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INTERFERENTIAL MONOCHROMATOR FOR NEUTRAL ATOMS

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Abstract

When a so called "co-moving" magnetic field – i.e. a field moving at a velocity close to the atom ones – is used as a phase shifter in a Stern-Gerlach atom interferometer the resulting accumulated phase shift takes non negligible values for only those atomic velocities which are close to that of the field. The interferometer is then an adjustable interferential velocity filter. This effect has been demonstrated by means of a time-of-flight measurement on a metastable hydrogen atom beam the velocity distribution of which is wide ($\delta v/v = 1$). By scanning the field velocity, the velocity distribution of a *continuous* H* beam is readily obtained. Extension to accelerated magnetic fields and their application to gravimetry are proposed.

Keywords : Atom interferometry ; Zeeman and Stern-Gerlach effects.

1. Introduction

Since 12 years atom interferometry has accomplished such a considerable progress that nowadays almost all kinds of applications of the traditional light interferometry have become feasible with atoms [1]. To be true this is done sometimes with more technical difficulties than with light, but the extreme shortness of de Broglie wave lengths (usually a fraction of an Angström) generally provides a great sensitivity. Moreover the internal structure of atoms, especially their resonant interaction with light, is a specific richness which has permitted to elaborate a wide variety of interferometer schemes. The so called Stern-Gerlach interferometer [2] is the counterpart of the polarization light interferometer in which a birefringent crystal plate placed in between two parallel or orthogonal linear polarizers produces a sum of two coherent interfering amplitudes. As it will be seen further the counterpart of the birefringence is given here by a magnetic field which splits the energies of Zeeman states. This gives to the device a great versatility since, in principle, any configuration of static or time-dependent magnetic fields can be used. The aim of the present paper is to show that the use of a "co-moving" field [3], i.e. a field profile which moves along the beam axis at a velocity comparable to the atomic ones, makes the interferometer work as an adjustable velocity filter, in other words as a monochromator. Then it can be used not solely as a simple filter but it can also serve – by scanning the selected velocity – to determine the velocity distribution in an atom beam, with the great advantage over traditional time-of-flight techniques that it operates continuously, with no need of chopping and a consequent gain (a few 10^2) on the signal.

The paper will be organized as follows. In part 2, the general principle of Stern-Gerlach interferometers is briefly recalled and the special case of co-moving fields is considered. In part 3 the way to produce such fields by using an extremely simple device is explained. Part 4 is devoted to experimental results dealing with the use of the interferometer as a monochromator. Conclusions and perspectives offered by this method are given in part 5.

2. Stern-Gerlach interferometer with a co-moving field

Our experiment operating with a beam of metastable hydrogen atoms $H^*(2s_{1/2})$ has been the subject of several previous papers [4,5] and only a brief description will be given here (Fig. 1). Starting with a "natural" (unpolarized) atomic beam, the first step is a spin polarization by a filter from which emerge atoms in a well defined Zeeman state $\left|M_P\right\rangle$ referred to a fixed axis (here the axis z of the beam). Then atoms are passed through the first beam splitter. It is here a zone where a magnetic field of a tiny amplitude ($\leq$ 1 mG) rotates in space by 90°over a short distance (5 mm). Owing to the relatively high atomic velocities (~ 10 km/s) this rotation is accomplished in a short time (0.5 µs) during which the spin precesses by only 6 mrd, in other words it remains almost fixed while the quantization axis rotates which generates a linear superposition of Zeeman states referred to the final direction of the field (Majorana transition [6]).

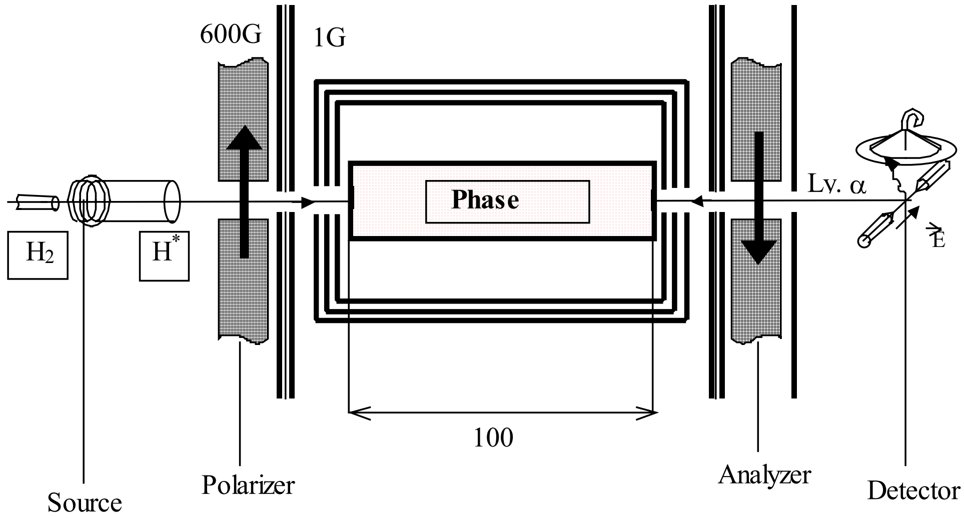

Figure 1 : Scheme of the experiment : a beam of H_2 molecules is bombarded by electrons to produce H* metastable atoms.

This transition has almost no effect on the external atomic motion. Then for an incident plane wave, the complete atom state at the output of the beam splitter is

$$\psi_1(z,t) = e^{i(kz-\omega t)} \otimes \sum_{M=-J}^{+J} c_M \left|M\right\rangle, \tag{1}$$

where $\omega = \hbar k^2 / (2m)$, m being the atom mass. Then follows a "phase object", i.e. a zone ($0 \le z \le L$) where each Zeeman state accumulates its own phase shift in a transverse time-dependent magnetic field profile. This adiabatic evolution is warranted by the fixed direction of the field. Atoms emerging from the phase object are then in state

$$\psi_2(z,t) = e^{i(kz-\omega t)} \otimes \sum_{M=-J}^{+J} c_M \, e^{iM\phi} \left|M\right\rangle, \tag{2}$$

where, in a semi-classical picture largely valid in our case

$$\phi(k) = \frac{g\,\mu_B\, m}{\hbar^2 k} \int_0^L B(z, \frac{m}{\hbar k} z)\, dz\,, \tag{3}$$

g is the Landé factor, μ_B the Bohr magneton and k the wave number. It may be noticed that the k dependence of ϕ means that the external motion is affected by the phase object (longitudinal Stern-Gerlach effect). The last part of the device is symmetric to the first one : a second Majorana zone replaces each state $\left|M\right\rangle$ by a linear superposition referred to a new rotated axis (e.g. z) which leads to the atomic state

$$\psi_3(z,t) = e^{i(kz-\omega t)} \otimes \sum_{M,M'} c_M \, e^{iM\phi} \, b_{MM'} \left|M'\right\rangle, \tag{4}$$

where $b_{MM'}$ are constant coefficients (terms of a Wigner rotation matrix). Then beyond an analyzer picking one specific Zeeman state $\left|M'_A\right\rangle$ the detected intensity has the form

$$I = \left| \sum_M c_M \, b_{MM'_A} \, e^{iM\phi} \right|^2, \tag{5}$$

in which appear interference terms such as

$$2\left|c_M \, c_{M''} b_{MM'_A} \, b_{M''M'_A}\right| \cos[(M-M'')\phi]\,. \tag{6}$$

As usual the experimental conditions are not as perfect as those considered in the calculation : (i) for H*($2s_{1/2}$, F=1) atoms only a partial polarization is achieved by use of the Lamb-Retherford method [7] : atoms traversing at a velocity v a transverse magnetic field of 600 G experience a motional electric field $\mathbf{v} \times \mathbf{B}$ able to quench (via 2s – 2p – 1s transitions) Zeeman states $\left|F=1, M=-1\right\rangle$ and $\left|0,0\right\rangle$; there remain two *incoherent* populations in states $\left|1,0\right\rangle$, $\left|1,+1\right\rangle$ and the final intensity is the sum of two intensities of the form (5); this reduces the contrast but not too dramatically (contrast of 30%) ; (ii) the atomic beam is far from being monokinetic : the velocity distribution is close to a Maxwellian one with $\delta v/v_m \approx 1$ and $v_m = 10$ km/s. As a consequence the intensity has to be averaged over this distribution which gives (as in light interferometry with a white source) a decreasing contrast at increasing interference orders.

Let us now come to the special case of a phase object containing a co-moving magnetic field, namely a transverse field of the form (for $0 \le z \le L$)

$$B(z,t) = B_0 \cos[Kz - 2\pi\,\nu\,(t-t_0)]$$
$$= B_0 \cos(Kz - 2\pi\,\nu\,t + \alpha). \quad (7)$$

The velocity of this field is : $u = \nu\,\Lambda$, where $\Lambda = 2\pi / K$. We shall see in part 3 how such a field can be produced, with a velocity adjustable within the range of atomic velocities. From Eq. (3) one readily gets

$$\phi = \frac{g\mu_B\, B_0 L}{\hbar v}\left[\, Sinc[KL(1-u/v)]\;\cos\alpha - \frac{1-\cos\,[KL(1-u/v)]}{KL(1-u/v)}\;\sin\alpha\,\right], \quad (8)$$

where $Sinc(x) = \sin x / x$. For sake of simplicity let us assume that the co-moving field is synchronized with the atomic motion, i.e. $t_0 = 0$, $\alpha = 0$. If a large number of field periods, $N = KL/(2\pi)$, are present in the phase object then, as a function of v, ϕ is strongly peaked at $v = u$ and it is almost zero elsewhere, the width of $\phi(v)$ being about u/N. This behavior is easily understood. For $v = u$ the atom "sees" a constant field and a phase shift is accumulated. On another hand, if v is slightly higher or lower than u, the atom sees an alternating field and the accumulated phase shift is almost zero. An interferometer is aimed to transform a phase shift into a change of intensity. By choosing a proper operating mode of the Majorana zones (coefficients c_M, $b_{MM'}$ in Eqs. (2) and (4)), it is possible to obtain a *dark* central fringe in the interference pattern, i.e. a minimum I_{min} of intensity at $\phi = 0$. The amplitude B_0 of the co-moving field being chosen such that $\phi(u) = \pi$, a narrow maximum of intensity (I_{max}) is obtained at $v = u$ (see Fig. 2). Under such conditions the interferometer works as a velocity filter, with a background signal (I_{min}) which can be eliminated by substracting the signal obtained with $B_0 = 0$. As the field velocity u can be chosen at will (see part 3) it is actually a monochromator.

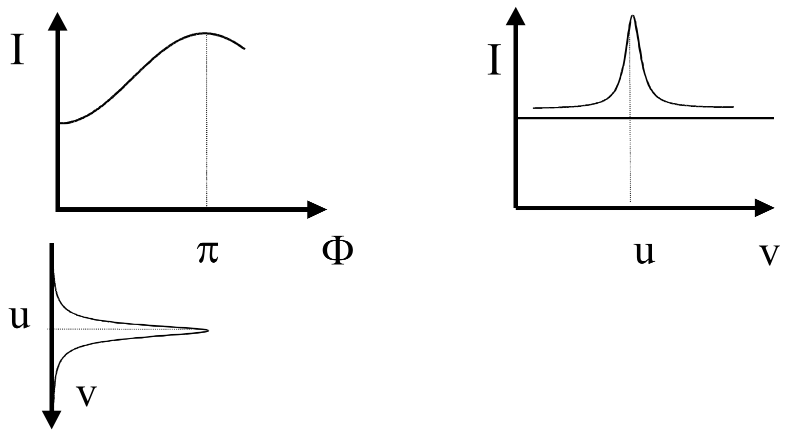

Figure 2 : Principle of the velocity selection. Up left : intensity as a function of the phase-shift ϕ, Down left : phase-shift as a function of the atom velocity v. Up right : Resulting intensity as a function of v.

Its maximum transmission factor $(I_{max} - I_{min}) / I_0$ is independent of the velocity resolution ($\delta v/u \approx 1/N$). It may be also noticed that for small values of the argument KL(1-v/u) the second term in Eq. (8) is negligible, therefore the lack of synchronization just results into a factor $\cos\alpha$ in ϕ which does not affect the principle of the filter, but it can reduce its transmission. It should be noticed that the device works as well with a *bright* central fringe (I_{max}) : in that case the intensity is minimum (I_{min}) at $v = u$ and it rapidly increases up to I_{max} when v differs from u. The net signal is then $I_{max} - I_{min}(v)$. Because of a slightly improved contrast we shall use this latter configuration in the following experiments.

3. Production of the co-moving field

Let us first consider the simpler following problem : how to produce along the z axis a *time-independent* transverse magnetic field of the form

$$B(z) = B_0\;\cos Kz. \quad (9)$$

This can be achieved by using two identical planar periodic currents as those shown in Fig. 3a. For symmetry reasons the field at any point on the z axis is perpendicular to the current planes, i.e. is transverse. It can also be shown that it is stationary (with respect to coordinates x, y) in the vicinity of the z axis. Neglecting fringe effect one gets

$$B(z) = B_1\, f_\Lambda(z), \qquad (10)$$

where $f_\Lambda(z)$ is a periodic function of period Λ. This function has a Fourier series expansion which can be written, by a proper choice of the origin

$$f_\Lambda(z) = \sum_n a_n \cos(nKz)\,, \qquad (11)$$

where n is a positive integer. The amplitude B_1 in Eq. (10) is proportional to the current i in the wires. Let us assume that we use a low-frequency alternating current : $i(t) = I_0 \cos[2\pi\nu(t-t_0)]$. This current produces the space and time-dependent field

$$\begin{aligned} B(z,t) &= \sum_n B_n \cos[2\pi\nu(t-t_0)]\cos(nKz) \\ &= \sum_n \frac{B_n}{2}\left[\cos[2\pi\nu(t-t_0)-nKz] + \cos[2\pi\nu(t-t_0)+nKz]\right] \end{aligned} \qquad (12)$$

Actually not much care has to be paid in trying to exactly reproduce the form (7). Indeed if the geometric parameter K and the frequency ν are chosen such that the field velocity coincide with an atom velocity then the second cosine term in Eq. (12) which is counter-propagating, as well as upper harmonics (which are of a single parity) give negligible contributions to the phase shift. Therefore the field given in Eq. (12) as it is is readily exploitable in the experiment. In our case Λ = 18 mm, then the selected velocity ranges from 2 to 40 km/s when ν is varied from 0.11 to 2.2 MHz. Because of the limited size of our magnetic shields protecting the phase object from external fields, the number of periods is limited to N = 3.5 which gives a relative width of about 30% sufficient to demonstrate the filtering operation.

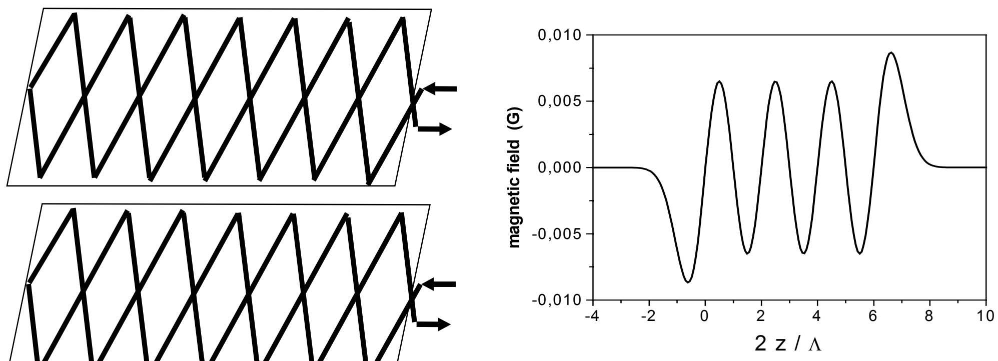

Figure 3 : Left : Circuits used to produce the co-moving field.
Right : static magnetic field profile.

This half integer value has the advantage to eliminate edge effects at z = 0 and z = L (see Fig. 3b). These effects could be also suppressed by restricting the current i(t) to a time interval such that atoms be inside the phase object sufficiently far from the ends. This latter method has the advantage to synchronize the field with the atoms but it implies the use of a pulsed source.

4. Experimental results

To study the effect of the interferometer on the velocity distribution it is first necessary to determine this distribution. To do that a usual time-of-flight technique is used. The voltage applied to the electron gun producing H* atoms is pulsed (pulse duration : 2.5 µs, amplitude : -100 V , period : 250 µs). At a distance D = 400 mm from the source metastable H* atoms are specifically detected by means of the Stark effect : a localized electrostatic field induces the 2s – 2p – 1s transitions followed by the spontaneous emission of a Lyman α photon (λ = 123 nm). These photons are detected by a channel electron multiplier placed behind a MgF_2 window. The time-of-flight distribution (see Fig. 4a) exhibits two contributions : the dominant one is that of "slow" atoms with a mean velocity v_m = 10 km/s produced by the dissociation process $H_2 + e \rightarrow H^*(2s) + H(1s) + e$; the second contribution is that of "fast" atoms (v_m = 40 km/s) produced by a dissociation with double excitation : $H_2 + e \rightarrow H^*(2s) + H^*(n=2) + e$. The frequency range used here (0.2 to 0.8 MHz) together with our limited resolution will allow us to explore the only "slow" part of the distribution.

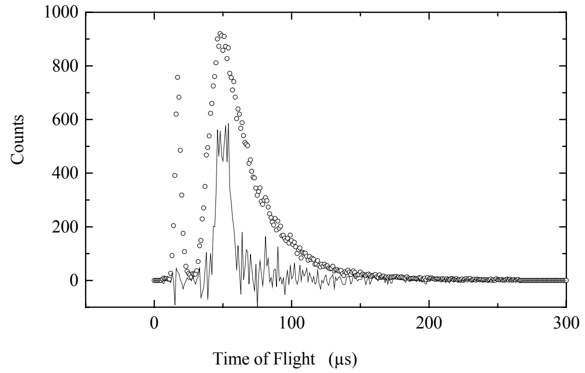

Figure 4 : Time-of-flight distributions. Points : without any field in the phase object, full line : with the co-moving field in the phase object.

With the following arrangement of the magnetic field directions [polarizer P : +x ; fringe field of P : +z ; field in the phase object : +x ; fringe field of the analyzer A : +z ; A : -x], a bright central fringe is obtained in the interference patterns. Then the amplitude B_0 of the co-moving field is adjusted in such a way that $\phi(u) = \pi$. This value is easily found by determining the magnitude of a time-independent field corresponding to the first lateral dark fringe. Fig. 4 shows the time-of-flight distribution obtained at u = 10 km/s (the signal I_{min} is substracted from the constant signal (I_{max}). The filtering effect is clearly seen, with the expected resolution (about 30%). Other slices of the time-of-flight distribution can be obtained as well, with the same transmission and resolution, by varying the current frequency ν. Nevertheless the best way to show that the device actually works as a monochromator is to use a *continuous* H* source and measure the signal as a function of the frequency ν. Then $I_{max} - I_{min}(\nu)$ should reproduce the velocity distribution f(v) in the atom beam. From this distribution it is easy to pass to that ρ(τ) of the time of flights τ = D/v : $\rho(\tau) = \frac{D}{\tau^2} f(\frac{D}{\tau})$.

The resulting measured distribution ρ(τ) is shown in Fig. 5. The range in τ is limited by the frequency range used here (0.2 – 0.8 MHz). It is seen that within this range the distribution is very close in shape to the previous one (Fig. 4a) except for a convolution effect due to the limited resolution and, as expected, a considerable gain on the signal (~ 10^2).

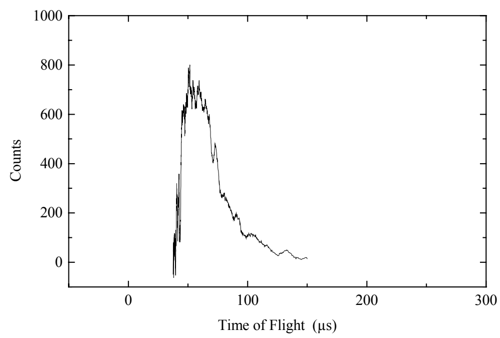

Figure 5 : Time-of-Fight distribution reconstructed from the velocity distribution measured by scanning the time frequency of the co-moving field (see text).

5. Conclusion and perspectives

The operation of a Stern-Gerlach interferometer as a monochromator for neutral atoms has been demonstrated. As it has been mentioned previously [8] further developments can be found by using instead of a simple alternating current a current i(t) having some spectrum in the frequency domain since in that case the dependence of the phase shift on the atom velocity reproduces this spectrum. Actually this technique can be applied to any atom possessing a spin. Work is in progress to transpose the present experiment to Argon metastable atoms (Ar* $3p^5$ 4s, $^3P_2$), using optical transitions at 811 and 801 nm to achieve the polarization and the analysis of Zeeman states. On another hand the present resolution could be highly improved by simply increasing the number N of spatial periods.

A natural extension of the method deals with *accelerated* co-moving fields. By use of a time dependent current frequency such as : $\nu(t) = \nu_0 + At$, one gets an adjustable acceleration of the field $a = \Lambda A$. Such a field could be used in the measurement of gravity. Falling cold atoms (at a temperature of a few µK) traversing a zone of accelerated field will accumulate a phase shift only if a is close to g. A simulation taking in account both the width of the cloud in space (1 mm) and its velocity spread (1 cm/s) shows that a variation of 10% of the interference signal is obtained, for a falling height of 80 cm and a spatial period Λ = 1 mm, as soon as $(a-g)/g = 2.10^{-8}$. It might seem rather tedious to build two circuits containing each 800 periods. In fact this is not necessary : two limited zones of 100 periods (e.g.), placed at the entrance and at the end of the phase object, and separated by a free (falling) path, give about the same result, as in a separated oscillating field zones Ramsey experiment [9]. The sensitivity of the device could even be improved by selecting the time of flight of the atoms, which is easily done for metastable atoms. Nevertheless the greatest improvement should be to use a Bose-Einstein condensate of metastable toms such as those recently obtained for He* [10].

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