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# Enhancing an Atom Interferometer Area using Double-diffraction

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In this paper we demonstrate a new scheme for Raman transitions which realize a symmetric momentum-space splitting of  $4\hbar k$ , deflecting the atomic wave-packets into the same internal state. Combining the advantages of Raman and Bragg diffraction, we achieve a three pulse state labelled interferometer, intrinsically insensitive to the main systematics. This splitting scheme can be extended to  $4N\hbar k$  momentum transfer by a multipulse sequence and is implemented on a  $8\hbar k$  interferometer. Measuring inertial phase shifts, we demonstrate an area enhancement of a factor of 3.46 with respect to the traditionally used geometry.

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Atom interferometers are of interest for precision measurements of fundamental constants [1, 2, 3, 4] and for inertial measurements [5, 6]. The sensitivity of these apparatus is closely related to the ability to diffract the atomic wave-packet in a coherent way. The efficiency of this process determines the enclosed area of the interferometer and so its sensitivity. Many techniques have been implemented to coherently separate atomic waves and increase the angular deflection using material gratings [7], magneto-optical beam-splitters [8, 9] or momentum transfer by adiabatic passage [10]. For precision measurements, the use of two photon transitions are the most frequently used since they guarantee the control of the momentum transfer during the diffraction process.

Bragg matter-wave gratings made of a near resonant standing light wave, permit the diffraction of the atoms along two coherent paths, separated by  $2\hbar k$ . As in this kind of interferometer [11, 12] atoms always travel in the same internal state, the output phase-shift is intrinsically insensitive to many systematics such as the AC Stark shift and the Zeeman effect. This method require the use of highly collimated atomic sources to perform the output phase measurement. Alternatively, stimulated Raman transitions [13], which split a wave packet into two distinct internal states, are well adapted for use with non-collimated atomic sources such as optical molasses. In addition, they allow to realize interferometers which benefit from an internal state labelling [14] for the output phase measurement, as populations of the output ports can be detected using a state selective fluorescence technique.

Many improvements have been made to increase the momentum-space splitting of Bragg [12, 15, 16, 17, 18, 19] and Raman [20] based interferometers. Recent works

have also permitted an enhancement in the momentum space splitting by using conventional Raman and Bragg schemes coupled to Bloch oscillations [21, 22].

Here, we demonstrate a new scheme based on Raman transitions, which achieves a symmetric momentum-space splitting of  $4\hbar k$  (Fig. 1). It combines the advantages of these two methods. First, starting with atoms from an optical molasses, we realize an interferometer where partial wave packets propagate along its two arms in the same internal state. Second, the measurement of the output phase shift can still be realized thanks to the state labelling. The area of the interferometer is then increased by a factor of two compared to the traditional  $\pi/2-\pi-\pi/2$  three pulse configuration. This splitting scheme can be easily extended to perform a  $4N\hbar k$  momentum transfer thanks to a multipulse sequence technique. As an example, we utilize a  $8\hbar k$  interferometer for inertial measurements.

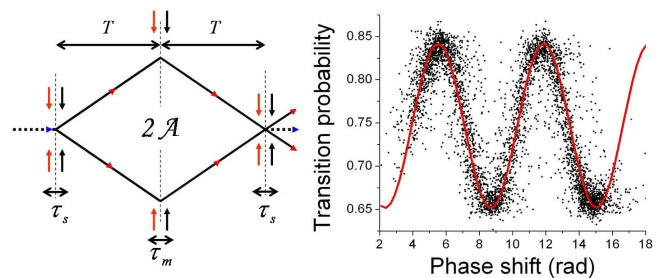


FIG. 1: Left: Scheme of the  $4\hbar k$  interferometer realized using three double-diffraction pulses of duration  $\tau_s$ ,  $\tau_m$ ,  $\tau_s$ . Dotted and solid lines respectively represent wave packets in the state  $|g\rangle$  and  $|e\rangle$ . Right: Interferometer signal for the source  $S_1$  as a function of the phase-shift calculated from the tiltmeter signal.

In our apparatus, described in [23],  $10^7$  Caesium atoms are loaded from a vapor into two independent magneto-optical traps. Two Caesium clouds are then launched at a temperature of  $1.2 \mu\text{K}$  into two opposite parabolic trajec-

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tories using moving molasses at velocity  $v = 2.4 \text{ m.s}^{-1}$ , oriented at an angle of  $8^\circ$  with respect to the vertical direction. At the apex of their trajectory the atoms interact with horizontal Raman laser pulses which act on the matter-wave as beam splitters or mirrors, and generate an interferometer with  $2T = 60 \text{ ms}$  of total interaction time. The use of two atomic sources ( $S_1$  and  $S_2$ ) launched along opposite directions allows discrimination between the acceleration and rotation [6].

Raman transitions are implemented in a retroreflected geometry. The two laser beams of parallel polarizations at  $\lambda = 852 \text{ nm}$  are guided to the setup through the same polarizing fiber. The beams pass through the vacuum chamber and are reflected by a mirror, crossing a quarter-wave plate twice. The wave plate is set in such a way that the reflected lasers have orthogonal linear polarization compared to the incident ones. As a result, counterpropagating Raman transitions are allowed while copropagating Raman transitions are forbidden. This commonly used geometry limits the impact of wave-front aberrations and provides a simple way to implement the  $k$  reversal technique [24]. In fact, in this scheme, atoms interact with four laser waves which drive Raman transitions with effective wave vectors  $\pm \mathbf{k}_{\text{eff}} = \pm(\mathbf{k}_1 - \mathbf{k}_2)$ .

Atoms are initially prepared in the ground state  $|6S_{1/2}, F = 3, m_F = 0\rangle$ , which is written as  $|g\rangle$ . Our four laser design, efficiently couples this initial state to the excited state  $|6S_{1/2}, F = 4, m_F = 0\rangle$  by transferring a  $2\hbar k$  momentum along two opposite directions. The state  $|g, p\rangle$  is then coupled to the two states  $|e, p + 2\hbar k\rangle$  and  $|e, p - 2\hbar k\rangle$  where  $p$  is the initial momentum state of the atom. Due to the Doppler shift  $\omega_D = (p \cdot k_{\text{eff}})/M$ , employing a retroreflected configuration only allows the deflection of matter-waves in one momentum state or the other. In our new method, we take advantage of a null Doppler shift to simultaneously couple the atoms in the two symmetric momentum states. This double-diffraction scheme results in a momentum splitting of  $4\hbar k$  with the same internal state  $|e\rangle$  in the two paths.

First, we investigate the efficiency of this beam splitter scheme by comparing experimental results and numerical simulations of the evolution of the atomic states, when interacting with the four laser waves. The Fig. 2 shows the measurement of the transition probability from the ground state  $|g\rangle$  to the excited state  $|e\rangle$  obtained for the atomic clouds as a function of pulse duration. The effective Rabi frequency, defined as usual [25], is  $\Omega_{\text{eff}} = 2.77 \times 10^4 \text{ rad.s}^{-1}$ . Experimental data are in good agreement with the results of a numerical calculation, displayed as a thick line, in which the basis states are restricted to five momentum states, adding the  $|g, p \pm 4\hbar k\rangle$  detuned states to the three previous ones. We verified that the population in the higher momentum states are negligible taking into account our experimental parameters. We consider the case in which the frequency difference between the lasers is set to

$\delta\omega_1 = (\omega_e - \omega_g) + \omega_R$  where  $\omega_R = (\hbar k_{\text{eff}}^2)/2M$  is the recoil frequency. By extension of the calculation presented in [25], we solve the Schrödinger equation and calculate the evolution of the populations. The calculation takes into account the Doppler shift linked to the velocity dispersion of the atoms and the spatial dependence of  $\Omega_{\text{eff}}$  due to the expansion of the atomic clouds in the gaussian profile of the Raman beam. In order to keep only the atoms in the two symmetric states  $|e, p \pm 2\hbar k\rangle$ , a pushing beam is implemented after the Raman pulse so as to remove remaining atoms in the ground state  $|g\rangle$ . In addition, using this scheme, we have verified on the experiment that the beam splitter also realizes a velocity selection of the input momentum state.

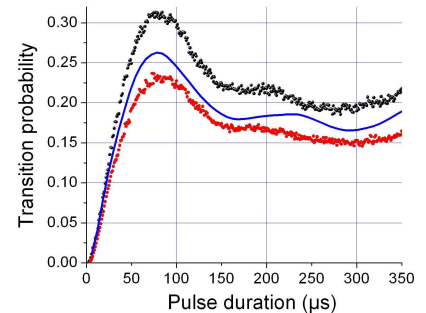


FIG. 2: Rabi oscillation profiles obtained for the two atomic sources  $S_1$  and  $S_2$  at the apex of their trajectory (dots). The curve is the result of a numerical simulation.

Using this double-diffraction scheme, we realize an interferometer with a three pulse sequence (Fig. 1). The first pulse of duration  $\tau_s = \pi/\sqrt{2}\Omega_{\text{eff}}$  splits the input state  $|g, p\rangle$  into  $|e, p \pm 2\hbar k\rangle$  symmetrically. The second pulse of duration  $\tau_m = \sqrt{2}\pi/\Omega_{\text{eff}}$  acts as a mirror by coupling each path to its opposite momentum state. Finally, matter-waves are recombined thanks to a third pulse, of duration  $\tau_s$ , to form a symmetric interferometer in which the matter-waves propagate in the same internal state  $|e\rangle$ . A pushing beam is implemented after each of the two first Raman pulses so as to suppress spurious interferometers. The Raman transition scheme still enables the use of state labelling at the output of the interferometer even if the matter-waves travel in the same internal state. The output phase-shift can thus easily be measured thanks to a fluorescence technique. The output atomic phase-shift of our device is sensitive to acceleration  $a$  and rotation  $\Omega$  as  $\Delta\Phi = 2 \mathbf{k}_{\text{eff}} \cdot (\mathbf{a} - 2(\mathbf{v} \times \boldsymbol{\Omega}))T^2$  [23], increasing the sensitivity of the traditional  $\pi/2$ - $\pi$ - $\pi/2$  three pulse geometry by a factor of two.

As with a Bragg interferometer, our apparatus is, in principle, insensitive to the AC Stark shift and the Zeeman effect. Moreover, the interferometer phase does not depend on the laser phase difference as its influence is identical over the two paths.

In order to scan the phase, a controlled acceleration phase shift is induced on the interferometer. This is simply achieved by tilting the apparatus ( $\pm 50 \mu\text{rad}$ ) to get a small projection of the gravity along the axis of the light-pulses. The inclination is measured thanks to a calibrated tiltmeter (Applied Geomechanics 701-2A). Fig. 1 displays the transition probability as a function of the phase shift deduced from the tilt measurement. We observed a contrast of 20% identical for the two atomic sources.

Using horizontal Raman beams makes the interferometer sensitive to the vertical component of the Earth rotation rate  $\Omega_z^E = 5.49 \times 10^{-5} \text{ rad.s}^{-1}$  at the latitude of Observatoire de Paris. The quadratic scaling of the rotation and acceleration phase shifts with the interaction time  $T$  is verified from  $T = 10$  to 30 ms (Fig. 3). The measurements, obtained with this extended interferometer area, are in a good agreement with the expected behavior.

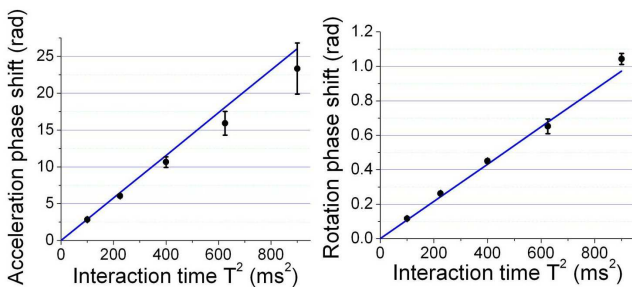


FIG. 3: Quadratic scaling of the acceleration phase shift induced by the projection of  $g$  for an angle of  $100 \mu\text{rad}$  with respect to the horizontal plane (Left) and of the rotation phase shift induces by the vertical component of the rotation rate  $\Omega_z^E$  (Right) as a function of the interaction time  $T^2$ . The measurements (dots) are compared with the expected behaviors (lines).

The double-diffraction scheme can be extended to higher momentum space splitting thanks to the retroreflected configuration. After splitting the atoms into the two symmetric states  $|e, p \pm 2\hbar k\rangle$  with the first pulse, a second pulse can be implemented to efficiently couple these two resulting states to the next momentum states  $|g, p \pm 4\hbar k\rangle$ . The Raman frequency difference of the second pulse has to be changed to  $\delta\omega_2 = (\omega_e - \omega_g) - 3\omega_R$  in order to fulfill the resonance condition between the momentum states and the two pairs of Raman lasers. This scheme can be extended to a  $N$  pulse sequence to reach up to  $4N\hbar k$  momentum space splitting. In order to conserve the resonance condition, Raman frequency difference of the  $i^{\text{th}}$  pulse has to be changed and set to  $\delta\omega_i = (\omega_e - \omega_g) + (-1)^{i-1}(2i-1)\omega_R$ . Following this argument, symmetric Raman transitions are suitable to realize a large area interferometer with  $4N\hbar k$  momentum space splitting.

Here, we demonstrate an interferometer realized with  $N = 2$ , reaching a  $8\hbar k$  momentum space splitting be-

tween the two paths, using seven Raman pulses. In this configuration (Fig. 4), the first atomic beam splitter is composed of two light-pulses respectively set with detunings  $\delta\omega_1$  and  $\delta\omega_2$ . In this manner, matter-waves are coupled from the state  $|g, p\rangle$  to  $|g, p \pm 4\hbar k\rangle$ . The mirror is realized by three successive pulses at  $\delta\omega_2, \delta\omega_1, \delta\omega_2$  in order to deflect the atoms in their opposite momentum-state. Finally, the two interferometric paths are recombined with the symmetric  $\delta\omega_2, \delta\omega_1$  light-pulse sequence. The durations of the seven pulses are respectively  $\tau_s, \tau_\pi, \tau_\pi, \tau_m, \tau_\pi, \tau_\pi, \tau_s$ , where  $\tau_\pi = \pi/\Omega_{eff}$ . In addition, four pushing pulses are applied to blow away residual atoms remaining in the internal state  $|g\rangle$ .

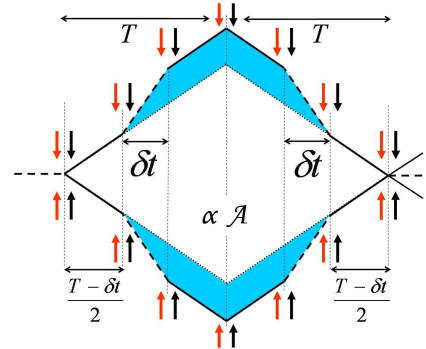


FIG. 4: Recoil diagram for the  $8\hbar k$  interferometer reaching a total area enhanced by a factor of  $\alpha$ . Dotted lines represent wave packets in the  $|g\rangle$  hyperfine ground state while solid lines depict the  $|e\rangle$  ground state. Colored surface represents the area enhancement compared with the corresponding three pulses configuration.

The total interaction time of this interferometer is  $2T = 60$  ms. Atoms propagate in the states  $|g, p \pm 4\hbar k\rangle$  during  $2\delta t = 40$  ms with a delay of  $(T - \delta t)/2$ . The interferometric area increases by a factor of  $\alpha = 2(1 + \delta t/T)$  compared with the previous configuration. The sensitivity to inertial effects is then proportionally enhanced up to  $\Delta\Phi = \alpha \mathbf{k}_{eff} \cdot (\mathbf{a} - 2(\mathbf{v} \times \boldsymbol{\Omega}))T^2$ . As before, this phase is scanned by tilting the interferometer. In Fig. 5 we show the fringe patterns of the two sources, obtained with the  $8\hbar k$  interferometer. The phase shift between the two interferometers corresponds to the rotation phase shift induced by the vertical component of the Earth rotation rate  $\Omega_z^E$ . The linear scaling of the acceleration phase shift with  $\alpha$  was investigated by changing  $\delta t$ . Figure 5 displays the result of the measurement for  $\delta t = 0$  to 20 ms which shows a good agreement with the expected slope. This corresponds to an enhanced sensitivity of a factor of 3.46 compared to the usual configuration.

With respect to the previous case of a three pulse interferometer, the atoms do not remain into the same internal state all along the two paths. Nevertheless, as the internal state changes at the same time for the two partial wave packets, the enhanced interferometer remains insensitive to the same systematics as in the Bragg case.

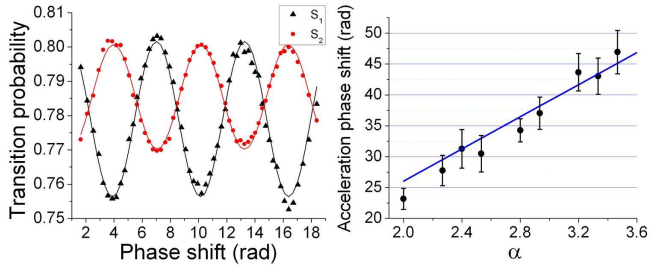


FIG. 5: Left: Fringe patterns averaged over 450 samples. Right: Linear scaling of the acceleration phase-shift induced by the projection of  $g$  for an angle of  $100 \mu\text{rad}$  with respect to the horizontal plane as a function of the area enhancement factor  $\alpha$ . The measurement (dots) is compared with the expected values (line).

To conclude, we demonstrated a new method of achieving symmetric Raman transitions with  $4\hbar k$  momentum-space splitting, deflecting the atoms into the same internal state. Using this double-diffraction technique, we have realized an interferometer of increased area which has been tested by performing acceleration and rotation measurements. The splitting scheme has been extended to reach a  $8\hbar k$  interferometric geometry in a seven pulse configuration, opening the way for enhanced  $4N\hbar k$  path separation geometry.

This scheme provides a simple way to increase the sensitivity of the apparatus without any significant changes in the experimental setup thanks to the retroreflected Raman configuration. In particular, it does not require extra laser power compared to standard Raman transition based interferometers. Furthermore, as matter-waves are symmetrically driven in the same ground state, interferometers are intrinsically insensitive to the AC Stark shift, the Zeeman effect and Raman laser phase-noise. The enhanced area geometry thus combines the advantages of Raman and Bragg based interferometers. Moreover, the principle of the double-diffraction can be extended to the case of a non-zero Doppler shift, providing that the two opposite Raman transitions remain resonant simultaneously. This general case requires at least three different laser frequencies.

Finally, this work provides insight into space-atom interferometer design [26]. Indeed, for inertial sensors in zero-gravity environments, Doppler effect can not be used to select one or the other effective Raman transitions in the current retroreflected configuration needed for accuracy [27]. The symmetric Raman diffraction offers a promising solution to circumvent this constraint.

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