# ATOMIC GRADIOMETER WITH COMOVING FIELDS

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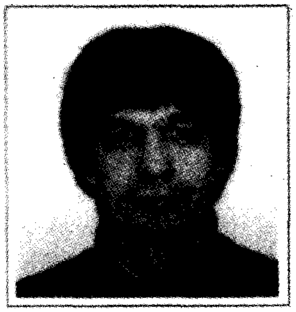

We present results obtained with phase objects produced by comoving fields in Stern Gerlach atom interferometry with metastable $2s^2S_{1/2}$ hydrogen atoms. We show how the genericity property of this kind of fields can be used in accelerometry. We discuss the feasability of an experiment involving cold atoms falling in the earth gravitational field.

## 1 Introduction

We have built a magnetic field profile that is able to follow [1,2] our fast(10 km/s) metastable $H(2s^2S_{1/2})$ hydrogen atoms. We have shown that this field configuration produces a well characterised interference pattern when it is used in a Stern Gerlach atom interferometer. The sharp velocity resonnance sensitivity of this device when the magnetic field is created by sine currents makes it a kind of de Broglie wave Lyot filter. An accurate analysis of the properties of this phase object when non sine currents are used, has lead us to the genericity property of comoving potential: the possible generation of almost any dispersion relation for the atomic waves, allowing to compensate for the natural spreading of wave packets or to follow any velocity change during the passage of the atoms through the interferometer. This last point shows a way to built an accelerometer with reasonnable performances, that can be applied to the measurement of the earth gravitationnal field and its gradients.

## 2 Stern Gerlach Atom Interferometry with $H(2s^2S_{1/2})$ atoms

A detailed description of the apparatus can be found elsewhere [3]. Its basic principle is similar to that of an optical polarization interferometer which consists in a birefringent crystal plate between two crossed linear polarizers with, in addition here the possibility to modify the birefringence value by adjustment of an external parameter. The metastable hydrogen atoms are produced by a 120 eV electronic bombardment of an effusive beam of molecular hydrogen. The polarizer and analyser are of the Lamb Retherford type [4]; they filter $2s^2S_{1/2}$, F = 1, $M_F$ = 0,+1 hyperfine states. A coherent superposition of Zeeman states is created by a sudden change in the magnetic field direction, resulting in a diabatic evolution of the incoming state (Majorana transition). Then a magnetic field profile acts as a "trirefringent" plate, the difference of refraction indices being replaced by the difference of energy levels between states. At last the outcoming atoms undergo another Majorana transition and are detected by a quenching electric field and a Lyman $\alpha$ photon detector after projection on the analyser magnet direction.

## 3 Phase shift and signal computations

The Zeeman energies $\epsilon_M$(z,t) = M $\epsilon$(z,t) of the different magnetic substates M involved in the interference pattern play the role of potential energies for the atomic center of mass motion. They are related to the value of the magnetic field which produces the phase object by $\epsilon(z,t) = g\mu_B B(z,t)$. The Glauber high energy approximation can be used to compute the 1D phaseshift when one neglects backscattering effects. This leads to two expressions; the first one is dispersive with respect to atomic velocity $v_{at}$ when permanent fields are used:

$$\phi_M \;=\; M\,\frac{1}{v_{at}\hbar}\int_{z_{in}}^{z_{out}} dz\,\epsilon(z,t(z)) \;=\; M\,\phi(B) \tag{1}$$

The second one which can be non dispersive with respect to atomic velocity, is obtained by the use of pulsed magnetic interactions: then no forces act on the system, which is the mark of a toplogical effect [5]. Then one gets:

$$\phi_M \;=\; M\,\frac{1}{\hbar}\int_{t_{in}}^{t_{out}} dt\,\epsilon(z(t),t) \;=\; M\,\phi(B) \tag{2}$$

For H($2s^2S_{1/2}$) metastable hydrogen atoms, in our experimental conditions with an imperfect polarisation, the signal is given by:

$$S(B) \;=\; \frac{1}{16}\,(11 \,+\, 4\cos\phi(B) \,+\, \cos 2\,\phi(B)\,)$$

## 4 Comoving magnetic fields

The production of comoving magnetic fields [2] is linked with the formula:

$$\vec{B}\,(\omega,K;z,t) \;=\vec{u}_B\;B_0\cos\left(\omega\,t\;-\;K\,z\right)$$

where $\vec{u}_B$ is the constant direction of the magnetic field, perpendicular to the atomic velocity. It is realised by feeding two wires with $\pi/4$ dephased currentsand twisted in such a way that they respectively make a right and a left handed helix of spatial period $\Lambda \,=\, 2\pi\,/\,K$ and with a symetry axis parallel to the mean atomic velocity. Then the phase velocity $u \,=\, \omega\,/\,K \,=\, \Lambda\,\nu$ of the field is tunable by the tuning of the current frequency $\nu$. If $\Lambda$ is of the order of 1 cm then $\nu$ is given by any LF generator for $u \,=\, 0$ to $100\,km/s$. This device can select by interferences the atoms whose group velocity is resonnant with u with a $\frac{\sin x}{x}$ type resolution. We have checked this interferential filter by two techniques, (i) by time of flight, operating with a constant frequency $\nu$, (ii) by scanning the frequency $\nu$ in CW operation for the atomic beam. Both techniques give the same result wich is, as usual, that the filter resolution is dependent of the number of field period seen by the atomic wave [6].

## 5 Genericity property of comoving fields

It has been shown that the selection of a sharp velocity distribution results from the use of single frequency currents. In the limit of perfect helices of infinite length this corresponds to a $\delta(v_{at} - \nu/\Lambda)$ selection. Then one can easely deduce that the phase shift $\phi(B)$ will be a copy of the frequency spectrum H($\nu$) of the current producing the magnetic field [8]. As a result, one can make a medium for atomic waves with an arbitrary dispersion curve, directly related to the H($\nu$) function. Such a device can be used (i) as a monochromator or as a bichromator for de Broglie waves [7], (ii) to compensate the natural spreading of atomic wave packets, (iii) by shirping the frequency $\nu$ to create accelerated comoving fields whose phase velocity u(t) can fit any form of the group velocity v(t) of accelerated atoms.

## 6 Gravity measurement with cold atoms

The simplest experiment to be proposed could run as follows: let a cloud of cold (or BEC) atoms fall from a definite location in space to a region where exists a pulsed frequency shirped comoving magnetic field, whose axis is parallel to that of the mean earth gravity field. The expected phase shift reads as follows:

$$\phi = \frac{g\,\mu_B\,B_0}{\hbar} \int_{t_1}^{t_2} dt\ \cos(\omega(t) - Kz(t)) = \phi_0\,\theta\,/\,T$$

$$\text{where}\ \phi_0 = \frac{g\,\mu_B\,B_0}{\hbar}\ \text{and}\ T = t_2 - t_1$$

The semiclasical approximation remains valid because the atoms acquire a suffisant velocity when falling, that allows us to chose

$$z(t) = z_0 + v_0\,t + \frac{g\,t}{2}\ \text{and}\ \omega(t) = \omega_0 + \frac{a}{2}$$

for the determination of the constant part of the gravity field, and any other forms for the succesive gradients of this fields. The use of pulsed magnetic fields (with $t_2 - t_1 \leq \tau$, $\tau$ being the transit time of the atoms in the field) makes that the magnetic forces acting on the atoms act in a non dispersive way. The phaseshift is then independent on the atoms initial velocities. The use of successive interaction zones or pulses as used in spin echoes thecniques or Ramsey's SOF will certainly be of great help to improve the sensitivity and resolution of the device.

In an experiment where the length of the magnetic field is L = 1 m with K = $10^3\,m^{-1}$, for initial velocties distributed in the $\pm 1\,cm/s$ domain, $t_1$ = 45ms and $t_2$ = 450ms, and initial conditions such that $\omega_0 + K\,g\,t_0 = 0$, we get for the two independant parameters the values:

$$(\frac{a}{Kg} - 1) \approx \pm 10^{-3} \longleftrightarrow \theta \approx \pm 0,05\,s$$

and

$$B_0 = 1\,\text{to}\,10\,G \longleftrightarrow \frac{\phi_0}{T} = 2\,10^6\,\text{to}\,2\,10^7\,\text{Hz}$$

The typical dephasing is then $\phi \approx \pm 10^5\,\text{to}\,10^6$, and the determination of the ratio $\frac{a}{Kg} - 1$ goes from $\pm 10^{-8}$ to $10^{-9}$. These values reache the range of performances of the other atom interferometers [9].

## 7 Conclusion

We have shown theoretically that the combination of comoving fields and atomic interferometry allow measurements of particles accelerations with an encouraging sensitivity. To go to real measurements and metrological applications one has to optimise the procedure and find the conditions that make the phaseshift stationnary with respect to typical initial conditions. This magnetic method can fit with any magnetic atom or molecule or eventually cluster. Work is in progress to extend its principle to fictious spin systems to include the metrological qualities of optical methods.

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