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Abstract

In this paper, we present a brief overview of atom interferometry. This field of research has developed very rapidly since 1991. Atom and light wave interferometers present some similarities but there are very important differences in the tools used to manipulate these two types of waves. Moreover, the sensitivity of atomic waves and light waves to their environment is very different. Atom interferometry has already been used for a large variety of studies: measurements of atomic properties and of inertial effects (accelerations and rotations), new access to some fundamental constants, observation of quantum decoherence, etc. We review the techniques used for a coherent manipulation of atomic waves and the main applications of atom interferometers.

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I. INTRODUCTION

Several atom interferometers [1, 2, 3, 4] gave their first signals in 1991 and atom interferometry has developed very rapidly since. Some review papers have already appeared [5, 6] and the book "Atom interferometry" edited by Berman [7] in 1997 represents an excellent introduction to this field. The present paper gives an overview of atom interferometry. After a comparison of atomic and light waves, we describe the sources of atomic waves and the tools used for their coherent manipulation. We then present the main types of interferometers and their applications. The non-linear effects due to atom-atom interactions (recently reviewed by Bongs and Sengstock [8]) are not discussed here.

II. MAIN NEW FEATURES OF ATOM INTERFEROMETRY

The main differences between light waves and atomic waves are their dispersion relations and their group velocities. As we neglect here atom-atom interactions in the atomic wave, we may consider only single-atom plane waves described by a ket $|\mathbf{k}, i\rangle$, where $\mathbf{k}$ is the wave vector and i is the atom internal state which replaces the polarization vector ε of a light wave. The total energy $E_{tot} = \hbar\omega$ of such a state is the sum of the internal energy E_i (including the rest mass energy mc^2) and the kinetic energy given, in the non-relativistic limit, by $E_{kin} = \hbar^2\mathbf{k}^2/(2m)$:

$$\hbar\omega = E_i + \hbar^2 \frac{\mathbf{k}^2}{2m} \tag{1}$$

from which we get the group velocity equal to the classical velocity $\mathbf{v}$:

$$\partial\omega/\partial\mathbf{k} = \hbar\mathbf{k}/m = \mathbf{v} \tag{2}$$

The dependence of the group velocity on k induces the well-known wave packet spreading: vacuum is dispersive for matter waves while it is not for light. From a practical point of view, a very important quantity is the de Broglie wavelength given by:

$$\lambda_{dB} = \frac{2\pi}{k} = \frac{h}{mv} \approx \frac{4 \times 10^{-7}}{Av} \text{ meter} \tag{3}$$

where A is the mass number and v is the velocity in meters per second. For thermal atoms or molecules with $v \sim 10^3$ m/s, the de Broglie wavelength is $\lambda_{dB} \sim (0.4/A)$ nanometers. For cold and ultra-cold atoms, with velocities in the millimeter/second to meter/second range, the de Broglie wavelength may be comparable to 1 micrometer or even larger.

Finally, the sensitivity of atomic waves to inertial effects is considerably larger than the one of light waves and this is a consequence of their considerably smaller group velocity: during the time spent by an atom inside an interferometer, a rotation or an acceleration changes the lengths of the interfering paths, thus inducing a phase shift of the interference signals.

III. MAIN TOOLS OF ATOM INTERFEROMETRY

A. Sources of atomic waves and detectors

The simplest source is a thermal atomic beam, either effusive or supersonic, this last type providing a narrower velocity distribution and, in both cases, the flux at the interferometer output is very small. Very efficient detectors are needed and most experiments with thermal atoms have been done either with alkali or with metastable atoms which can be very efficiently detected using surface ionization.

Cold atoms give access to very long interaction times, which improves the ultimate resolution of a measurement. Therefore, many experiments use laser-cooled gases with the following scheme: an atomic trap is first loaded; after a final cooling step and optical pumping in a particular sub-level, the gas cloud is accelerated by laser beams and sent into the interferometer. The usual detection technique is then based on laser fluorescence, which allows the selective measurement of the populations of the ground state hyperfine levels. In most cases, the interference signal is to be found in the repartition of the population among these hyperfine levels. The possibility of measuring on each atomic cloud the populations of two hyperfine levels reduces the noise, down to the quantum projection limit [9, 10], well below the fluctuations from shot to shot.

Degenerate quantum gases, Bose Einstein condensate (BEC) or Fermi degenerate gases, can be used as sources for atom interferometers and the atom-laser beams extracted from BEC are analogous to laser beams in optics. For the high densities achieved in BEC, the atom-atom interactions are not negligible and, at the present state of the art, these sources are especially interesting for non-linear atom optics (as reviewed by [8]). Only some experiments, in which these non-linear aspects are weak, will be discussed here.

B. Coherent manipulation of atomic waves

1. Diffraction by material structures

Diffraction of atoms by crystal surfaces, first observed by Stern and Estermann in 1929-1930 [11, 12], is used nowadays to study surface order and surface excitations. This diffraction process has not been used for an atom interferometer, because of the extreme requirements on surface quality and positioning.

Diffraction by material slits is obviously possible and a Young's double slit experiment was realized by Carnal and Mlynek [1] in 1991.

Diffraction by a grating made of nanowires is also possible and high quality gratings with periods down to 100 nm can be made by nanolithography techniques [13, 14] with areas close to 1 mm^2. These gratings can diffract any atom, molecule or cluster [15]. Schöllkopf and Toennies [16] have used diffraction of a supersonic beam as a mass selection process for weakly bound helium clusters.

As discussed below, the atom-surface van der Waals interaction cannot be neglected. The use of gratings and nanostructures with cold atoms is not common, probably because of the strength of the atom-grating van der Waals interaction. However, Shimizu and co-workers have developed atom holograms in transmission [17, 18] and also in reflection [19], using the quantum reflection regime.

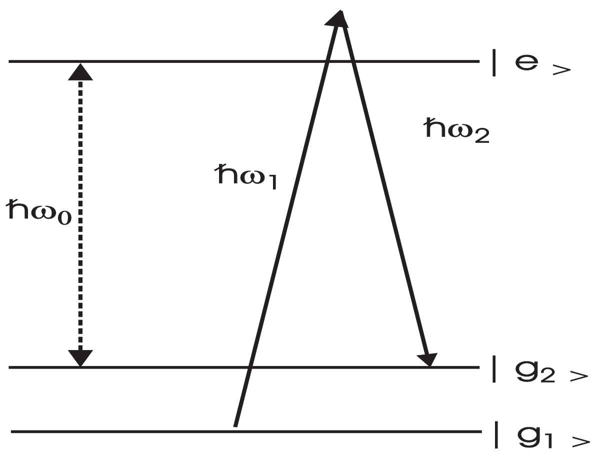

FIG. 1: Principle of atom diffraction by laser using a Raman process: the atom absorbs a photon of energy $\hbar\omega_1$ and emits a photon of energy $\hbar\omega_2$ by stimulated emission, thus making a transition from state $|g_1\rangle$ to state $|g_2\rangle$. The case of elastic diffraction is deduced from the Raman case by making $|g_1\rangle = |g_2\rangle$ and $\hbar\omega_1 = \hbar\omega_2$. In this last case, diffraction of order p can be observed, as the absorption-stimulated emission cycle may occur p times.

2. Diffraction by a laser standing wave

In 1933, Kapitza and Dirac [20] proposed to diffract an electron beam by a standing light wave, in order to prove the existence of stimulated emission of radiation but this experiment was feasible only with lasers [21]. In 1966, Altshuler et al. [22] extended this idea to the diffraction of atoms: the diffraction probability was predicted to be considerably larger, especially if the laser frequency is close to a resonance transition.

During a diffraction process (see Fig. 1), the atom absorbs a photon $|\omega, \mathbf{k}\rangle$ going in one direction and makes a stimulated emission of a photon $|\omega, -\mathbf{k}\rangle$ going in the opposite direction. If the two photons have the same polarization, this process is fully elastic, i. e. the initial and final internal states are identical. Conservation of energy and momentum is exactly fulfilled in the Bragg geometry, as shown in Fig. 1 and 2. Usually, the laser standing wave has a finite spatial width (respectively a finite duration): the corresponding dispersion of the photon momentum around its mean value $\mathbf{k}$ (respectively of its frequency around its mean value ω) relaxes the conservation laws. In the simplest case, laser diffraction can be described as a coherent evolution of the atom among two states differing by their momentum and this process is therefore a Rabi oscillation.

A standing wave moving in the laboratory with a velocity v can be produced by using two counter-propagating laser beams with different frequencies (the velocity being proportional to the frequency difference). This possibility is widely used to characterize the momentum distribution of ultra-cold atoms [8, 23].

The calculation of the diffraction probability has been the subject of many works, corresponding to limiting cases, such as the Raman-Nath case (thin grating) [24] or the Bragg case (thick grating and weak potential) [25]. The various possible regimes are discussed in reference [26]. Bloch states, which have been introduced by Letokhov and Minogin [27] (see also [28]) to describe the motion of the atom in a standing wave provide an unified treatment of atom diffraction [29].

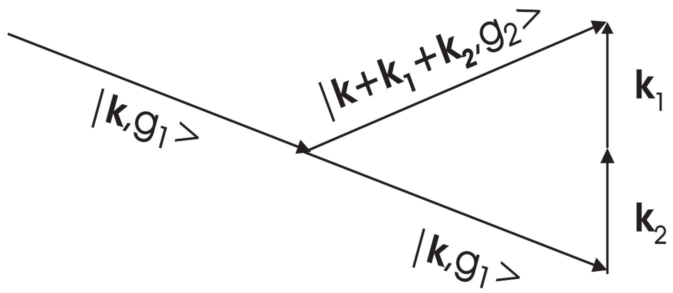

FIG. 2: Momentum conservation in atom diffraction by laser: the atom receives a momentum kick equal to $\hbar\mathbf{k}_1$ due to the absorption of a photon of energy $\hbar\omega_1$ going in one direction and a second kick equal to $\hbar\mathbf{k}_2$ in the same direction, due to the stimulated direction of a photon of energy $\hbar\omega_2$ going in the opposite direction. The conservation of the atom kinetic energy requires the Bragg geometry, as illustrated in this figure. As in Fig. 1, elastic diffraction is deduced from the Raman case by making $\hbar\mathbf{k}_1 = \hbar\mathbf{k}_2$.

The photon recoil effect was first observed in a saturated absorption spectroscopy experiment by Hall and Bordé [30] in 1976. Resolved diffraction peaks were observed [31] in 1983 and Bragg scattering [32] in 1988, both by Pritchard and co-workers. Siu Au Lee and co-workers [25] were able to observe Bragg diffraction up to the sixth order and to build an interferometer operating with any diffraction order p from $p = 1$ to 3 [33].

This diffraction process can be generalized to several cases as explained by Bordé [34, 35]. We will discuss here only the case of Raman diffraction (see Fig. 1 and 2). The atom has two ground state hyperfine sub-levels $|g_1\rangle$ and $|g_2\rangle$, with an energy splitting $\hbar\omega_{12}$. The laser standing wave is replaced by two counter-propagating waves of frequencies ω_1 and ω_2, with $\omega_1 - \omega_2 = \omega_{12}$. The diffraction corresponds to the absorption of a photon ω_1 and the stimulated emission of a photon ω_2, while the atom makes a Raman transition from state $|g_1\rangle$ to state $|g_2\rangle$. The main advantage of such an inelastic diffraction process is that the transmitted and diffracted beams differ by their internal states. It is therefore very easy to detect selectively the direct and diffracted beams, but this diffraction process is coherent only if the laser beat note $(\omega_1 - \omega_2)$ is phase-locked on a stable oscillator.

Finally, we have not discussed the limitations of this diffraction process. The laser frequencies are usually chosen close to resonance but not exactly at resonance, so that the probability of a spontaneous photon emission remains negligible. A different regime is based on adiabatic transfer and, then, the laser is exactly at resonance [36]. In this case, the transfer of a very large number of photon momenta has been demonstrated [37].

Diffraction by laser has a very important advantage with respect to diffraction by material gratings: the diffraction amplitude can be rapidly modulated as a function of time and this possibility is widely used to build temporal interferometers.

3. Mirrors, traps and microtraps

A repulsive potential can be used to build mirrors for atomic waves:

- the Earth gravitational potential reflects an atomic beam going upward, producing an atomic fountain.

- laser evanescent waves with a positive detuning $(\omega > \omega_0)$ have been used as mirrors

[38]. The atom feels the sum of the van der Waals attractive potential of the surface and the dipole repulsive potential due to the evanescent wave [39].

- periodic magnetic structures can produce a magnetic field which decreases exponentially far from the structure and such a field can be used as mirrors for cold atoms with a non vanishing magnetic moment. For slow atoms, the angular momentum projection M is quantized on the magnetic field direction and follows adiabatically the field, thus creating an attractive or repulsive potential. This idea [40, 41] has been demonstrated by several experiments [42, 43].

The coherence of the reflected wave depends on the mirror roughness. Several experiments [44, 45] have tested the roughness of atomic mirrors: it is possible but difficult to produce very coherent reflection.

Many atom traps (too numerous to be listed here) have been developed for the production of quantum degenerate gases: these traps rely either on magnetic forces or on the dipole potential in far off-resonance laser beams. In an excellent vacuum (near 10^{-10} mbar), the atom residence time in such a trap can be quite long, (of the order 100 s), limited either by collisions with the residual gas or, for a dense trapped gas, by dimer formation by 3-body collisions. The atom coherence time, which is more difficult to measure, is also sensitive to the fluctuations of the trapping potential position and depth.

Miniature magnetic traps and waveguides are developed in order to build integrated atom optics on a chip. In such traps where the atom is very near a surface, new effects have been predicted by Henkel [46, 47, 48]: the low-frequency part of the thermal electromagnetic fields is considerably enhanced near a conducting surface and these fields may reduce the coherence lifetime in the trap. Some recent experiments have observed the reduction of the atom residence time in magnetic micro-traps when the atom-surface distance is reduced [49, 50, 51]. Finally, in 2005, after several unsuccessful attempts, a Michelson atom interferometer has been operated on a chip [52].

IV. MAIN TYPES OF ATOM INTERFEROMETERS

A. Polarization interferometers versus separated beam interferometers

With light waves [53], a distinction is classically made between polarization interferometers (made of a polarizer, a birefringent medium and an analyzer) and interferometers using division of wavefront or of amplitude (in which a light beam is split in two beams which recombine on the detector). Obviously, this distinction is more technical than fundamental. Among atom interferometers, all those using an inelastic diffraction process (Ramsey-Bordé or Raman process) have a mixed character: the wave follows two different paths but the beam-splitters have modified the atom internal state.

With atoms, the equivalent of pure polarization interferometers can be found in the Ramsey [54] or Sokolov [55] experiments and in atomic clocks. The two paths followed by the atom differ essentially by the internal states of the atom and the momentum transfer, which is due to the absorption of a microwave photon, is very small although not completely vanishing [56]. Recent developments on polarization interferometers, done by the group of Baudon and coworkers, are reviewed in [6]. Here, we will concentrate on interferometers in which the two atomic paths are noticeably different.

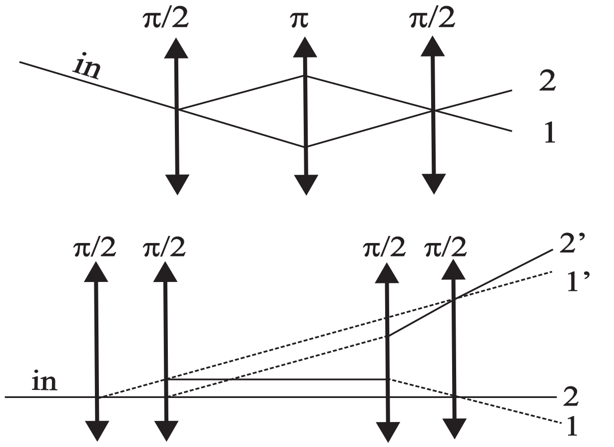

FIG. 3: Two examples of atom interferometers. The top panel represents the simplest Mach-Zehnder interferometer, with the input beam coming from the left and two complementary output beams labelled 1 and 2 on the right. The lower panel shows an asymmetrical atom interferometer with four diffraction processes and four exit beams and such an interferometer can be used to measure h/M (see text). In both cases, the Rabi phases of the diffraction processes are indicated, $\pi/2$ corresponding to an ideal beam splitter and π to a perfect mirror.

B. Interferometer designs

With atomic waves, a complete equivalent of the Fabry-Perot or Michelson interferometers is not feasible and, if we except some Young's double slit type experiments, most interferometers are based on the Mach-Zehnder design, with a diffraction process replacing the mirrors and the beam-splitters. The high symmetry of the Mach-Zehnder interferometer is very helpful to minimize the sensitivity to defects but less symmetrical designs are also interesting (see Fig. 3). The Mach-Zehnder design can be divided in various subtypes:

- temporal or spatial interferometers. In the simplest temporal interferometers, the diffraction gratings are produced by pulsing the laser beams at time $t = 0$, $t = T$ and $t = 2T$. In spatial interferometers, three gratings, located at $z = 0$, $z = L$ and $z = 2L$, are successively crossed by the atoms. While spatial interferometers are very similar to their traditional optics counterparts, temporal interferometers, which are almost unknown in optics, are easy to build with atoms thanks to laser diffraction and, with cold atoms, temporal interferometers are the usual choice.

  In many cases, the phase shift to be measured varies with the time interval T and an accurate knowledge of T is needed for a high precision measurement. In a spatial interferometer, $T = L/v$ and the dispersion of the phase shift due to the velocity distribution limits the maximum observable phase shift and the accuracy of its measurement. Several techniques [57, 58] have been proposed to overcome this difficulty.

- among temporal interferometers, some of them are based on an echo-type technique, as discussed by Sleator and co-workers [59]. With this technique, the atomic source transverse velocity distribution may be larger than one photon recoil velocity, an advantage shared with the Talbot-Lau interferometers.

- the diffraction process itself can be used in the far-field regime (the Fraunhofer regime where the beams associated to the various diffraction orders do not overlap) or the near-field regime. Near-field diffraction is used in Talbot-Lau interferometers [60], which is the only possible design with heavy molecules, because of their very small de Broglie wavelength: many such experiments have been done by Arndt, Zeilinger and co-workers [61, 62] but a Talbot-Lau interferometer has been developed with thermal atoms by the group of Clauser [63].
- although most interferometers involve only two atomic paths, a multiple path interferometer has been built and operated by Weitz and co-workers [64].

V. APPLICATIONS OF ATOM INTERFEROMETRY

Let us now review the main applications of atom interferometry, illustrating each case by some experimental results.

A. Young double slit interferometers and related experiments

A Young's double slit experiment was realized by Carnal and Mlynek in 1991 using a supersonic beam of metastable helium [1]. A similar experiment was made in 1992 with ultra-cold metastable neon by Shimizu and co-workers [65], who also observed the shift of the fringe position due to an inhomogeneous electric field [66]. Mlynek and co-workers have also used a charged wire to build a kind of Fresnel biprism interferometer [67, 68].

By modulating the laser power density of an evanescent wave mirror, Dalibard and co-workers were able to induce a phase modulation of an atomic wave [69] and they used this process to build a temporal Young double slit interferometer [70].

B. Effects of an electric field

The electric polarizability α is interesting to measure by atom interferometry, because spectroscopy can measure only the polarizability difference between internal states. The phase shift due to an electric field $\mathbf{E}$ applied on the interferometer is given by:

$$\Delta\phi = \frac{2\pi\epsilon_0\alpha}{\hbar v}\oint \mathbf{E}^2(s)ds \tag{4}$$

where the path integral is taken on a closed circuit following the two atomic paths inside the interferometer and v is the atom velocity. It is necessary to apply an electric field on only one of the interfering beams and this is possible, if the collimation is sufficient, by using a capacitor with a thin electrode (a septum) inserted between the two beams. With such an experiment, Pritchard and co-workers [71] have obtained a very accurate measurement of the sodium atom polarizability. With a similar experiment, Toennies and co-workers have compared the electric polarisabilities of helium atom and dimer [72] and our group has measured the electric polarizability of lithium atom [73, 74]. The velocity dependence of the phase shift has been compensated by applying time dependent phase shifts by Pritchard and co-workers [58].

With an interferometer using inelastic diffraction, a homogeneous electric field applied on the two interfering beams induces a phase shift proportional to the polarizability difference: such an experiment was done on magnesium [75] and on calcium [76].

With a multiple beam interferometer, Weitz and co-workers have observed the tensorial character of the phase shift due to the AC Stark effect of a pulsed optical field [77].

The Aharonov-Casher phase [78], which results from the application of an electric field on an atom with an oriented magnetic moment, has been measured by several experiments [79, 80, 81, 82].

C. Effect of a magnetic field

With paramagnetic atoms in a given F, M_F hyperfine sublevel, the phase shift due to the magnetic field B is given by :

$$\Delta\phi(F, M_F) = \frac{g_F \mu_B M_F}{\hbar v} \oint B(s) ds \tag{5}$$

where the field is assumed to vary slowly enough to insure an adiabatic behaviour. The resulting phase shift $\Delta\phi(F, M_F)$ vanishes for a homogeneous field and is proportional to the magnetic field gradient. This gradient may be created by a current sheet circulating between the two atomic beams [83, 84] or more simply by a coil [85, 86] or a wire [52] (in this last case, the gradient is pulsed).

In any case, it is difficult to evaluate the field integral very accurately, so that these experiments cannot provide competitive measurements of the Zeeman effect. In the experiments [83, 84, 85, 86], the fringe visibility $\mathcal{V}$, which was recorded as a function of the applied gradient, presents a series of revivals when all the $\Delta\phi(F, M_F)$ are multiples of 2π.

If the diffraction process is inelastic, a phase shift appears as soon as the magnetic moments in the two states are not equal. If the magnetic field is homogeneous and pulsed in time, the phase shift is non-dispersive (i.e. independent of the atom velocity) and this effect is a particular case of the scalar Aharonov-Bohm effect. This effect has been studied on sodium by Morinaga and co-workers [87]. As a weak magnetic field induces a large phase shift, most experiments try to cancel the sensitivity to the magnetic field by pumping the atom in a $M_F = 0$ sub-level (which has only a quadratic Zeeman effect) and by keeping the magnetic field weak and homogeneous but non zero, as in atomic clocks.

D. Measurement of h/M and of the fine structure constant α

With a proper design (see Fig. 3), the interference signal is sensitive to the photon recoil energy $\hbar\omega_{rec} = \hbar^2 k_L^2/(2M)$. The associated phase shift, which may be very large, can be measured only with temporal interferometers operated with cold atoms. The knowledge of $\hbar/M$, combined with the Rydberg constant and mass ratios which are very accurately known, gives access to the fine structure constant α. This new measurement is very interesting because it is almost completely independent of quantum electrodynamics (QED) calculations, while the best measurement of α, deduced from the anomalous Landé factor of the electron [88], rely on very complex QED calculations.

The first demonstration was made on cesium by Chu and co-workers [89, 90] with an uncertainty of 0.1 ppm on $\hbar/M$ but their result was lower than the accepted value by

0.85 ppm. Many improvements have been made and, in 2002, this experiment has given a measurement of α with an accuracy of 7.4 ppb [91].

Similar experiments have been started on rubidium [59] and hydrogen [92]. The contrast interferometer of Pritchard and co-workers [93], which operates with a sodium BEC, has given a precision of 7 ppm on h/M_{Na}, but the result differs by 200 ppm from the accepted value, a difference attributed to the mean-field interaction in the condensate. A recent experiment [94] by Aspect and co-workers with a rubidium BEC has observed a similar shift which has been quantitatively related to the mean-field interaction in the expanding BEC.

Bloch oscillations of an atom in a standing light wave were first observed by the research groups of Salomon [95] and Raizen [96] in 1996. Such an experiment can give a measurement of h/M by measuring the transferred momentum through a velocity measurement. A first experiment on rubidium ^{87}Rb has been made by Biraben and co-workers [97], with an uncertainty on α equal to 0.4 ppm and this uncertainty has been recently reduced to 6.7 ppb [98].

E. Measurement of inertial effects

The sensitivity of a matter wave interferometer to inertial effects is large [34, 99, 100] as first illustrated by the observation of the effect of gravity on a neutron interferometer in 1975 [101]. The classical aspects of the detection of inertial effects with an atomic beam have been discussed by the group of Zeilinger [102].

1. Measurement of accelerations

The phase-shift due to an acceleration $\mathbf{a}$ is given by:

$$\Delta\phi = \mathbf{k}_{eff} \cdot \mathbf{a}T^2 \tag{6}$$

where T is the time between laser diffraction pulses and $\hbar k_{eff}$ the momentum transferred to the atom by the diffraction process. In the case of the acceleration of gravity $\mathbf{a} = \mathbf{g}$, minor corrections due to the gravity gradient must be taken into account [103, 104].

The first measurement of $\mathbf{g}$ by atom interferometry was performed in 1991 by Kasevich and Chu [4, 105], with a temporal interferometer with Raman diffraction and laser cooled atoms. In 1997, Sleator and co-workers [59] realized a preliminary measurement of g with their echo interferometer. After a series of improvements, Chu and co-workers [104, 106] have obtained an uncertainty of 3×10^{-9} on g.

A gravity gradiometer has been built by the research group of Kasevich [107, 108], with an achieved sensitivity equal to 4×10^{-9} s^{-2} and this apparatus has been used for a preliminary measurement of the gravitational constant G [109]. Tino and co-workers are presently building an atom interferometer dedicated to the measurement of G, aiming at a 100 ppm accuracy [110, 111].

An atom interferometer using amplitude gratings made of laser standing waves has been built by Hänsch and co-workers and it has been used to test the equivalence principle with a 10^{-7} sensitivity [112].

The period of Bloch oscillations in a laser standing wave in the vertical direction is directly related to g and several experiments have used this property to measure g. Inguscio and co-workers [113] have compared two realizations of this experiment, one with a bosonic atom

^{87}Rb and one with a fermionic atom ^{40}K, thus proving the superiority of noninteracting fermions for such an experiment. Biraben and co-workers [114] have made a preliminary measurement of g with a 10^{-6} accuracy and pointed out several interesting features of this technique.

If an atom interferometer is placed in an homogeneous electric field, the atoms will be accelerated if their electric charge does not exactly vanish. Chu and co-workers [115] proposed to use the large sensitivity to accelerations of atom interferometers to test the charge neutrality of atoms. Following [116], it is possible to achieve a sensitivity near $10^{-21} q_e$ (q_e: electron charge), equal to the sensitivity achieved by experiments with neutrons [117] or molecules [118].

2. Measurement of rotations: atom gyros

The sensitivity of an interferometer to rotations is due to the Sagnac effect. We can use equation (5) and replace the acceleration **a** by the Coriolis term. Classically, the phase-shift is given by:

$$\Delta\phi = \frac{4\pi \mathbf{\Omega} \cdot \mathbf{A}}{\lambda_{dB} v} \tag{7}$$

$\mathbf{\Omega}$ is the angular velocity of the interferometer, $\mathbf{A}$ is the area enclosed by the interferometer paths (normal to its surface) and λ_{dB} is the de Broglie wavelength . As this phase shift is an inertial effect, it must be independent of the atom mass and this appears obviously if one writes:

$$\Delta\phi = 2\Omega v T^2 k_{eff} = 2\Omega L^2 k_{eff}/v \tag{8}$$

where v is the atom velocity, T the time between diffraction pulses or L the distance between diffraction gratings. The exact value of the area A is not a simple question [119, 120], because of the pulse duration or spatial width of the laser beams.

The first atom interferometer gyrometer was built by Helmcke, Bordé and co-workers [3] in 1991: it was a spatial Ramsey-Bordé interferometer using a thermal calcium beam. A spatial interferometer with a thermal sodium beam and material gratings, built by Pritchard and co-workers [121], has reached a sensitivity equal to 3×10^{-6} rad/s$\sqrt{Hz}$. A thermal cesium spatial interferometer with Raman diffraction by Kasevich and co-workers [122, 123] has reached a sensitivity equal to 6×10^{-10} rad/s$\sqrt{Hz}$. A temporal interferometer using Raman diffraction with a cold cesium fountain beam has been developed at BNM-SYRTE laboratory [124] and a somewhat similar apparatus aiming at a very high sensitivity needed for a direct detection of the Lense-Thirring effect (a frame-dragging effect predicted by general relativity [125]) is under development in a joint effort involving several European laboratories (HYPER project [126]).

F. Other interactions

Up to now, we have considered that the atoms inside the interferometers are isolated and submitted only to electromagnetic or inertial fields. In the following experiments, the atom interactions are more complex, usually with a stochastic or dissipative character.

1. *Effect of a gas on atomic wave propagation: index of refraction or decoherence*

Pritchard and co-workers have measured the index of refraction of various gases for sodium atomic waves [84, 127, 128]. Using a gas cell with a septum, a small gas density (corresponding to a gas pressure near 10^{-3} millibar) is introduced on one of the interfering beams (the atomic wave goes in and out of the cell through thin slits). The phase shift and attenuation of the transmitted wave are both detected on the interferometer signal. In the case of rare gases, the experimental results can be compared to calculations using the sodium-rare gas interaction potentials and the main features are well explained [127, 129, 130].

The presence of a gas in the interferometer can also induce a decoherence effect: this effect has been observed [131, 132, 133] in the Talbot-Lau interferometer developed by Arndt, Zeilinger and co-workers. The C_{70} molecules are very massive and a collision with an atom destroys the coherence of the spatial wavefunction, by transferring some momentum to the C_{70} molecules, but the resulting deviation is small enough so that the molecules still arrive on the detector: as the coherence is lost, the fringe visibility decrease with increasing gas density.

2. *Atom-surface van der Waals interaction*

When an atom goes through the narrow slits of a grating, the atom-surface interaction is quite large and, even at thermal velocities, this interaction cannot be neglected. Each slit can be viewed as a cylindrical lens, with a velocity dependent focal length. This effect modifies the diffraction amplitudes and it has been studied carefully by the group of Toennies [134]. Moreover, as predicted by our group [135], the transmitted wave receives a phase shift which has been recently measured by Cronin and co-workers [136].

3. *Decoherence effects by spontaneous photon emission*

If an atom is excited by a laser, a spontaneous emission of a photon occurs. This process transfers momentum to the atom and at the same time gives a signature of the presence of the atom. Such a process is therefore associated to a loss of coherence and the visibility of the interference signals is reduced when spontaneous photon emission occurs inside the interferometer.

This effect has been first studied by Mlynek and co-workers on the laser diffraction pattern of a metastable helium beam [137]. Then, Pritchard and co-workers were able to study in great detail the loss of coherence due to the spontaneous emission of a variable number of photons as a function of the distance between the two interfering paths [138, 139]. Mei and Weitz [140, 141] have extended this study, using their multiple path interferometer, and they have shown that, in some cases, decoherence can increase the fringe visibility.

Finally, an experiment due to Arndt, Zeilinger and co-workers [142] investigates the same effect on C_{70} molecules in their Talbot-Lau interferometer: the molecules, heated by a laser before entering the interferometer, emit infra-red photons and this emission induces decoherence.

4. Decoherence effects by gravitational waves and related topics

Several works [143, 144, 145], some being highly speculative, have discussed the detection of space-time fluctuations with atom interferometers. The particular case of the interaction of low-frequency gravitational waves with a matter-wave interferometer can be described without any approximation: a very intense background radiation of gravitational waves emitted by binary star systems is predicted by general relativity and its existence is commonly accepted. Because there is a very large gain of sensitivity for inertial effects when going from light wave to matter wave interferometers, the same gain was expected for the detection of gravitational waves. S. Reynaud and co-workers [146] have shown that this gain of sensitivity does not exist.

VI. CONCLUSION

This paper has given an overview of atom interferometry, limited to interferometers in which the two atomic paths are spatially different. We have also described the main applications of this technique. We have quoted most of the pioneering works as well as a large fraction of recent papers, illustrating the present state of art, but many interesting papers have been omitted because of lack of space. Let us summarize the main messages of this paper:

- atom interferometry has been rapidly expanding since 1991 and a wide variety of experiments have already been realized. These experiments give new access to the measurements of very different quantities (atomic properties, accelerations and rotations, fundamental constants α and G, quantum decoherence effects, etc). Even if this list is already large, new applications are still ahead!

- the possibilities opened by lasers to cool and manipulate coherently atoms are extremely wide. In particular, the atom internal states, which replace the polarization states of light, give a considerably larger set of possibilities and this property explains why so many different types of experiments can be developed.

- atom interferometry has already achieved an extraordinary sensitivity and many improvements are expected to provide further gains of sensitivity. Better sources of atomic waves and, in particular, the development of intense and continuous atom-lasers will provide extraordinary improvements. The atom-atom interactions, which give very impressive effects in quantum degenerate gases, will then play an important role which has no equivalent in traditional interferometry with photons.

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