2\}$ to $\{\hat{\mathbf{A}}, \hat{\mathbf{A}}'\}$.

The phase shift φ between two consecutive Zeeman states that is accumulated along the profile $B(z)$ is given by [15]

$$\varphi = \frac{g\mu_B}{\hbar v} \int B(z)dz,$$

where g (=2) is the Landé factor, μ_B is the Bohr magneton, and v is the atom velocity. The integral is extended over the whole range of the profile $B(z)$. Three methods are used to obtain the interference patterns. (i) One uses the wide velocity distribution given by the source and scans the magnitude of B. As the phase shift is velocity dependent, a loss of contrast towards large interference orders is observed: only the central fringe and two lateral fringes are clearly visible. (ii) By pulsing the source, through the electron bombardment, it is possible to get the time-of-flight distribution (for a fixed value of the magnitude of B), on which a sine modulation due to the interference is observed (φ is proportional to the time of flight). (iii) Finally, by pulsing the source and gating the detector with a fixed delay, one makes a time-of-flight selection. A larger number of fringes are then visible in the interference pattern, according to the quality of this selection [13].

D. Fast commutation of the analyzer

The validity of the description given previously for the spin-state evolution through the interferometer has been verified experimentally, without any velocity selection, in the following way. When the polarizer and analyzer are parallel, a central *dark* fringe is observed. It is thus so because the Zeeman state $M_F=+1$, for example, prepared by the polarizer, is adiabatically transported as $M_F=+1$ along the fringe field of the polarizer (i.e., along the $+z$ axis); it then comes out of the phase object, encounters the fringe field of the analyzer (oriented along $-z$), and is finally transported adiabatically (as $M_F=-1$) into the analyzer, where it is quenched. On the contrary, when the polarizer and analyzer are antiparallel, the emerging state is $M_F=+1$ along the fringe field of the analyzer and it is allowed to reach the detector giving rise to a central *bright* fringe.

By adding to the fringe field of the analyzer a longitudinal magnetic field produced by a cylindrical coil (BA) (20 turns, 21 mm in diameter) [Fig. 2(a)] and using a parallel polarizer and analyzer, it is possible to transform the dark central fringe into a bright one by simply increasing the current in BA towards negative values, i.e., by reversing the longitudinal fringe field in front of the analyzer [Fig. 2(b)]. This effect provides us with a simple method to quickly commute the analyzer: A second cylindrical coil (TA) (15 turns), coaxial to BA and smaller in diameter (14 mm instead of 21 mm), is wound upon a copper tube that is longitudinally segmented to reduce the damping effect from eddy currents. A pulsed current of about 0.32 A in TA is able to reverse again the axial field, changing the bright central fringe into a dark one. The low value of the self-inductance (less than 0.5 μH) allows for rise times shorter than 0.1 μs.

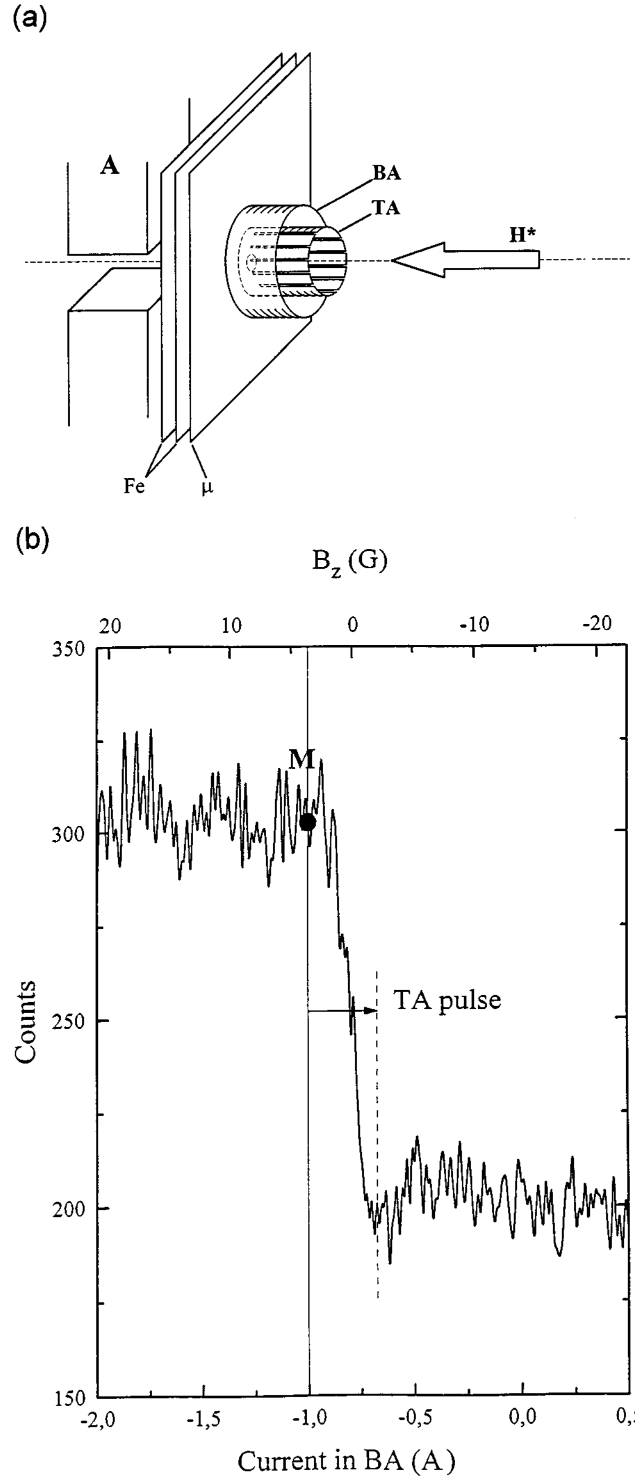

FIG. 2. (a) Magnetic shieldings and coils in front of the analyzer; a dc in coil BA is used to modify the longitudinal fringe field of the electromagnet; the coil TA has a similar effect, but it can be used with a pulsed current (its core is segmented in order to reduce the eddy currents). (b) Atomic signal as a function of the intensity in the coil BA; the interferometer is set on the central fringe ($B\equiv 0$ in the phase object); with both P and A fields directed upwards this fringe is dark. When a sufficiently negative dc is applied to BA, the fringe field of A, initially directed towards $-\hat{\mathbf{z}}$, is reversed and the central fringe becomes bright. Once the BA current is fixed at point M, a positive pulse of current (+0.32 A) applied to TA is able to change again the bright fringe into a dark one.

III. RESULTS AND DISCUSSION

Four different experiments have been carried out using a pulsed electron bombardment in the H* atom source (pulse duration $\delta t=1$ μs, repetition time $T=110$ μs). δt is small compared to the most probable time of flight (38.5 μs). In all these experiments the atom flux is very low (about 5 atoms/s or less); therefore the average time delay $\overline{\tau}$ between two successive atoms is very long compared to T ($\overline{\tau}\gtrsim 0.2$ s, which corresponds to a mean number of atoms present within the interferometer much smaller than one).

In experiment I, we have $B(z)\equiv 0$, which corresponds to the central fringe of the interference pattern. A time-of-flight

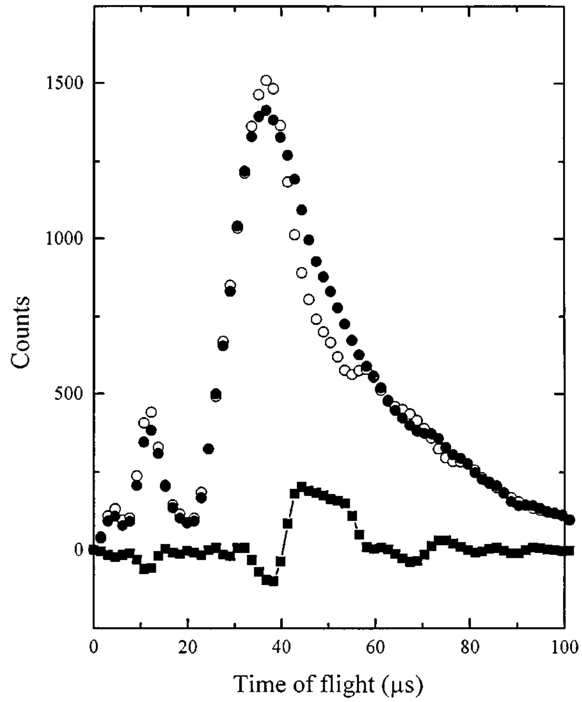

FIG. 3. Time-of-flight distributions obtained with a zero-magnetic field in the phase object. The analyzer operates under the conditions defined by point M in Fig. 2(a) (solid circles). When a positive pulse is applied to TA a dark fringe is obtained for all atoms that classically ''see'' this pulse (open circles). Solid squares denote the difference.

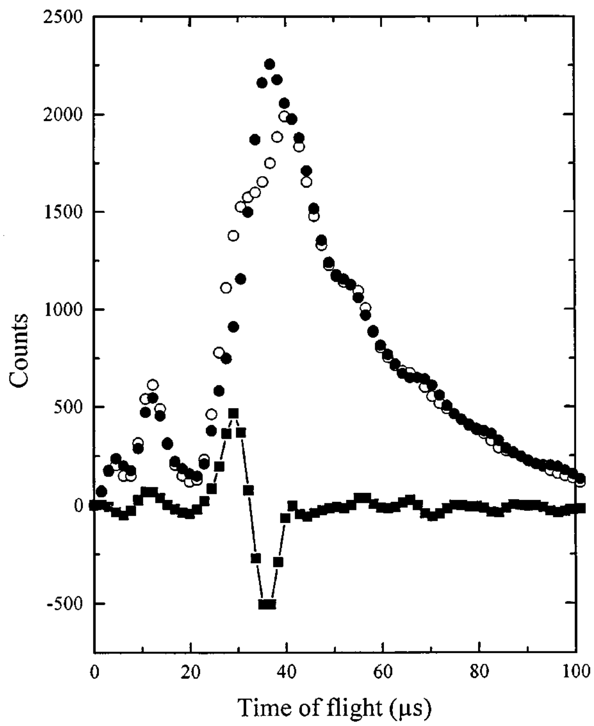

FIG. 4. Same as Fig. 3, but now the magnetic field in the phase object differs from zero (i_B=100 mA). Under static conditions of analysis (open circles) interference fringes modulate the time-of-flight curve. When the TA pulse is applied (solid circles) the fringes are reversed for all atoms that classically see the pulse. Solid squares denote the difference.

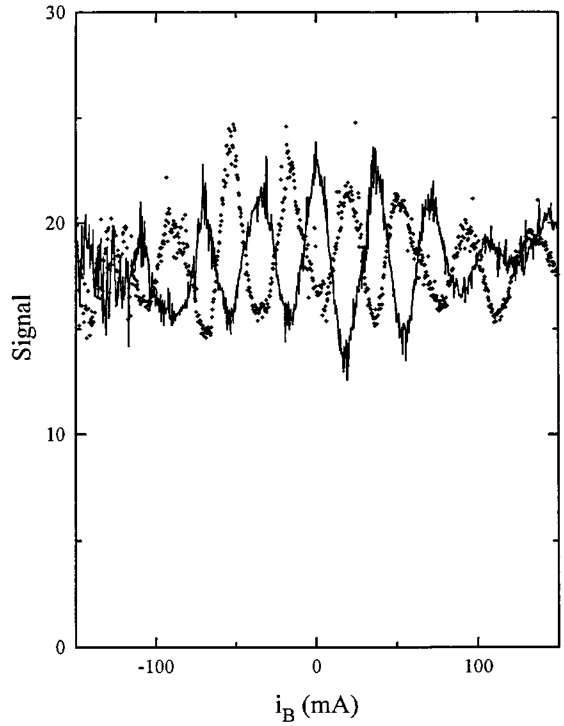

FIG. 5. Interference patterns obtained with velocity-selected atoms, by scanning the magnetic field in the phase object. Solid line, the analyzer is set at point M in Fig. 2(a) (central bright fringe); dots, a positive pulse is applied to TA within a time interval such that all selected atoms classically see it. The whole interference pattern is reversed.

distribution is measured under static conditions represented by point M in Fig. 2(b) (bright fringe for any velocity). Then a positive pulse of 0.32 A is applied to the coil TA, within the interval 30–40 μs (t=0 is the starting time of the source pulse). As is shown in Fig. 3, the delayed decision to have a central dark fringe affects only those atoms whose classical external motion experiences the TA pulse, i.e., atoms arriv-

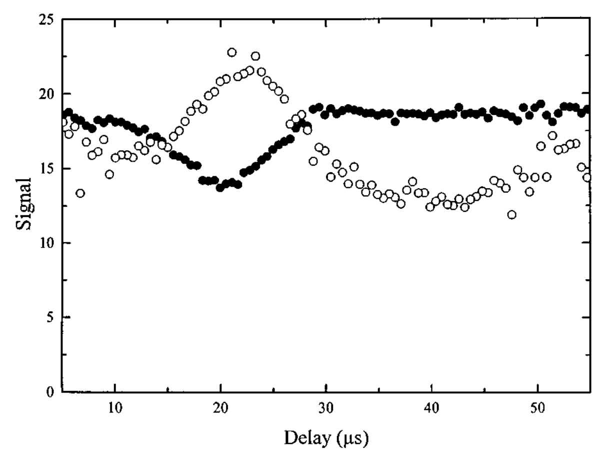

FIG. 6. Reversal of the central fringe when the delay between the starting time of the source and that of the TA pulse is scanned. Solid circles, i_B=0 (dark fringe with the TA pulse present); open circles, i_B=56 mA (bright fringe with the TA pulse present).

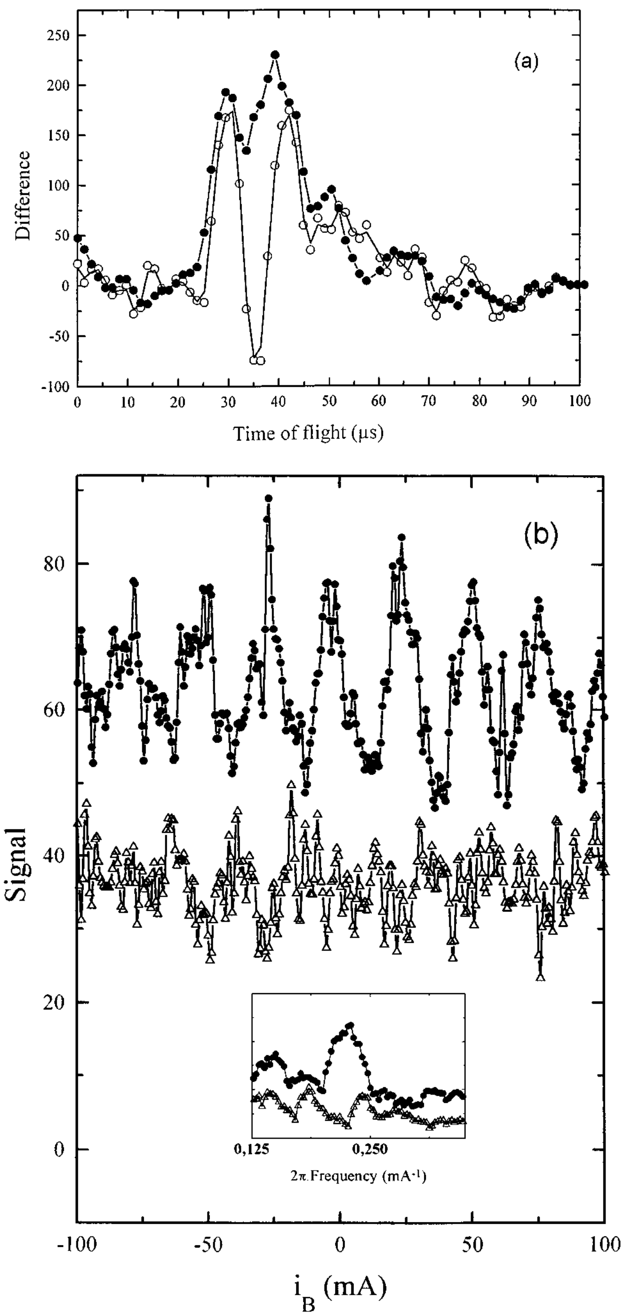

FIG. 7. (a) Same experiment as in Fig. 4, but now with a pulsed guiding field in the analyzer able to erase the interference (see the text). Open circles, difference between the TOF spectra obtained without and with a fixed magnetic field in the phase object (i_B=100 mA); solid circles, same difference when the pulsed guiding field is present (pulse of 0.32 A and time interval 23–33 μs). (b) Same experiment as in Fig. 5, but now with the pulsed guiding field present in the analyzer. Full line and solid circles: interference pattern with no pulse; open triangles, the pulse (0.32 A, 23–33 μs) is present. For clarity this latter signal is shifted by -20. The inset shows the Fourier transforms of both patterns (same symbols).

ing on the detector at times ranging from 41.5 to 56 μs.

In experiment II, a dc of i_B=100 mA is applied to the phase object [$B(z)\neq 0$]. As the phase shift is proportional to the time of flight (TOF), the TOF distribution exhibits an oscillation that is another form of the interference pattern. When the TA pulse is applied between 23 and 33 μs, it is observed (Fig. 4) that the fringes are reversed, again for those atoms classically ''able'' to experience the change of the analyzer caused by this pulse (arrival times within the interval 25–41.5 μs), i.e., those atoms that are subjected to our delayed decision.

In experiment III, a time-of-flight selection is made by gating the detector within the time interval 36–41 μs, centered at the most probable time of flight. Now the magnitude of $B(z)$ is varied by scanning the dc i_B over the interval [-150 mA, $+150$ mA]. The first interference pattern is obtained using the same static analysis parameters as in experiments I and II [point M in Fig. 2(b)]. As expected, a bright central fringe appears and a rather large number of fringes (8 in the present i_B range) are visible as the velocity selection ($\delta v/v\simeq 13\%$) yields a 175 pm coherence length for a mean de Broglie wavelength of 38 pm. When the coil TA is pulsed within a time interval (23–33 μs), all selected atoms classically experience the changed magnetic field of the analyzer and the pattern is reversed (Fig. 5).

One may think of artificially antibunching the atom beam by use of a selection of the time interval τ between successive atoms [12], by rejecting all pairs of atoms such that τ is smaller than the time of flight [16]. Unfortunately, this makes sense only if the detection efficiency is close to one. Actually, with the present efficiency of about 6%, only a few detected events are selected, which provides almost no information about the undetected atoms within the apparatus.

In a second experiment, the delay between the starting time of the source pulse and that of the TA pulse is scanned from 5 up to 55 μs, the pulse duration being a constant (10 μs). The velocity selection is the same as that used in experiment III. Two fixed values of the current i_B in the phase object (i_B=0 and 56 mA) are used, giving, respectively, a dark or a bright fringe for the atoms that classically experience the TA pulse and reversed fringes for the atoms that completely miss the TA pulse (solid circles and open circles in Fig. 6).

Experiment IV is a delayed-choice version of the standard complementarity or duality test. As explained in Sec. II, the principle of such an experiment is to commute the analyzer from a position giving an interference to another position, letting only one amplitude pass, i.e., in the present case only one M_F state referring to the quantization axis in the phase object; in this latter case one way is selected and the interference disappears. In the present device the buildup of the final linear superposition takes place in a region located between the magnetic shielding of the phase object and the fringe field of the analyzer. A guiding field, parallel to the transverse field in the phase object, is created, by two parallel wires in this transition region. This field is sufficiently large in magnitude and range to give an adiabatic connection from the phase-object field to the fringe field and then to the 600-G field of the analyzer, giving rise finally to a single outgoing amplitude. This interference eraser can be switched on and off as fast as the coil TA described above and can be used in a similar manner in delayed-choice experiments. Figure 7(a) shows the result of such an experiment carried out using a time-of-flight measurement (cf. experiment II). Within the classical arrival-time interval of atoms able to experience the pulse (0.32 A during the time interval 23–33

μs) applied to the parallel wires, the interference fringes are erased. Similarly, when a velocity selection identical to that of experiment III is made, all selected atoms (classically) experience the pulse, which leads to an almost complete cancellation of the whole interference pattern [see Fig. 7(b)].

IV. CONCLUSION

Within our experimental accuracy, we have shown that the statement made by Niels Bohr as it is quoted in the Introduction is fully reliable (as it is with photon beams, as shown previously by other authors) with atom beams, in a regime such that one particle is present at a time within the whole experimental device. It has been shown that the present setup enables us to manipulate the analyzer after the atom has passed the first beam splitter in order to get either a reversal or a cancellation of the interference pattern, depending on (i) the direction of the analyzing magnetic axis (respectively perpendicular or parallel to the field in the phase object) and (ii) the exact time at which the manipulation takes place. To gain constructive insight into the present results, one may consider that the state of the system is fully determined if both the dynamical evolution, given by the (local) Schrödinger equation, *and* the boundary conditions are known, the chronology in the Schrödinger operator being essentially governed by the group velocity, i.e., by the velocity of the particle, at least in all experiments realized so far. This is reminiscent of the Cauchy problem.

ACKNOWLEDGMENTS

B.J.L.-D. thanks the Association Louis de Broglie d'Aide à la Recherche for providing him with a Nicolas-Claude Fabri de Peiresc grant. R. A. thanks the Centre Régional des Oeuvres Universitaires for providing him with a grant from the French Government (No. 94/4290). Thanks are due to B. G. Englert and G. Lochak for enlightening discussions about fundamental concepts in Quantum Mechanics. We are very grateful to W. Schleich, who suggested to us to use the delay-time selection to produce an antibunched atom beam (in spite of the fact that our poor detection efficiency makes this good idea unpracticable in our experiment).

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