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Rapid Note

Longitudinal Stern-Gerlach effect for slow cesium atoms

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Abstract. The mechanical Stern-Gerlach effect is investigated in the case of a slow atomic cloud falling through an inhomogeneous magnetic field featuring a strong longitudinal gradient. The resulting Zeeman sublevel state selection is demonstrated under various experimental conditions. Longitudinal spatial separations are in agreement with numerical simulations that take into account the gravitational acceleration and both the transverse and axial magnetic forces. Since separations greater than 20 cm are obtained, potential applications in atom optics are outlined.

PACS. 03.75.Be Atom and neutron optics – 32.80.Pj Optical cooling of atoms; trapping – 39.10.+j Atomic and Molecular beam sources and techniques

1 Introduction

The past ten years have marked the emergence of the new field of Atom Optics [1]. This field was made possible by the development of laser cooling and trapping techniques [2]. Optical components such as mirrors, lenses and interferometers have been demonstrated for atomic beams and have already found numerous applications. The interaction between the atom magnetic moment and magnetic field gradients can be used to tailor atomic beams. Several magnetic atom optical components have been realized recently. Experimental efforts have concentrated either on mirrors [3] or on refractive components [4]. In these works, atoms are prepared prior to the magnetic interaction, in a single magnetic sublevel by means of optical pumping. The atoms are then acted upon by an inhomogeneous magnetic field and the resulting Stern-Gerlach (SG) force steers the atom beam. This, of course, has been well known since the 1920s [5] but the advantage of slow atom beams compared to thermal beams is that much more modest magnetic field amplitudes are required to yield even more dramatic effects. For example, the magnetic state spatial separation of a slow atom beam by SG effect has been demonstrated by the Melbourne and Clayton groups [6] using fields with amplitudes in the mT range and gradients in the T/m range. In their experiment, the spatial separation was transverse to the beam axis as in the historical SG experiment where the magnetic parameters were thousands of times greater [7]. In the present paper, we show that the separation of the different sublevels can be efficiently realized along the beam propagation axis using longitudinal gradients [8]. We report a detailed experimental study of this Longitudinal Stern-Gerlach (LSG) effect.

2 Experimental setup and procedures

In our experiment, a cold Cesium atom cloud is released from a standard cell magneto-optical trap (MOT) [9,10]. During its free fall under the influence of gravity, it crosses the magnetic field created by coils whose axis is along the mean vertical atomic trajectory. The magnetic field modulus gradient is mainly longitudinal. Adiabatic following is ensured and the resulting SG force is shown to yield nine separate clouds corresponding to the nine Zeeman components of the selected $F = 4$ Cesium ground state hyperfine level.

The MOT is located inside a UHV glass cell (residual pressure $\approx 10^{-7}$ Pa). The trapping magnetic field gradient is provided by anti-Helmholtz coils (0.3 T/m along the Ox-coil axis). The trapping light is provided by a high power (≈ 80 mW) laser diode (SDL-5411-G1) which is injection-locked. The master DBR-laser (Yokogawa) is frequency stabilized to the saturated-absorption signal of the Zeeman-shifted $6S_{1/2}\,F = 4 \to 6P_{3/2}\,F' = 5$ transition. Three pairs of circular-polarized ($\sigma^+ - \sigma^-$) beams are used, two of which are in the Oyz-plane at 45° with respect to the Oz-vertical direction. These two pairs are retro-reflected. The third cooling beam pair is parallel to the Ox-axis and its beams are independent, allowing a fine intensity balance. A DBR-laser (SDL-5712-H1) is frequency locked to the $F = 3 \to F' = 4$ transition and superimposed on the trapping beams to repump atoms

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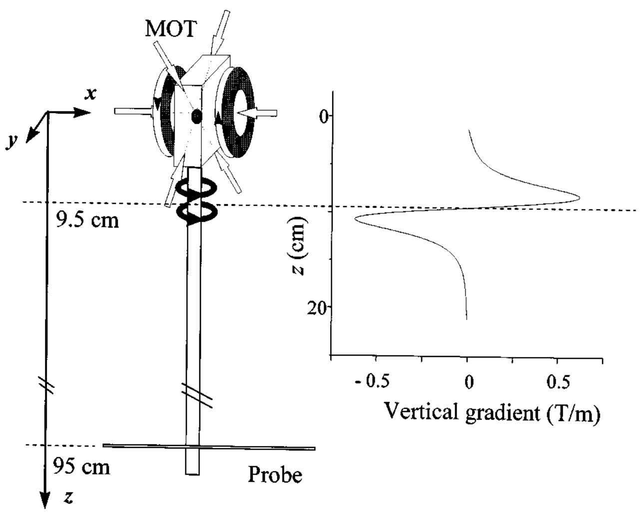

Fig. 1. Schematic diagram of the experimental setup. The inset shows the z-dependence of the $|\mathbf{B}_H|$ magnetic field vertical gradient for a static 5 A current in the coils.

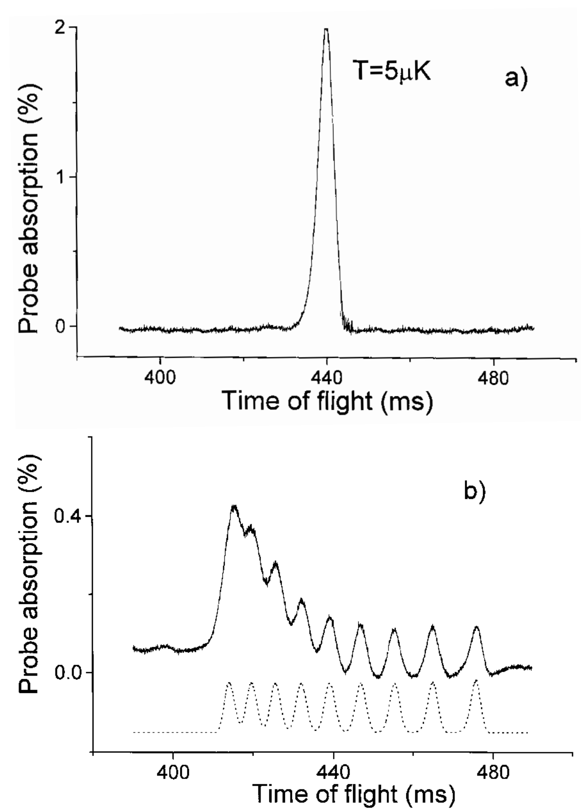

Fig. 2. TOF spectra: a) Reference spectrum registered without any magnetic force applied; b) LSG resolved spectrum for a $I = 5$ A current applied during the [140 ms, 190 ms] time interval after the cloud launching (full line); calculated TOF spectrum (dotted line). Experimental spectra are averaged for 10 repetitions. Calculated spectra are vertically shifted.

out of the lower hyperfine ground state. Three additional pairs of Helmholtz coils having diameters of approximately 70 cm, are used to cancel the earth magnetic field. The following sequence is repeated. Trapping laser detuning is -3Γ during the collecting phase (building time $\approx$ 1 s). At this stage, about 10^8 atoms are confined to a small volume ($\approx$ 1 mm in diameter). The trap is released by switching off the gradient coils ($\approx 10^{-4}$ s); a 10 ms molasses phase follows during which the detuning is swept to -8Γ. At last, the laser beams are shut off and the atoms drop ballistically. After a free fall through a distance of about 1 meter, the temperature of the cesium cloud is determined by a time-of flight (TOF) method. The cloud intersects an horizontal standing wave non saturating probe beam located 950 mm below the trap center. The probe cross section is a 5 mm high $\times$ 15 mm wide ellipse with a power of 50 μW per beam. This probe beam is produced by a further DBR laser (Yokogawa) frequency locked and tuned to the $F = 4 \rightarrow F' = 5$ resonance transition. The recorded signal is the absorption of the probe beam as a function of time; in our conditions of optical thickness, this signal is proportional to the number of atoms crossing the probe beam. The time origin for each cycle is chosen to be that of the molasses laser shut-off. A typical TOF signal is given in Figure 2a where the peak absorption value is 2%. We get a temperature of 5 μK by a Gaussian fit of this signal. The vertical thickness of the probe introduces a small 0.5 μK uncertainty. In the cloud frame, the rms velocity spread is thus 18 mm/s. Since the mean fall time is 440 ms, the cloud rms diameter at the probe altitude is 16 mm; the transverse dimensions of the vacuum components are such that thermal expansion of the cloud during its 1-meter long travel down to the probe beam should not be a limitating parameter.

To demonstrate the LSG effect, we arranged a pair of 60 mm-diameter, 90-turn Helmholtz coils with a center located 95 mm below the trap center. These coils are wrapped around the 40 mm-diameter glass neck of the upper cell (Fig. 1). The atoms cross the symmetry plane of the coils 140 ms after their launch time. The magnetic induction $\mathbf{B}_H$ experienced by the atoms has always its modulus maintained below a 0.03 T peak value corresponding to a 10 A current intensity in the coils. The ground state hyperfine splitting is thus much greater than the Zeeman energy shift and the $F = 4$ state effective magnetic moment remains very close to its weak-field value $\mu_{eff} = -m_F \mu_B/4$ where m_F stands for the magnetic quantum number [11]. Both the definition of the quantization axis and adiabatic following are ensured by an approximately 0.04 mT vertical magnetic field $\mathbf{B}_q$ that is switched on 10 ms after the atoms are launched from the trap. This field is uniform on a decimeter scale. When the Helmholtz coils are supplied with current, the force acting on the atoms in the $F = 4$ hyperfine sublevel, is given by $\mathbf{F}_{SG} = \mu_{eff} \boldsymbol{\nabla} |\mathbf{B}_H + \mathbf{B}_q|$ which remains close to $\mu_{eff} \boldsymbol{\nabla} |\mathbf{B}_H|$. Indeed, both the Helmholtz coil field and gradient are much larger than that of the $\mathbf{B}_q$ field. Among the advantages of coils compared to permanent magnets is the ability to switch them rapidly ($\approx 10^{-3}$ s) on or off. More specifically, in the present work, we choose to pulse the magnetic field in such a way that the atoms

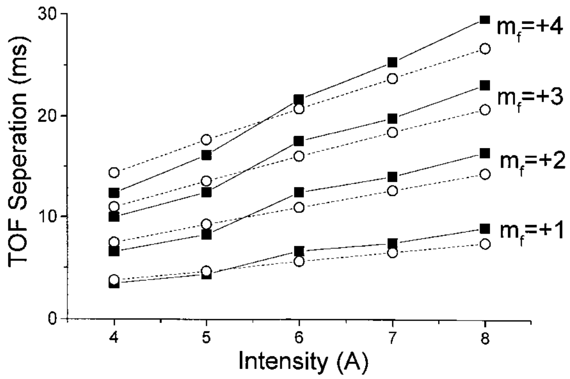

Fig. 3. TOF m_F to 0-peak separations as a function of the coil current intensity for a fixed [140 ms, 190 ms] pulse time interval. Full squares indicate experimental data and open circles are simulation predictions.

experience the strong magnetic gradient after they have crossed the center of the coil system. Then, the sign of the magnetic force acting on the atom external motion remains constant for a given Zeeman sublevel.

3 Experimental results and discussion

A clear demonstration of the LSG effect is given in Figure 2. TOF spectra are registered under the same conditions without any magnetic force (Fig. 2a), and with that due to a 5 A current intensity ($\approx$ 14 mT maximum field and $\approx$ 0.5 T/m maximum gradient) applied during the [140 ms, 190 ms] time interval. The TOF of the central $m_F = 0$-peak in Figure 2b is coincident with that of the sole peak of Figure 2a. The resolved spectrum is compared with a theoretical spectrum obtained by a numerical simulation that takes into account the initial velocity and position distributions and that integrates the semi-classical motion equations under the influence of the 3D-SG force. The peak central positions are well fitted. They are related both to m_F and to the m_F-dependent field variation during the current pulse. Atoms with different m_F's at the same position and having the same velocity at the beginning of the pulse experience distinct dynamics during the pulse; they are released at different spatial positions and with different velocities when the current is switched off. Furthermore, since it seems rather difficult to know the initial level populations, we assume that these sublevels are equally populated before the SG interaction takes place. The theoretical spectrum agrees with the experimental one except for the strong asymmetry in the m_F-populations that remains the only unexplained feature of the experiment. It is worth emphasizing that transverse lensing effects are almost negligible under our experimental conditions. Finally, it is significant that state selection is obtained without any heating or beam deflection.

TOF-spectra have been obtained for increasing values of the coil current intensity for a given pulse time interval. Figure 3 gives peak TOF splittings as a function of this parameter. It shows that the polarized cloud separations can be chosen very easily according to the desired application. The discrepancies between theory and experiment might be related to a simplification of the coil geometry in the simulation. Namely, while wire coils are wounded within grooves with outer diameter 64 mm, inner diameter 56 mm and thickness 4 mm, the magnetic field used in the simulation is that of two infinitely thin plane coils each of diameter 60 mm separated by a distance of 30 mm.

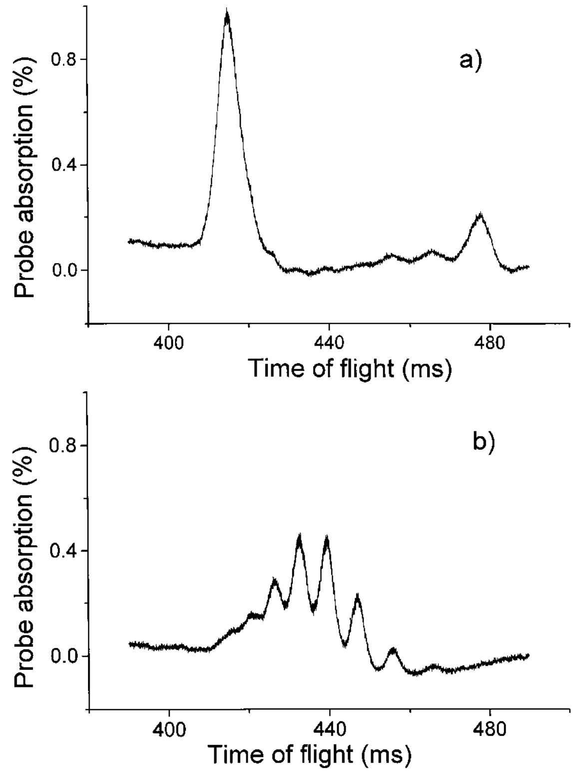

Fig. 4. LSG splitted TOF spectra under the conditions of Figure 2b plus optical pumping (see text). a) σ polarization; b) π polarization.

Since the demonstrated typical time separation between magnetic states is in the 10 ms range corresponding to spatial separations in the 5 cm range, a wide variety of applications can be devised, including atomic interferometry [12]. Some of them require well defined weights for the m_F-populations which can be obtained by optical pumping techniques. To do so, part of the light from the probe laser is used to optically prepare the atoms spin polarization [13] before they travel down the inhomogeneous magnetic field. The cloud intersects a horizontal (lin // lin) polarized standing wave non saturating beam located 40 mm below the trap center and tuned to the $F = 4 \rightarrow F' = 5$ resonance transition. The beam cross section is a 8-mm-diameter circle with a power of 20 μW per beam. The atoms interact with the beam after the vertical magnetic field $\mathbf{B}_q$ is switched on. LSG splitted TOF spectra are recorded as previously described with optical pumping implemented. When the π polarization is chosen, the low $|m_F|$ values are seen to be enriched (Fig. 4b). On the contrary, when the σ polarization is chosen, the high $|m_F|$ values are enhanced (Fig. 4a). These results are perfectly consistent with what one expects from elementary optical pumping theory. The relative intensity of the two outmost peaks in the alignement experiment seems to be due the already quoted asymmetry in the m_F-distribution. Due to technical difficulties, the most efficient polarizing scheme where the pumping light is directed along the magnetic field with circular polarisation [14] was not used since the demonstration of magnetic state selection has already been achieved in the reported experiments.

4 Conclusion

In this letter, we have demonstrated the efficiency of LSG separation for cold cesium atoms falling through inhomogeneous longitudinal magnetic fields. In spite of tedious but tractable problems related to transverse lensing, the field of slow atom optics with inhomogeneous magnetic fields appears more promising than initially foreseen [15]. The present technique can be applied to any paramagnetic species to control its internal degree of freedom. Collisions with cold polarized beams have not yet been performed but represent an attractive application. Spin-polarized beam scattering experiments might be carried out to study surface magnetism. In both cases, the redistribution over m_F levels can be observed while the state selection introduces no alteration of the beam properties.

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