EUROPHYSICS LETTERS 15 August 1992

Europhys. Lett., **19** (8), pp. 669-674 (1992)

Magnetically Induced Laser Cooling for Ne*: Approaching the Recoil Limit.

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(received 6 April 1992; accepted in final form 30 June 1992)

PACS. 32.80P – Optical cooling of atoms; trapping.
PACS. 42.50 – Quantum optics.

Abstract. – Magnetically induced laser cooling to temperatures close to the recoil limit is investigated in one dimension. For a metastable neon beam, we present high-precision measurements investigating the actual temperature limit in this cooling process. Using time-of-flight techniques to reduce the effect of the longitudinal velocity spread, we observe cooling at small magnetic field toward $v = 0$ with an r.m.s. width of the distribution of 5.4 cm/s, well below the Doppler limit. At a larger magnetic field (0.4 Gauss) the velocity-selective resonances are extremely sharp. Here we find the r.m.s. width of the distribution to be 3.4 cm/s, only 1.1 times the recoil speed $\hbar k/M$, corresponding to a temperature $T = 2.7\ \mu K$.

The subject of cooling atoms with laser light continues to undergo increasing activity in both theory and experiment. The theoretical understanding of laser cooling has grown rapidly over the last few years, and a large number of practical applications in other fields have been put forward. A very simple form of laser cooling (Doppler cooling) occurs when slowly moving two-level atoms are placed in a low-intensity standing wave of laser light, slightly red-detuned from an atomic optical transition. Slow atoms experience a friction force $F = -\beta_D v$ proportional and opposite to their velocities, caused by the different absorption rates from the Doppler detuned laser beams that compose the standing wave. The motion of atoms in such a laser field is similar to that in molasses: every movement is strongly damped. In this Doppler cooling scheme, the friction coefficient β_D is proportional to the laser intensity.

At the same time, atoms will be heated by the random recoils of spontaneous-emission events. If the atomic ensemble is assumed to undergo a Brownian-like motion in velocity space, with steps $\hbar k/M$ small compared to the average velocity of the atoms, the atomic ensemble can be described by a Fokker-Planck equation with a force F and a diffusion rate D. In the same low-intensity limit, the diffusion rate is proportional to the spontaneous-emission rate and thus to the laser intensity. Assuming the diffusion to be velocity independent, and the force to be a pure damping force, the ensemble approaches a Maxwell-Boltzmann distribution with an equivalent temperature $k_B T = D/\beta_D$, independent of the laser intensity.

At a detuning $\Delta \equiv \omega_{\text{laser}} - \omega_{\text{atom}} = -\Gamma/2$ the temperature reaches the low limit of this cooling scheme, the so-called «Doppler limit» $T_D = \hbar\gamma/2k_B$. Although the first experiments reported this limit [1], later more careful experiments yielded much lower temperatures [2]. Recent insight [3, 4] has shown that the light shifts and optical-pumping–induced population differences among the magnetic sublevels of the lower state can provide the explanation of these sub-Doppler temperatures. This results, for some particular laser configurations, in a friction coefficient β that is much larger than β_D and independent of the laser intensity. Since the heating by momentum diffusion is still linear in the laser intensity, the final temperature can be much lower than T_D at lower laser intensity.

The atomic recoil from one single photon poses a limit to this temperature. When atoms have momentum $p \sim$ few $\hbar k$, the approximation of small momentum steps necessary for the Fokker-Planck treatment begins to fail, since the atoms suffer momentum kicks comparable to their average momentum. Furthermore, their deBroglie wavelengths approach the optical wavelength so they can no longer be localized in the standing wave, as required by these pictures [3, 4]. At very low intensity, the velocity capture range of the cooling mechanism can become smaller than the recoil from one photon [5]. The actual temperature limit has been calculated for some specific cases [6]. Experimentally, the final temperature has been measured for several «sub-Doppler» cooling schemes [7, 8].

In this paper we report measurements of the temperatures resulting from Magnetically Induced Laser Cooling (MILC) [9-11] in a one-dimensional optical molasses. We investigate this cooling process in a magnetic-field range $0 < B < 1$ G, and compare our data with the results of a Fokker-Planck description of our experiment. The force was obtained from the operator-based theory of laser cooling by Nienhuis *et al.* [11, 12], which can be used to calculate the force as a function of velocity averaged over a wavelength for an arbitrary one-dimensional laser field.

MILC can occur in a standing wave of circularly polarized laser light in the presence of a small magnetic field perpendicular to the light propagation axis. The standing laser field induces spatially varying light shifts (a.c. Stark shifts) of the lower-level substates. For the limit of large detuning and low intensity, this light shift of the lower states is equal to $\hbar\Omega_{m_g} = \hbar\Delta s_{m_g}/2[1 + (2\Delta/\Gamma)^2]$ with s_{m_g} the on-resonance saturation parameter for the different substates of the lower level. The competition between optical pumping of the atoms to the most light-shifted magnetic substate and redistribution of them by the Larmor precession in the nodes of the laser field results in cooling of the atoms toward $v = 0$.

At larger magnetic field, this picture involving competition between optical pumping and Larmor precession breaks down because these rates are no longer comparable. The physical mechanism is different and there is now cooling toward two nonzero velocities $v = \pm v_r$, where $v_r = \omega_{\text{Larmor}}/2k$. The forces in this regime have been described in the model studied by Shang *et al.* [10] for the $J_g = 1/2 \to J_e = 3/2$ optical transition. They obtained analytical results for this specific transition by transforming the evolution equations of the density matrix to a frame rotating around the magnetic-field axis with the Larmor frequency ω_{Larmor}. The force is then approximated by assuming the optical pumping rate to be small compared to the Larmor precession rate. Using their notation, we find

$$F = -\frac{\beta(v - v_r)}{1 + [(v - v_r)/v_c]^2} - \frac{\beta(v + v_r)}{1 + [(v + v_r)/v_c]^2}. \tag{1}$$

The damping coefficient β is independent of the laser intensity, however the capture range v_c

is proportional to the optical pumping rate and therefore linear in the laser intensity. Equation (1) shows that for $v_r > v_c$ (magnetic field not too small) cooling to two velocities $v = \pm v_r$ should occur. However, the assumptions leading to eq. (1) are valid only for $v_r \gg v_c$. Numerical calculations show that, even for $v_r \approx 4v_c$, the low-field mechanism dominates; the force has a single zero and the atoms are cooled towards $v = 0$, with a damping coefficient larger than in the regime of eq. (1). At zero magnetic field $\beta = 0$ and the cooling force disappears, since no magnetic redistribution over the lower-level substates takes place.

Our experiment was performed in an atomic-beam apparatus previously used for an atomic-beam deflection experiment [13]. We drive the optical transition from the metastable $\{3s\}\,^3P_2$ state to the short-lived (19.3 ns) $\{3p\}\,^3D_3$ state in neon (Paschen notation). This transition is in the red ($\lambda = 640.225$ nm) and has a natural width of $\Gamma/2\pi = 8.2$ MHz. The metastable state g-factor is 1.50. This constitutes an effective two-level system except for its magnetic degeneracy. The supersonic beam of metastable neon atoms was formed in a DC discharge source with an average velocity of 1200 m/s and with an r.m.s. spread of 200 m/s [14].

The atomic beam is defined by a (50×500) μm slit, that effectively acts as a skimmer. Directly thereafter the atoms cross a transverse, circularly polarized standing wave, 45 mm in diameter. The average interaction time is thus ~ 38 μs or ~ 2000 upper-state lifetimes. The magnetic field in the interaction region is controlled by a full set of Helmholtz coils, giving a magnetic field that is constant to within 1% over the interaction region. It is carefully zeroed using the Hanle effect on the transition to the $\{3p\}\,^3D_2$ state, which decays in cascade to the $\{1s\}\,^1S_0$ ground state. The resulting atomic-beam profile is sampled by a (50×2000) μm movable slit, 2.82 m downstream of the interaction region, in front of an Auger-type metastable atom detector. The atomic beam can be chopped to enable time-of-flight analysis of the longitudinal velocity of the atoms. Combined with the high angular resolution of 18 μrad FWHM, this yields resolution of about 0.7 times the recoil velocity $\hbar k/M \simeq 3.1$ cm/s.

The laser beam is produced by a frequency-stabilized spectra physics ring dye laser locked to a saturated absorption gas discharge cell. The laser frequency was thus known with respect to the center of the optical transition frequency to an accuracy $\Delta\omega/2\pi \simeq 1$ MHz, much less than the natural linewidth $\Gamma/2\pi = 8.2$ MHz. The laser light is transported to the atomic-beam apparatus in a polarization-maintaining single-mode optical fiber. There the laser beam is collimated using a microscope objective and a cylindrical telescope to cover the interaction region. The laser beam has a waist radius (half width at $1/e^2$ of the intensity) in the atomic-beam propagation direction of 18 mm in the interaction region. The approximately Gaussian laser beam profile is cut off, due to the aperture of the lenses, at, relative to the center of the laser beam, -10 mm at the upstream side and 35 mm at the downstream side. The atoms experience light intensity that varies by about a factor of 50 over the interaction region.

In fig. 1*a*) a typical directly measured atomic-beam profile is shown. The profile is measured by scanning the narrow slit in front of the metastable atom detector across the atomic-beam profile. The profile shown is obtained by dividing the signal with the cooling laser «on» by that with the laser «off», thus eliminating the influence of source fluctuations. One observes a strong enhancement of the atomic-beam intensity at zero velocity, as well as a depletion region, from where the atoms are «swept» inward to the central peak by the cooling process. A small increase in baseline is observed, which is a result of residual Doppler cooling. The results were analyzed by a least-squares fitting procedure, using a model function of two Gaussians with the same area and the same central position, but with opposite sign of the amplitudes. In velocity space, the width of the positive Gaussian, *i.e.* the central peak, is far below the value corresponding to the Doppler temperature.

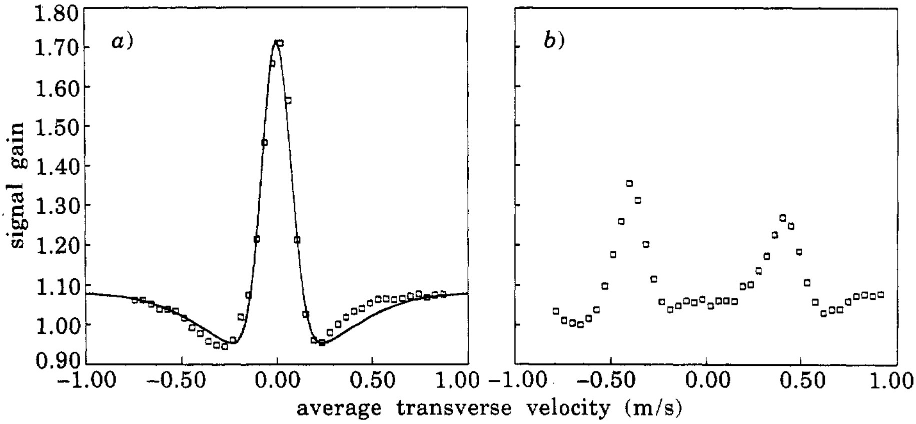

Fig. 1. – Typical directly measured beam profiles without time-of-flight analysis of the longitudinal velocity, with *a*) magnetic field $B = 0.09$ G with cooling to $v = 0$ and *b*) magnetic field $B = 0.60$ G with cooling to $v = \pm v_r$. Both profiles were measured at a laser intensity $I/I_{sat} = 1.5$ and a detuning $\Delta/2\pi = -25$ MHz. The squares represent the measurements, whereas the drawn line in *a*) represents a least-squares fit to the data.

These data were taken with an incident laser intensity (at the center of the profile) of $6.1\,\text{mW/cm}^2$ ($I/I_{sat} = 1.5$), a detuning of $\Delta/2\pi = -25$ MHz (-3Γ) and a magnetic field $B = 0.09$ G in the direction orthogonal to both the laser beam and the atomic beam. With these parameters, the conditions where a single zero exists in the force *vs.* velocity curves are fulfilled except in the low-intensity tail of the laser beam profile. The influence of Doppler cooling is much smaller than that of sub-Doppler cooling mechanisms. As a check the detuning was also reversed, showing a strong depletion of atoms at zero velocity. At zero magnetic field no sub-Doppler cooling is observed as expected.

In fig. 1*b*) a typical measurement at a higher magnetic field of 0.60 G at the same laser power and detuning is shown. Two peaks at a velocity v_r and $-v_r$ are observed, which are slightly broader than the peak at $v = 0$ in fig. 1*a*). This is caused by finite longitudinal-velocity spread ($\Delta v_\parallel / v_\parallel = 16\%$) of the atomic beam. Because we actually measure the position of the cooled atoms on the detector, a spread in longitudinal atomic velocity will cause atoms with equal transverse velocity to spread out over the detector. The inequality of the peak heights is probably due to an imbalance of the laser beams, which destroys the antisymmetry in the force *vs.* velocity curves. This has been confirmed by numerical simulations. We checked the linear dependence of the resonance velocity on the magnetic field, and found excellent agreement.

To eliminate the spatial broadening of the peaks cooled to nonzero velocity, the atomic beam was chopped to enable time-of-flight analysis of the longitudinal velocity of the cooled atoms, resulting in $\Delta v_\parallel / v_\parallel = 3\%$. Thus the combined longitudinal-velocity and transverse-position measurements yield a strongly improved transverse-velocity resolution. These measurements show that the broadening of the peaks at larger magnetic field was indeed an effect of the finite longitudinal-velocity spread of the atomic beam.

Typical measurements are shown in fig. 2. At $v_\perp = \pm v_r$ (fig. 2*b*)), the width of the individual peaks is smaller than the width of the peak at $v = 0$ (fig. 2*a*)). The r.m.s. spread $\sigma_\perp = \sqrt{\langle \Delta v_\perp^2 \rangle}$ of the narrowest fitted Gaussian profile at $v_\perp = -v_r$ is only $\sigma_\perp = 1.1\hbar k/M$, corresponding to a «temperature» $T_\perp = 2.7\,\mu\text{K}$. The width of the peak at the $+v_r$ resonance is $1.5\hbar k/M$. Again the asymmetry can be attributed to an imbalance of the laser beams.

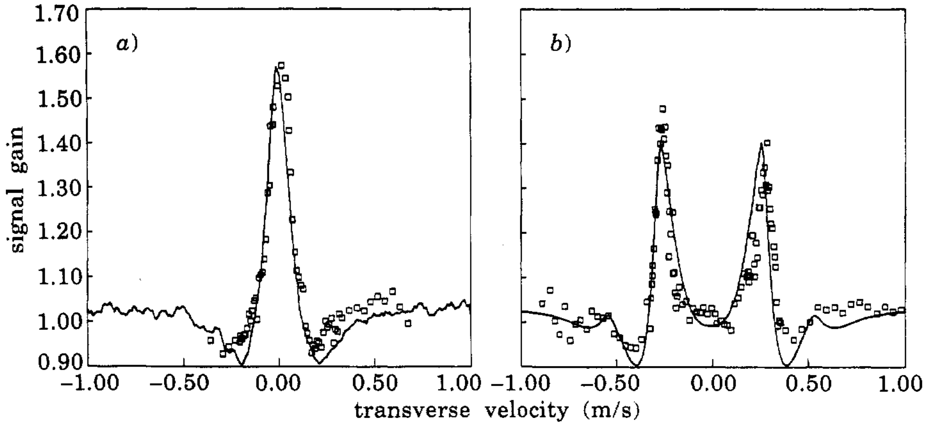

Fig. 2. – Measured final velocity distributions using the time-of-flight analysis ($\Delta v_{\parallel}/v_{\parallel} = 3\%$) at *a*) small magnetic field $B = 0.07$ G and $I/I_{sat} = 1.3$ and *b*) larger magnetic field $B = 0.40$ G and $I/I_{sat} = 1.8$. Both profiles were taken at a detuning $\Delta/2\pi = -32$ MHz (-3.9Γ). The squares represent the experimental data, whereas the drawn line represents the theoretical calculations.

These velocity-resolved measurements are compared to the results of a numerical integration of the Fokker-Planck equation using the force as calculated using the formalism by Nienhuis *et al.* [12]. The direct numerical integration of the Fokker-Planck equation with the parameters of the experiments proved to be difficult, especially for the low-field data (fig. 2*a*)), because of the very sharp resonances in the force *vs.* velocity curves at low light intensity. Therefore, we used a Monte Carlo integration technique to calculate the theoretical curve in fig. 2*a*). The diffusion coefficient for the low–magnetic-field measurements is based on the random character of spontaneous emission plus a stimulated contribution which is assumed to be 0.5 times the spontaneous contribution. To obtain good agreement for cooling to $v_\perp = \pm v_r$ at a larger magnetic field, it was necessary to assume the stimulated diffusion term equal to zero. Even so, the experimental peaks are markedly sharper (fitted width approximately 30% smaller) than the theoretical curves. The physical background of this phenomenon is yet not clear. With these assumptions, the agreement with the experiment is good.

Summarizing, we have carefully analyzed sub-Doppler laser cooling of metastable neon atoms with high-precision measurements using velocity analysis of the longitudinal velocity. We confirmed the dependence of the resonance velocity on the magnetic field, and the disappearance of the cooling process at zero magnetic field [10]. The ultimate «temperature» is very close to the recoil limit, which raises questions on the validity of the physical picture and approximations that are generally used. Nevertheless, the agreement with calculations based on the general theory by Nienhuis *et al.* [12] and the Fokker-Planck equation is very good.

However, for higher magnetic field the diffusion seems to be reduced to purely the contribution of the spontaneous emission, or even below that. The latter might be taken as an indication for suppression of the diffusion near the resonance velocities. Such suppression has been predicted for the σ^+-σ^- configuration [15]. On the other hand, the breakdown of the Fokker-Planck description does not necessarily mean that the actual velocity distributions should be broader than those predicted by the Fokker-Planck equation [6]. Only fully quantum-mechanical calculations can provide the answers to these questions.

In the future, we plan to extend our measurements to different polarization configurations and magnetic fields. If a relatively large magnetic field is used in a σ^+-σ^- laser configuration, the degeneracy of the magnetic lower-level substates can be lifted. In this configuration, «pseudodark states» can occur in these $J_g = 2 \rightarrow J_e = 3$ transitions of the metastable states of the noble gases. We will try to answer the tantalizing question if these dark states can produce velocity selective coherent population trapping [16, 17], and whether there is a connection between this and velocity selective magnetic resonances.

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We acknowledge the support of the Dutch Foundation for Fundamental Research on Matter (FOM), the Dutch Royal Academy of Sciences (KNAW), NSF, ONR and NATO.

REFERENCES

[1] Chu S., Hollberg L., Bjorkholm J. E., Cable A. and Ashkin A., *Phys. Rev. Lett.*, **55** (1985) 48.

[2] Lett P., Watts R., Westbrook C., Phillips W. D., Gould P. and Metcalf H., *Phys. Rev. Lett.*, **61** (1988) 169.

[3] Dalibard J. and Cohen-Tannoudji C., *J. Opt. Soc. Am. B*, **6** (1989) 2023.

[4] Ungar P. J., Weiss D. S., Riis E. and Chu S., *J. Opt. Soc. Am. B*, **6** (1989) 2058.

[5] Cohen-Tannoudji C. N. and Phillips W. D., *Phys. Today*, **43**, no. 10 (1990) 33.

[6] Castin Y., Dalibard J. and Cohen-Tannoudji C., *Proceedings of the LIKE Workshop*, edited by L. Moi (ETS Editrice, Pisa) 1991.

[7] Lett P. D., Phillips W. D., Rolston S. L., Tanner C. E., Watts R. N. and Westbrook C. I., *J. Opt. Soc. Am. B*, **6** (1989) 2084.

[8] Salomon C., Dalibard J., Phillips W. D., Clarion A. and Guellati S., *Europhys. Lett.*, **12** (1990) 683.

[9] Sheehy B., Shang S.-Q., van der Straten P. and Metcalf H. J., *Phys. Rev. Lett.*, **64** (1990) 858.

[10] Shang S.-Q., Sheehy B., van der Straten P. and Metcalf H. J., *Phys. Rev. Lett.*, **65** (1990) 317.

[11] van der Straten P., Shang S.-Q., Sheehy B., Metcalf H. and Nienhuis G., preprint (1992).

[12] Nienhuis G., van der Straten P. and Shang S.-Q., *Phys. Rev. A*, **44** (1991) 462.

[13] Hoogerland M. D., Wijnands M. N. H., Senhorst H. J., Beijerinck H. C. W. and van Leeuwen K. A. H., *Phys. Rev. Lett.*, **65** (1990) 1559.

[14] Verheyen M. J., Beijerinck H. C. W., Driessen J. P. J. and Verster N. F., *J. Phys. B*, **10** (1984) 15.

[15] Walhout M., Dalibard J., Rolston S. L. and Phillips W. D., preprint (1992).

[16] Mauri F., Papoff F. and Arimondo E., *Proceedings of the LIKE Workshop*, edited by L. Moi (ETS Editrice, Pisa) 1991.

[17] Aspect A., Arimondo E., Kaiser R., Vansteenkiste N. and Cohen-Tannoudji C., *Phys. Rev. Lett.*, **61** (1989) 826.