Measurement of the Friction Coefficient in 1D Corkscrew Optical Molasses by Stimulated Rayleigh Spectroscopy

B. Lounis,[(2)] J.-Y. Courtois,[(1)] P. Verkerk,[(1)] C. Salomon,[(2)] and G. Grynberg[(1)]

[(1)]*Laboratoire de Spectroscopie Hertzienne de l'Ecole Normale Supérieure, Université Pierre et Marie Curie, Case 74, F-75252 Paris CEDEX 05, France*

[(2)]*Laboratoire de Spectroscopie Hertzienne de l'Ecole Normale Supérieure, 24, rue Lhomond, F-75231 Paris CEDEX 05, France*

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The transmission spectrum of a probe beam interacting with one-dimensional cesium optical molasses made from two circularly cross-polarized cooling beams (corkscrew molasses) displays a narrow ($\approx$30–70 kHz) Rayleigh resonance. From the width of this resonance we deduce the friction coefficient of the cooling force to be $\alpha=(5.8\pm0.4)\hbar k^2$ for a detuning from resonance equal to 3Γ. This value is in quantitative agreement with theoretical predictions. We also show that the shape of the Rayleigh resonance depends dramatically on the efficiency of the sub-Doppler cooling mechanism.

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Laser cooling of neutral atoms has been a subject of considerable interest during the last few years [1]. In particular, a large number of experiments have focused on temperature measurements of three-dimensional (3D) optical molasses [2], providing important qualitative tests of the sub-Doppler cooling mechanisms. However, a quantitative comparison between experiment and theory remains a challenge because of the lack of 3D models. By contrast, the possibility to obtain one-dimensional optical molasses in a transient way [3–5] by taking advantage of the high density [6] and large number [7] of cold atoms achievable in magneto-optical traps permits quantitative tests of 1D theories [8–10]. For example, quantization of the atomic motion in 1D lin⊥lin optical molasses was observed in pump-probe experiments [4,11] or by analyzing the fluorescence of the molasses [5]. We present here an experimental investigation of 1D σ^+-σ^- molasses which is very different from lin⊥lin molasses because of the absence of atom localization. Using probe transmission spectroscopy, we observe Raman resonances due to the occurrence of differently populated and light-shifted ground-state Zeeman sublevels and a narrow ($\approx$30–70 kHz) Rayleigh resonance. We prove that the width of this resonance is equal to $2\alpha/M$, where α is a friction coefficient of the cooling force and M is the atomic mass. Our measured value of α and its dependence on laser intensity and detuning are found in quantitative agreement with the recent theory of Castin [12] to better than 10%. This method thus gives direct access to the cooling mechanism alone, by contrast with temperature measurements which are sensitive to the balance between heating and cooling effects.

The principle of our experiment is to probe 1D σ^+-σ^- optical molasses with a weak beam. The molasses is obtained as follows: Cesium atoms are cooled and trapped by three pairs of σ^+-σ^- counterpropagating beams in a magneto-optical trap. After this loading and cooling phase both the inhomogeneous magnetic field and the trapping beams are completely switched off [13]. A pump wave of frequency ω made of two counterpropagating beams having σ^+-σ^- polarizations is then switched on. 1D optical molasses is thus achieved in a transient way (typically 15 ms during which the atomic density decreases slowly). We monitor the transmitted intensity of a weak traveling probe wave frequency ω_p making a 5° angle with the pump wave. The cooling beams as well as the beams of frequencies ω and ω_p are derived from a stabilized diode laser and are tuned to the red side of the $6S_{1/2}(F=4)\rightarrow 6P_{3/2}(F'=5)$ transition. Typical intensities for the pump and probe beams are, respectively, $I=10$ mW/cm^2 and $I_p=0.1$ mW/cm^2. We show in Fig. 1 the probe transmission spectrum versus

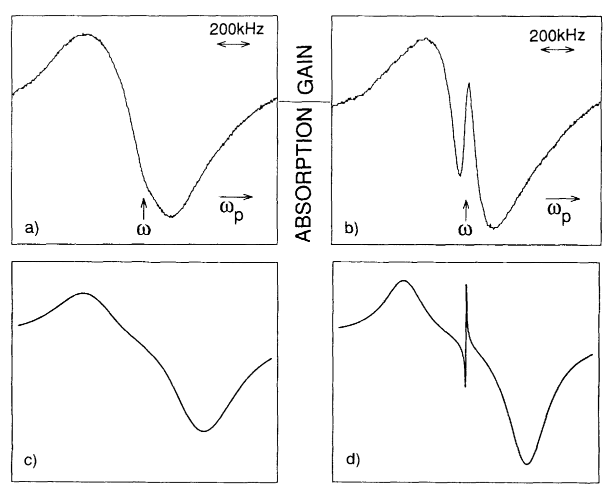

FIG. 1. Probe transmission spectra through 1D σ^+-σ^- optical molasses for two different polarizations of the probe beam. (a),(b) Experimental recordings obtained for a pump intensity equal to 10 mW/cm^2 and a detuning $\Delta=-2\Gamma$. (c),(d) Associated theoretical spectra calculated for a $J_g=1\rightarrow J_e=2$ transition. (a) [(b)] The probe has a circular polarization orthogonal (parallel) to that of the copropagating cooling beam. The theoretical Rayleigh resonance appears much narrower than the experimental curve. This is because the friction coefficient for a $J_g=1\rightarrow J_e=2$ transition is about 10 times smaller than in the case of a $J_g=4\rightarrow J_e=5$ transition.

$\omega_p - \omega$ for two different polarizations of the probe beam and for a detuning from resonance $\Delta = -2\Gamma$ (where $\Gamma/2\pi = 5.3$ MHz is the natural linewidth of the excited state). Figure 1(a) corresponds to the case where the probe has a circular polarization orthogonal to that of the beam ω which propagates in the same direction. For this situation the absorption varies smoothly around $\omega_p - \omega = 0$ with a maximum for $\omega_p = \omega + \Omega_R$ and a minimum for $\omega_p = \omega - \Omega_R$. These structures have already been reported in 3D experiments [14,15] and interpreted in terms of stimulated Raman processes between differently populated and light-shifted ground-state Zeeman sublevels [15]. Figure 1(b) corresponds to the case where the probe beam has the same circular polarization as the copropagating cooling beam ω. In this situation, the probe absorption spectrum exhibits the preceding Raman resonances and an additional narrow dispersionlike Rayleigh resonance (width ≈ 70 kHz). As long as the sub-Doppler cooling mechanism is efficient, this structure holds and its width varies as $1/\Delta$ and is independent of I, as shown in Fig. 2.

We now sketch an interpretation of these spectra by indicating a few elements of a full theoretical treatment which will be published in a forthcoming article. Consider the simple case of a $J_g = 1 \to J_e = 2$ atomic transition with cooling beams having the same intensity and all laser beams being collinear (along the $0z$ axis). To interpret the origin and the different features of the central resonance of Fig. 1(b), we combine the probe beam with the cooling beam that propagates in the same direction. One then obtains a circularly polarized beam whose intensity exhibits a time-modulated component at frequency $\delta = \omega_p - \omega$. The modification of the light shifts of the ground-state Zeeman sublevels by this beam can be described by a fictitious magnetic field [16] oscillating at frequency δ along the direction of propagation $0z$ of the laser beams [17]. In the rotating frame attached to the atom moving with velocity v along $0z$ [8], the Hamiltonian part of the atom-field coupling is

$$H = H_0 + kvJ_z - \Omega_B \cos(\delta t) J_z \,, \tag{1}$$

where H_0 includes the reactive effects of the pump beams (light shifts Δ'), and J_z stands for the component of the atomic angular momentum along $0z$. The second term of the right-hand side of (1) corresponds to the inertial term discussed in [8]. The third term, where Ω_B is proportional to the probe amplitude, describes the effect of the fictitious magnetic field. In the limit where $|\delta| \ll \Delta'$ the internal state of the atom follows adiabatically the time evolution of H. Following [8], one derives the mean value of the longitudinal angular momentum for an atom of velocity v:

$$\langle J_z(v) \rangle \propto \hbar \frac{kv - \Omega_B \cos(\delta t)}{\Delta'} \,. \tag{2}$$

From the expression of $\langle J_z(v) \rangle$, one can deduce the average force due to the radiation pressure experienced by an atom of velocity v [8]:

$$F = -\alpha v + (f_P + f_B)\cos(\delta t) \,, \tag{3}$$

where $\alpha \propto \hbar k^2 \Gamma/\Delta$ is the friction coefficient of the cooling force due to the pump beams. f_P and f_B account for the modification of the radiation pressure due to the probe beam. Because our approach is linear in the probe amplitude this modification arises from only two processes. First, f_P originates from the interference of the probe and the copropagating pump beams which causes the intensity and hence the radiation pressure on an atom (whose internal state is determined by the cooling beams) to oscillate at frequency δ. Second, it is well known from the theory of cooling in 1D σ^+-σ^- molasses [8,9] that any modification of the atomic internal state results in a modification of the radiation pressure. The component f_B ($\propto \Omega_B \hbar k \Gamma/\Delta$) is associated with such an effect: The perturbation of the internal state by the probe-induced fictitious magnetic field leads to a modification of the radiation pressure of the cooling beams. In steady state, the average velocity $\bar{v}$ of the molasses is obtained by solving the equation of dynamics. This yields

$$\bar{v} = \frac{f_P + f_B}{M} \frac{1}{\delta^2 + (\alpha/M)^2} [\delta \sin(\delta t) + (\alpha/M)\cos(\delta t)] \,. \tag{4}$$

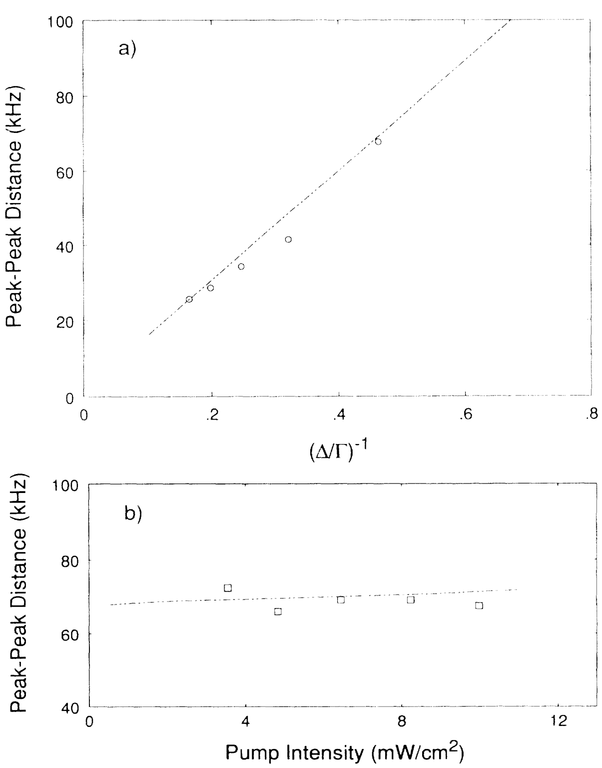

FIG. 2. Dependence of the width of the Rayleigh resonance (a) on the detuning from resonance Δ and (b) on the laser intensity I. The dashed lines correspond to the theoretical predictions of Castin.

Experiments performed with a real static longitudinal magnetic field B_0 [18] have demonstrated a locking of the mean atomic velocity around a value proportional to B_0. In the present situation, the mean velocity oscillates at frequency δ and is dephased with respect to the fictitious magnetic field because of the finite response time (M/a) of the atomic velocity. The average longitudinal angular momentum of the molasses is expected to be on the order of $\langle J_z(\bar{v})\rangle$ which is deduced from Eqs. (2) and (4):

$$\langle J_z(\bar{v})\rangle \propto \frac{\hbar k}{M\Delta'}\left[\frac{(f_P+f_B)\delta}{(a/M)^2+\delta^2}\sin(\delta t)+\frac{(a/M)f_P-(M/a)\delta^2 f_B}{(a/M)^2+\delta^2}\cos(\delta t)\right]. \tag{5}$$

The polarization P of the atomic sample induced by a circularly polarized light depends on $\langle J_z\rangle$ because the Clebsch-Gordon coefficients are not the same for transitions starting from different Zeeman sublevels of the ground state $[P\propto(\chi_0+\chi_1\langle J_z\rangle)E]$. The energy transfer between the probe and the medium is

$$\propto \overline{E_p\,dP/dt}=\chi_1\overline{E_pEd\langle J_z\rangle/dt}\,,$$

and thus arises only from the component of $\langle J_z(\bar{v})\rangle$ which is $\pi/2$ phase shifted with respect to the modulated part E_pE of the incident field intensity. The Rayleigh resonance is thus a dispersive curve [19] with peak-to-peak distance equal to $2a/M$. Whereas this energy transfer is only sensitive to the $\sin(\delta t)$ component of $\langle J_z(\bar{v})\rangle$, other signals such as the four-wave-mixing phase conjugation that we also observed depend on both components of $\langle J_z(\bar{v})\rangle$. As shown in [8,12] a/M is predicted to be independent of the pump beams' intensity and to vary as $1/\Delta$. Our experimental observations (Fig. 2) confirm these predictions and validate the interpretation of the Rayleigh resonance [20]. Our measured value of a is [21]

$$a/M\Gamma \approx (13.4\pm0.8)\times10^{-3}\Gamma/\Delta$$

and is in good quantitative agreement with a theoretical calculation performed by Castin [12] in the case of a $F=4\rightarrow F'=5$ transition, which predicts a slope of 14.1×10^{-3}. Note that this value is a factor of 10 larger than the value predicted for a $J_g=1\rightarrow J_e=2$ transition. The interpretation of the central resonance is also supported by a more rigorous calculation based on a Fokker-Planck equation for the atomic momentum distribution, performed for a $J_g=1\rightarrow J_e=2$ transition, which allows one to reproduce probe transmission spectra in good qualitative agreement with the experiment [Fig. 1(d)].

In the rotating frame attached to the atomic rest frame the pump wave keeps a *fixed* linear polarization, so that the Hamiltonian part of the atom-cooling field interaction is completely space independent and couples a small number of levels belonging to the same closed family [8]. Because the interaction between the probe field and the atoms is also space independent in the rotating frame for the polarization configuration of Fig. 1(b), the probe beam can only induce stimulated transitions between levels belonging to the same family. In contrast, in the polarization configuration of Fig. 1(a), the atom-probe field coupling exhibits a spatial dependence of the form e^{2ikz} in the rotating frame. The probe beam thus induces stimulated transitions between states of *different* families whose energy separation is roughly proportional to the atomic velocity. As a result, the resonances of the probe transmission spectrum of Fig. 1(a) are more sensitive to the Doppler broadening and appear broader than in Fig. 1(b). A calculation of the probe transmission spectrum performed by using the atomic momentum distribution derived from a Fokker-Planck equation and by neglecting recoil-induced resonances [22] is shown in Fig. 1(c). The Raman resonances actually appear broader than in Fig. 1(d), and the difference of width between the two polarization configurations of the probe beam is related to the longitudinal Doppler width of the optical molasses [21].

We now describe what is observed near the sub-Doppler cooling threshold. The central resonance progressively changes shape and finally transforms into an inverted narrower dispersionlike structure (Fig. 3). Below threshold a non-negligible part of the atoms has a momentum out of the capture range of the sub-Doppler cooling force, so that the damping rate of the probe-induced momentum modification is now affected by the weaker *Doppler* cooling friction force [8]. However, the observation of a width proportional to the Doppler fric-

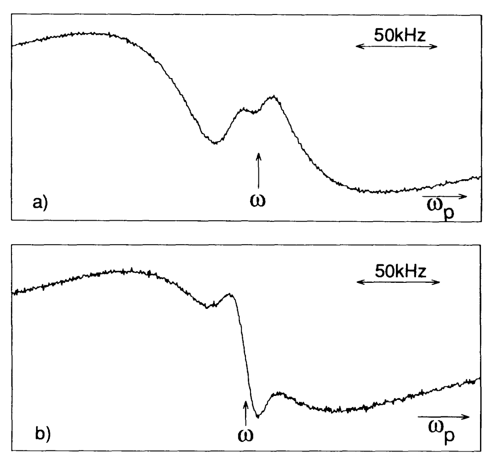

FIG. 3. Central resonance near the sub-Doppler cooling threshold. The pump polarization of the probe beam is the same as in Fig. 1(b), and the detuning is $\Delta=-3\Gamma$. (a) Pump beam intensity $I=2.5$ mW/cm^2 (near threshold). (b) $I=1.6$ mW/cm^2 (below threshold). Note that the narrower resonance is inverted.

tion coefficient is hidden by other broadening mechanisms and in particular by the residual transverse Doppler broadening.

In conclusion, we have demonstrated that Rayleigh spectroscopy is a powerful and convenient method to measure directly the friction coefficient of the sub-Doppler cooling force in σ^+-σ^- molasses. The good agreement with theoretical predictions obtained both for σ^+-σ^- and for lin⊥lin [11] molasses proves that the physical characteristics of 1D optical molasses are now well understood. Pump-probe experiments appear to be a technique of remarkable interest to investigate the properties of optical molasses and we are currently performing similar experiments in 2D and 3D configurations. In fact, using a molasses made of three pairs of counterpropagating σ^+-σ^- beams and using a probe beam having the same circular polarization as a copropagating molasses beam, we have observed a central resonance having a width as narrow as 400 Hz [23]. The fact that this width is more than 1 order of magnitude smaller than the width obtained in 1D molasses may be related to the fact that the 3D sub-Doppler friction coefficient is much smaller than the 1D friction coefficient [24]. However, this interpretation still needs to be confirmed by theoretical calculations.

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