Non-ergodic laser cooling

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Atoms can now be laser cooled, in one, two and three dimensions, below the limit corresponding to the recoil energy of an atom absorbing or emitting a single photon. Recent works have shown that all subrecoil cooling schemes are based on an anomalous random walk of the atom in momentum space which does not obey the central limit theorem and which introduces a fundamental non-ergodicity in the cooling process. Lévy statistics turn out to be very useful for analysing such a situation, since they provide quantitative results for the long time limit of the momentum distribution. In this paper, we briefly review these theoretical works and we give a few references where more details can be found. We also mention a few recent experiments which have been stimulated by these theoretical developments.

Laser cooling consists of using resonant exchanges of momentum between atoms and photons for reducing the momentum spread δp of an ensemble of atoms. A natural momentum scale in laser cooling is the photon momentum $\hbar k$. Because of the randomness of spontaneous emission (fluorescence photons are emitted in random directions and at random times), it is not easy to achieve $\delta p < \hbar k$, i.e. to reduce δp below the so-called *single photon recoil limit*. Up to now, two *subrecoil* cooling methods have been proposed and demonstrated: velocity selective coherent population trapping (VSCPT) (Aspect *et al.* 1988) and Raman cooling (Kasevich & Chu 1992).

The basic idea of subrecoil cooling is to achieve a situation where the photon absorption rate $R(\boldsymbol{p})$ vanishes for atoms with zero momentum. During their random walk in momentum space, atoms can then remain trapped in the neighbourhood of $\boldsymbol{p} = \boldsymbol{0}$ during a very long time τ. They accumulate there and their momentum distribution gets a width δp which is found to decrease indefinitely when the interaction time θ tends to infinity. The vanishing of $R(\boldsymbol{p})$ when $\boldsymbol{p} \to \boldsymbol{0}$ is achieved by using destructive quantum interference between absorption amplitudes (VSCPT), or appropriate sequences of stimulated Raman and optical pumping pulses (Raman cooling).

In fact, a connection can be established between subrecoil cooling and the theory of *anomalous random walks* where the *central limit theorem* (CLT) of usual Gaussian statistics is no longer valid. The key point is that the distribution $P(\tau)$ of the trapping times τ in the small zone near $\boldsymbol{p} = \boldsymbol{0}$ is a broad distribution, with a power-law tail decreasing as $\tau^{-(1+\mu)}$ when $\tau \to \infty$. The exponent μ is equal to D/α, where D is the number of dimensions to be cooled ($D = 1, 2, 3$) and where α characterizes how $R(\boldsymbol{p})$ behaves near $\boldsymbol{p} = \boldsymbol{0}$: $R(\boldsymbol{p}) \propto p^{\alpha}$, with $p = |\boldsymbol{p}|$. When $\mu < 1$, $P(\tau)$ is so broad that $\langle\tau\rangle$ diverges. When $\mu < 2$, $\langle\tau\rangle$ exists but the variance of τ diverges. In such cases, the

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central limit theorem can obviously no longer be used for studying the distribution of the total trapping time after N entries in the trap separated by N exits. We suppose here that, due to additional friction mechanisms, the distribution of the first return times $\hat{\tau}$ in the trap (time spent out of the trap between two successive visits in the trap) is a narrow distribution, so that the mean value and the variance of $\hat{\tau}$ both exist.

It is possible to extend the CLT to broad distributions with power-law tails (Gnedenko & Kolmogorov 1954; Bouchaud & Georges 1990). The corresponding statistics, called *Lévy statistics*, provide new physical insights into subrecoil cooling (Bardou *et al.* 1994; Bardou 1995; Cohen-Tannoudji 1996; Bardou *et al.* 1998). Numerical simulations can easily demonstrate the importance of rare events which dominate the anomalous random walks (Bardou 1995). Another important feature of subrecoil cooling is the absence of steady-state. Regardless of how long the interaction time θ is, there are always atomic evolution times (trapping times when p is small enough) which can be longer than θ. This introduces a fundamental non-ergodicity in the problem and this is why such a cooling can be called *non-ergodic cooling*. Another interest of such a new approach based on Lévy statistics is to provide quantitative predicitions for the momentum distribution $\mathcal{P}(\boldsymbol{p})$ of the cooled atoms. Analytical expressions can be derived for the maximum height, the half-width, the area under the narrow peak and the decrease of the wings of $\mathcal{P}(\boldsymbol{p})$.

New experiments have been stimulated by these theoretical developments. The first one concerns an improvement of one-dimensional Raman cooling (Reichel *et al.* 1995; Reichel 1996). By changing the shape of the laser pulses which are used for the stimulated Raman transitions, it is possible to change the exponent α characterizing the increase of the photon absorption rate $R(\boldsymbol{p})$ near $\boldsymbol{p} = \boldsymbol{0}$. Depending whether one uses Blackman pulses, as in the original experiment (Kasevich & Chu 1992), or square pulses, α is equal to 4 or 2. It turns out that square pulses are not only simpler to use, but that they are more efficient: they lead to a more rapid decrease of the width δp of the momentum distribution with the interaction time θ. Experiments performed on Cs atoms with square pulses confirm these predictions: one-dimensional temperatures as low as 3 nK have been obtained. The variation of δp with θ has been studied and found in agreement with the theoretical law. It is also possible to use the analytical expression obtained for the height of the peak of the momentum distribution for finding the optimal values of the cooling parameters corresponding to a given value of θ.

Obtaining a momentum spread δp smaller than the photon momentum $\hbar k$ is also very interesting for demonstrating the wave nature of atomic motion, since condition $\delta p < \hbar k$ is equivalent to having spatial atomic coherence lengths $h/\delta p$ larger than the laser wavelength $2\pi/k$. Atoms are then delocalized in the laser wave. Using one-dimensional Raman cooling with square pulses, it has been possible recently to observe the *Bloch oscillations* of ultracold Cs atoms which appear when these atoms are submitted to a constant inertial force in a periodic optical potential (Ben Dahan *et al.* 1996).

Finally, one can mention recent experimental developments of VSCPT subrecoil cooling which have provided 3D-atomic wave packets with very long spatial coherence lengths (Lawall *et al.* 1995, 1996; Kulin *et al.* 1997).

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References

Aspect, A., Arimondo, E., Kaiser, R., Vansteenkiste, N. & Cohen-Tannoudji, C. 1988 Laser cooling below the one-photon recoil energy by velocity-selective coherent population trapping. *Phys. Rev. Lett.* **61**, 826–829.

Bardou, F. 1995 Subrecoil laser cooling by dark resonances: experiments with metastable helium atoms; quantum Monte-Carlo and Lévy flight approaches. Paris XI University thesis. (In French.)

Bardou, F. Bouchaud, J.-P., Emile, O., Aspect, A. & Cohen-Tannoudji, C. 1994 Subrecoil laser cooling and Lévy flights. *Phys. Rev. Lett.* **72**, 203–206.

Bardou, F., Bouchaud, J.-P., Aspect, A. & Cohen-Tannoudji, C. 1998 Non-ergodic cooling: subrecoil cooling and Lévy statistics. (In the press.)

Ben Dahan, M., Peik, E., Reichel, J., Castin, Y. & Salomon, C. 1996 Bloch oscillations of atoms in an optical potential. *Phys. Rev. Lett.* **76**, 4508–4511.

Bouchaud, J.-P. & Georges, A. 1990 Anomalous diffusion in disordered media: statistical mechanisms, models and physical applications. *Phys. Rep.* **195**, 127–293.

Cohen-Tannoudji, C. 1996 *Lecture notes.* Collège de France.

Gnedenko, B. V. & Kolmogorov, A. N. 1954 *Limit distributions for sums of independent random variables.* Addison-Wesley.

Kasevich, M. & Chu, S. 1992 Laser cooling below a photon recoil with three-level atoms. *Phys. Rev. Lett.* **69**, 1741–1744.

Kulin, S., Saubamea, B., Peik, E., Lawall, J., Hijmans, T. W., Leduc, M. & Cohen-Tannoudji, C. 1997 Coherent manipulation of atomic wavepackets by adiabatic transfer. *Phys. Rev. Lett.* **78**, 4185–4188

Lawall, J., Kulin, S., Saubamea, B., Bigelow, N., Leduc, M. & Cohen-Tannoudji, C. 1995 Three-dimensional laser cooling of helium beyond the single-photon recoil limit. *Phys. Rev. Lett.* **75**, 4194–4197.

Lawall, J., Kulin, S., Saubamea, B., Bigelow, N., Leduc, M. & Cohen-Tannoudji, C. 1996 Subrecoil laser cooling into a single wavepacket by velocity selective coherent population trapping followed by adiabatic passage. *Laser Phys.* **6**, 153–158.

Reichel, J. 1996 Raman cooling and Lévy flights: cesium atoms cooled down to the nanokelvin range. Paris VI University thesis. (In French.)

Reichel, J., Bardou, F., Ben Dahan, M., Peik, E., Rand, S., Salomon, C. & Cohen-Tannoudji, C. 1995 Raman cooling of cesium below 3 nK: new approach inspired by Lévy flight statistics. *Phys. Rev. Lett.* **75**, 4575–4578.