ATOMIC INTERFEROMETRY WITH INTERNAL STATE LABELLING

Ch.J. BORDÉ

Laboratoire de Physique Théorique, Gravitation et Cosmologie Relativistes, CNRS/URA 769, Université Pierre et Marie Curie, Institut Henri Poincaré, 11, rue Pierre et Marie Curie, 75231 Paris Cedex 05, France

Received 30 May 1989; accepted for publication 6 June 1989
Communicated by J.P. Vigier

It is shown that the interaction geometry comprising four travelling laser waves which is used to obtain optical Ramsey fringes in atomic spectroscopy, is also well suited to build an atom interferometer based on the atomic recoil. Since two different internal states are associated with the two arms of the interferometer, the de Broglie phase, induced by rotation or acceleration, manifests itself as a frequency shift of the Ramsey fringes.

Everybody has in mind the beautiful experiments performed with neutron interferometers [1,2] and much effort has been recently devoted to build an interferometer for heavier species such as neutral atoms [3], stimulated by new techniques in cooling and handling atomic beams. The key component is, of course, the beam splitter for which the atomic recoil in a standing wave (analog of the Kapitza–Dirac effect) represents an attractive possibility demonstrated both in the frequency [4] and momentum [5] domains.

As opposed to neutrons, atoms offer the possibility of easily providing the additional labelling of their internal states when the corresponding lifetimes are long enough. As we shall see, different external paths can be labelled by different internal quantum numbers, and it is therefore possible to associate the external phase with internal degrees of freedom which can be probed by usual spectroscopic techniques.

As an example, we shall consider the case of a molecular beam of two-level systems ($E_a<E_b$) interacting with two counterpropagating sets of pairs of copropagating travelling laser waves as in the interaction geometry which has been used for Ramsey fringes in the optical domain [6–12] (fig. 1).

Owing to the energy and momentum exchanges during the resonant absorption/emission processes in each interaction zone the matter waves are coherently split into two components with an internal state $|a\rangle$ or $|b\rangle$ and with wavevectors differing by the laser wavevector $\boldsymbol{k}$ in the direction $\hat{z}$ of light propagation.

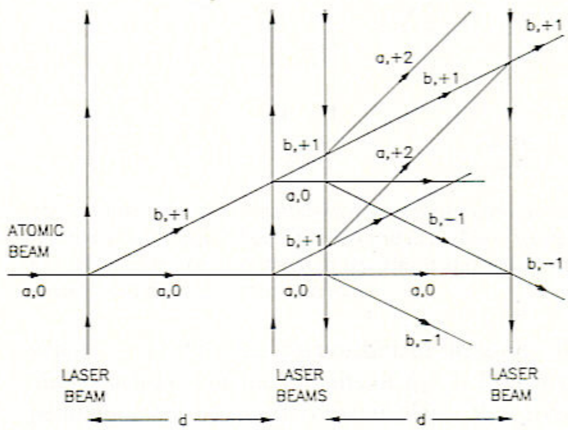

Fig. 1. Interaction geometry of the four travelling laser beams (ω, $\pm k\hat{z}$) with the atomic beam (E_a, $\boldsymbol{p}_0$). Each ray is labelled by its energy and momentum state $|\alpha, m_\alpha\rangle \equiv |E_\alpha, \boldsymbol{p}_0+m_\alpha\hbar\boldsymbol{k}\rangle$ (α=a or b).

All possible rays originating from the ground state ($|a\rangle$) incident beam have been drawn on the figure. Each segment is labelled by a given state a or b and by an integer m_α (α=a or b) which indicates the net number of light momentum quanta $\hbar k$ which have been exchanged from the initial momentum $\boldsymbol{p}_0$. For a definition of energy–momentum states

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$|\alpha, m_\alpha\rangle = |E_\alpha, \boldsymbol{p}_0 + m_\alpha \hbar \boldsymbol{k}\rangle$

see refs. [7,8,13].

We shall be interested in the transition probability to state $|b\rangle$ in the last zone, which can be monitored either through the excited population or through the absorbed laser power. This probability can be obtained from the product of amplitudes corresponding to two quantum mechanical paths. Such a calculation is given in matrix form in refs. [7,8]: it leads to oscillations in the transition probability as a function of laser detuning known as Ramsey fringes which result from an interference of two paths where only the internal degrees of freedom have been considered to play a role (with the exception of the recoil shifts and of second-order Doppler corrections).

Owing to the final integration over a broad distribution of velocity components v_z, only the contributions associated with the two closed circuits of fig. 2 are non-vanishing. They correspond to the two recoil components of the Ramsey fringes (the third closed circuit of fig. 1 is a parallelogram which corresponds to a photon echo in the same direction as the first two waves). These two circuits having a finite area will behave as matter-wave interferometers with a phase difference sensitive to *both* internal and external degrees of freedom.

Let us observe that each of these interferometers has two arms labelled by a different internal state (if the small central dark space is ignored). If the system is now submitted to an external inertial field (rotation or acceleration) the induced de Broglie phase corresponding to each arm will therefore appear in association with a given internal state in the final transition probability and thus, we expect a frequency shift of the Ramsey fringes.

As an example let us consider the rotation of this system with the angular velocity $\boldsymbol{\Omega}$. The corresponding additional Hamiltonian is [14]

$$H_R = -\boldsymbol{\Omega} \cdot (\boldsymbol{r} \times \boldsymbol{p}) ,$$

where $\boldsymbol{r}$ and $\boldsymbol{p}$ are respectively the position and momentum operators of the atoms. In the basis of unperturbed energy–momentum states and to first order in Ω the extra phase factor for the evolution operator is

$$\exp\left(\frac{i}{\hbar} \int [\boldsymbol{\Omega} \times \boldsymbol{r}(t')] \cdot (\boldsymbol{p}_0 + m_\alpha \hbar \boldsymbol{k})\, dt'\right),$$

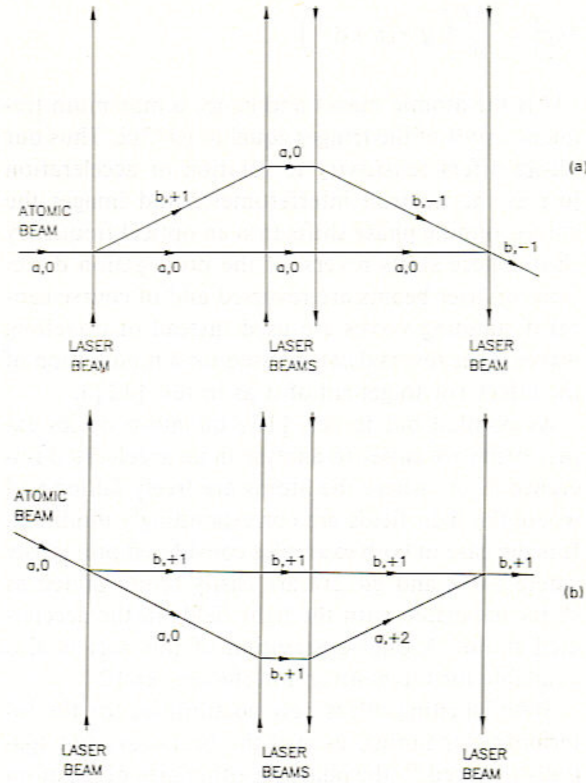

Fig. 2. Closed circuits of matter-wave rays which correspond respectively to the higher frequency (a) and to the lower frequency (b) recoil components of the Ramsey fringes and which constitute two distinct atom interferometers.

where $\boldsymbol{r}(t')$ is the classical position of the atom taken along each arm of the circuits of fig. 2. If Ω is perpendicular to the interferometer plane, this gives

$$\exp(2ik\Omega d^2/v)$$

for the round-trip phase factor which enters into expressions (16) and (17) of ref. [8] for the transition probability, and yields fringe terms proportional to

$$\cos[(\omega - \omega_0 + 2\pi\Omega d/\lambda + \phi) 2d/v]$$

which are shifted from the central frequency ω_0 by the amount $\delta\nu = \Omega d/\lambda$ (d is the distance between zones in fig. 1). For $2d = 21$ cm [15] and the earth rotation rate, the calcium line at 6573 Å is shifted by $\delta\nu \approx 12$ Hz which should be easily detectable.

Similarly the gravitation field $\boldsymbol{g}$ would give a phase factor

$$\exp\left(-\frac{iM}{\hbar}\oint g\cdot r(t')\,dt'\right)$$

(M is the atomic mass) and hence a maximum frequency shift of the fringes equal to $gd/2v\lambda$. Thus our set-up offers sensitivity to rotation or acceleration just as the neutron interferometer and images the corresponding phase shifts into an optical frequency shift. These shifts reverse if the propagation directions of laser beams are reversed and of course cancel if standing waves are used instead of travelling waves. This reversal can be used for a modulation of the effect (or to get rid of it as in ref. [12]).

As pointed out in ref. [16] quantum optics experiments are easier to analyse in an accelerated reference frame where the atoms are freely falling and where the light fields are correspondingly modified. It is the case in both examples considered previously where $\Omega d/\lambda$ and $gd/2v\lambda$ are easily reinterpreted as shifts associated with the light fields in the accelerated frame. A dual description of this sort is also available for the neutron interferometer [2].

State labelling offers new possibilities for the interferometer tuning: even if the beams are not spatially resolved [#1], the phase on either arm of the atom interferometer can be modified through any state selective mechanism or through interaction with auxiliary light fields which may be resonant with transitions involving either state $|a\rangle$ or $|b\rangle$ and a third level $|c\rangle$. Adiabatic fast passage in a spherical wave [7,17] can be used to achieve any number of exact π pulses, in order to investigate the spinorial character of the pseudo-spin.

It should be stressed that such a set-up has already been successfully demonstrated with various atomic systems [6–12]. It was simply not realized that it could be described as a matter-wave interferometer with separated beams. Its sensitivity to rotations and accelerations remains to be investigated experimentally.

Other possible realisations of the same idea involve more complicated interactions in each zone: two-photon transitions connecting states with long lifetimes could be used (e.g. the transition 1s–2s in atomic hydrogen).

[#1] For full spatial resolution of the beams, the recoil splitting should be larger than the residual Doppler width, which itself should be larger than the Ramsey fringe period.

A detailed theoretical analysis of these systems will be given elsewhere. Beyond the consequences for optical frequency standards and a possible new class of gyros or accelerometers they offer the conceptual interest of a new playground where quantum physics and gravitation physics interact strongly.

The author would like to thank Professor Ph. Tourrenc for many fruitful discussions and for his encouragement on this subject.

References

[1] S.A. Werner, Phys. Today (Dec. 1980) 24, and references therein.

[2] D.M. Greenberger and A.W. Overhauser, Rev. Mod. Phys. 51 (1979) 43.

[3] D.W. Keith, M.L. Shattenburg, H.I. Smith and D.E. Pritchard, Phys. Rev. Lett. 61 (1988) 1580, and references therein.

[4] J.L. Hall, Ch.J. Bordé and K. Uehara, Phys. Rev. Lett. 37 (1976) 1339, and references therein.

[5] P.L. Gould, G.A. Ruff and D. Pritchard, Phys. Rev. Lett. 56 (1986) 827.

[6] Ch.J. Bordé, S. Avrillier, A. van Lerberghe, Ch. Salomon, D. Bassi and G. Scoles, J. Phys. (Paris) Colloq. 42 (1981) C8-15; Appl. Phys. B 28 (1982) 82.

[7] Ch.J. Bordé, Rev. Cethedec - Ondes et Signal NS83-1 (1983) 1.

[8] Ch.J. Bordé, Ch. Salomon, S. Avrillier, A. van Lerberghe, Ch. Bréant, D. Bassi and G. Scoles, Phys. Rev. A 30 (1984) 1836.

[9] Ch. Salomon, S. Avrillier, A. van Lerberghe and Ch.J. Bordé, in: Laser spectroscopy, Vol. VI (Springer, Berlin, 1983) p. 159.

[10] J. Helmcke, D. Zevgolis and B.U. Yen, Appl. Phys. B 28 (1982) 83.

[11] F. Riehle, J. Ishikawa and J. Helmcke, Phys. Rev. Lett. 61 (1988) 2092.

[12] A. Morinaga, F. Riehle, J. Ishikawa and J. Helmcke, Appl. Phys. B 48 (1989) 165.

[13] Ch.J. Bordé, Density matrix equations and diagrams for high resolution non-linear laser spectroscopy: application to Ramsey fringes in the optical domain, in: Advances in laser spectroscopy (Plenum, New York, 1983) p. 1.

[14] L.D. Landau and E.M. Lifshitz, Mechanics (1960) p. 129.

[15] Ch. Salomon, Ch. Bréant, Ch.J. Bordé and R.L. Barger, J. Phys. (Paris) Colloq. 42 (1981) C8-3.

[16] Ch.J. Bordé, J. Sharma, Ph. Tourrenc and Th. Damour, J. Phys. (Paris) Lett. 44 (1983) L983.

[17] S. Avrillier, J.M. Raimond, Ch.J. Bordé, D. Bassi and G. Scoles, Opt. Commun. 39 (1981) 311;
Ch.J. Bordé, Ch. Chardonnet and D. Mayou, in: Laser spectroscopy, Vol. VIII (Springer, Berlin, 1987) p. 381.