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Laser Manipulation of Neutral Atoms

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Abstract

We present an overview of the field of laser manipulation of atoms. Examples and trends are given for: laser cooling and trapping; subrecoil cooling; probes of cold atoms; collective effects in cold atoms samples; atom optics and interferometry.

1. Introduction

The possibility of changing the trajectory of atoms by resonant interaction with light was experimentally demonstrated as early as 1993 by F. Frisch [1] who reported the deflection of an atomic beam irradiated at right angle by the resonant light from a discharge lamp. Manipulation of atoms by light really started as a field of research when it was realized, in the late seventies, that even a modest power of resonant laser light (a few milliwatts per square centimeter) allows one to achieve huge accelerations, as large as $10^6\,\mathrm{ms}^{-2}$ for sodium atoms. Significant changes of the velocities of atoms at room temperature (typically several hundreds of ms^{-1}) thus become achievable in a vacuum chamber of reasonable size [2, 3]. The next step consisted in the demonstration of the possibility of compensating the changing Doppler effect during the deceleration of the atoms of an atomic beam, either by Zeeman tuning the atomic transition frequency [4] or by chirping the laser frequency [5].

The atoms can then be brought at rest, and it is possible to stop a thermal atomic beam on a distance of the order of one meter, so that the stopped atoms can be captured by a magnetic trap [6]. However, the "stopped" atoms have in fact a remaining kinetic energy corresponding to a temperature of a few kelvins, and only a small fraction of them can be captured in the shallow traps available for neutral atoms. This difficulty can be overcome thanks to laser cooling, the first demonstration of which [7] provided atoms at a temperature below one millikelvin inside a so-called Optical Molasses.

After these two major achievements of 1985, the field litterally exploded, as well for the number of groups working in the field as for the variety of new effects which have been discovered. Two special issues on The Mechanical Effects of Light [8] and on Laser Cooling and Trapping of Atoms [9], respectively published in 1985 and 1989, allow the interested reader to follow the dramatic advances in a few years. An excellent and very complete theoretical presentation can be found in the Les Houches course by C. Cohen-Tannoudji [10]. Several interesting reviews may be found in the proceedings of the Enrico Fermi school of 1991 [11].

* Some of the work described in this paper has been achieved when the authors were with Collège de France and Ecole Normale Supérieure, Paris (A.A., C.I.W., R.K., N.V.), or with NIST, Gaithersburgh (C.I.W).

Nowadays, the field is so broad that it is totally impossible to make a complete review of the achievements. Our aim is to give a flavour of the field to an audience which is mostly composed of non-experts. The examples are understood as illustrations, and not as an exhaustive review.

We will first describe laser cooling: since the realization of the first optical molasses of 1985, many unanticipated results have been found, and one can now cool atoms in the microkelvin range, and even below. The second subject, of major importance for applications, is trapping of neutral atoms: it will be presented in Section 3.

Although they are not as simple as sometimes claimed, the experimental methods of laser cooling and trapping are now well enough mastered that interesting applications have already been reported. We present two types of applications. The first one, which includes collisions, is devoted to collective effects in samples of cold atoms. The second field of applications is Atom Optics, which is using the methods of laser manipulation of atoms in order to do with atoms what ordinary optics does with photons, i.e. reflection, refraction, diffraction, interferences [12, 13].

2. Laser cooling

2.1. *Doppler cooling*

The resonant radiation pressure force, exerted by a laser wave (wavevector $\boldsymbol{k}_{\mathrm{L}}$, angular frequency ω_{L}) onto an atom with a quasi-resonant two-level transition at ω_{At}, depends on the atomic velocity $\boldsymbol{v}$, because of the Doppler effect. In 1975, it has been suggested [14, 15] that this dependence may be used for cooling an ensemble of atoms [16]. Indeed, an atom placed in counterpropagating laser waves detuned below resonance (Fig. 1) will be more in resonance with the waves opposed to its motion, because of the Doppler effect. The radiation pressure will thus damp the atomic motion.

An expansion around $\boldsymbol{v} = 0$ of the total radiation pressure leads to a simple equation of evolution of the atomic velocity:

$$\frac{\mathrm{d}\boldsymbol{v}}{\mathrm{d}t} = \frac{1}{\tau_{\mathrm{D}}}\,\boldsymbol{v}, \tag{1a}$$

where the damping time τ_{D} is of the order of

$$\tau_{\mathrm{D}} \cong \left(\frac{\hbar k_{\mathrm{L}}^2}{M}\right)^{-1} \tag{1b}$$

provided that the laser detuning is chosen negative (below resonance) of the order of the linewidth Γ of the atomic transition. This atomic velocity damping time is typically a few tens of microseconds, i.e. the laser waves act as a very viscous medium, called "Optical Molasses". The rms atomic

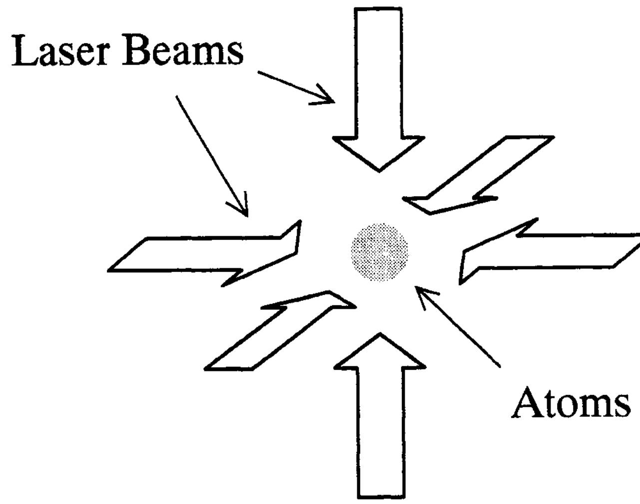


Fig. 1. Optical molasses. An atom placed in the intersection of three pairs of counterpropagating laser waves detuned below resonance is submitted to a radiation pressure always opposed to its motion. The laser waves act as a very viscous medium which damps the velocity of the atoms: an atomic vapour can thus be cooled.

velocity thus decreases, amounting to cooling. On the other hand, in addition to the average force responsible for the cooling effect, the radiation pressure force has also a fluctuating part due to the discrete nature of the momentum exchanges between the atoms and the photons (each photon has a linear momentum $\hbar k_L$). This provokes a random motion in the velocity space, which amounts to heating, competing with the Doppler cooling effect. The equilibrium situation corresponds to the so-called "Doppler Temperature" which, for an adequate choice of the laser parameters (intensity, detuning), is expected to be as low as the "Doppler limit"

$$T_D = \frac{\hbar\Gamma}{2k_B} \quad (2)$$

(k_B is the Boltzmann constant). For current situations, for instance with alkali atoms, the Doppler limit is in the hundred microkelvins range.

In the first demonstration of optical molasses [7], a temperature about 240 microkelvins was found, in agreement with the expected value from eq. (2) for the case of sodium atoms. A similar result (i.e. agreement with the expected value of eq. (2)) was also found for cesium [17]. In addition to these quite low temperatures, it was also found that optical molasses, although not a trap, is a remarkable method for confining atoms for a long time, more than one second. Indeed, it takes a long time, for an atom caught in a molasses, to diffuse to the edge of the lasers intersection, and the molasses can thus act as an accumulator of atoms provided that it is fed by atoms slow enough to be captured.

2.2. *Below the Doppler limit*

More precise temperature measurements, first carried out on sodium [18], then confirmed on cesium [19] and on sodium [20], have shown that the temperature of atoms in an optical molasses may be much lower, by almost two orders of magnitude, than the Doppler "limit" of eq. (2).

One should not be surprised by this evolution of the experimental situation, since these measurements are extremely difficult. They rely on ballistic methods, aiming at determining the velocity distribution of the atoms in the molasses. The first method [7], called "Release and Recapture", consisted in switching off the lasers for a controlled amount of time during which atoms fly away, and applying the lasers again, (the switching off and on of the laser can easily be done in a time short compared to any mechanical evolution of the atoms). The number of atoms which have escaped is evaluated by comparing the total atomic fluorescence rate before and after the laser switching. This number of lost atoms is clearly related to the initial atomic velocity distribution in the molasses, which can thus be deduced from such measurements, yielding eventually a value for the temperature.

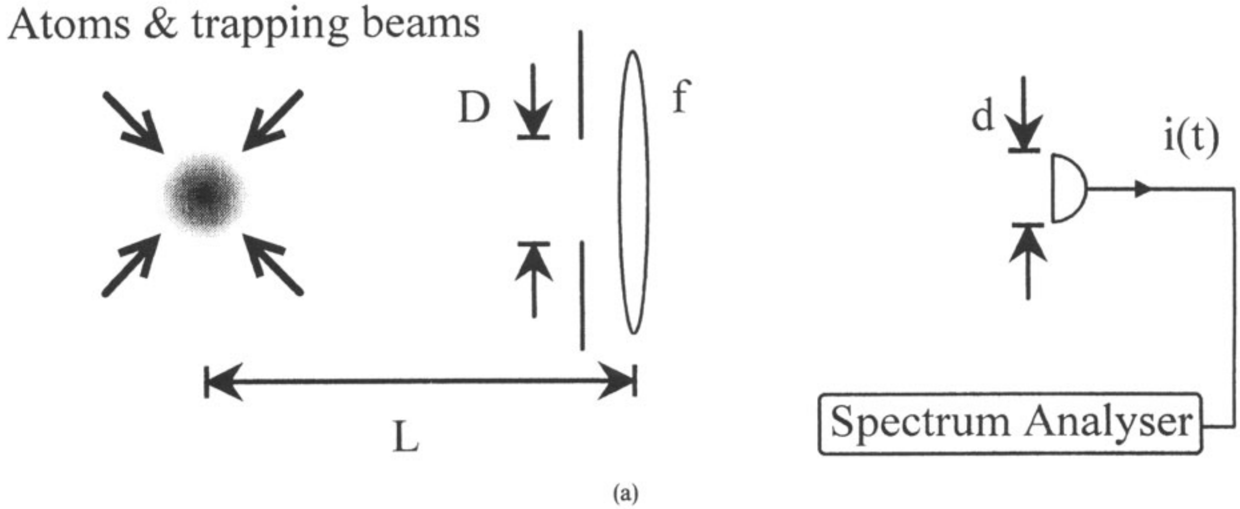
This method becomes more and more imprecise when the velocities are so small that the released atoms escape because of gravity rather than because of their initial velocity. This is why more sophisticated methods have been developed [18–21], which have allowed sub-Doppler temperatures to be determined with a good accuracy.

A most used method is the Time Of Flight (TOF) measurement, in which the atoms in the molasses, released by suddenly turning off the molasses laser beams, fall onto a probe laser beam situated a few centimeters below the molasses center, where they are detected by fluorescence. The distribution of the arrival times reflects the initial velocity distribution. Temperatures in the microkelvin range, two orders of magnitude smaller than the Doppler limit, have been observed [22].

These surprising observations have been theoretically interpreted by a new cooling mechanism based on the existence of gradients of polarization [23, 24], in the complicated electromagnetic field resulting from the addition of at least four non-coplanar travelling waves, the polarisation of which cannot be all identical. A subtle interplay between the modulated light-shifts, and the changes of optical pumping rates related to the modulation of the light field, leads to efficient mechanisms for loosing atomic kinetic energy, such as "Sisyphus cooling in the ground state" [10]. The extensive experimental studies of references [21, 22] support the theoretical models, which can now make quantitative predictions in three dimensions [25].

In subsequent works, it has been demonstrated that Sisyphus sub-Doppler cooling can also be obtained, at least at one dimension, with different configurations where there is no light polarisation gradient, but in presence of a transverse magnetic field [26, 27]. It has been possible to experimentally differentiate Doppler cooling and Sisyphus cooling, thanks to a choice of the atomic transition and of the polarisation scheme, where the two effects have opposite signs and compete [28].

Most of the first methods that have been developed in order to measure sub-Doppler temperatures, like TOF, rely on the fact that the laser beams can be turned off almost instantaneously (compared to the typical time scale of the atomic motion), and the velocity distribution is then analyzed by a balistic method. However, another type of method has appeared, in which one can obtain *in situ* information about the atomic velocities inside the molasses, without destroying the molasses. The basic idea is to analyse the spectrum of the laser light elastically scattered by the atoms in the molasses. This spectrum should reflect the velocity distribution because of the Doppler effect. A



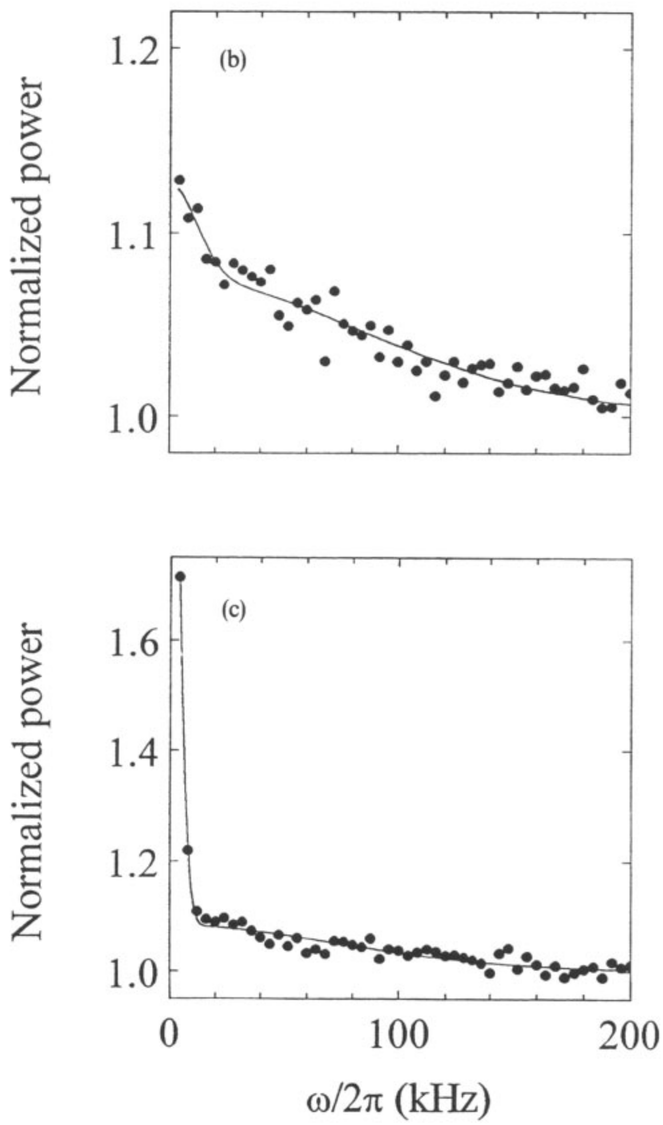


Fig. 2. Intensity correlations in the scattered light from laser cooled atoms, as a non-destructive probe of the atomic motion (after Ref. [31]). (a) Schematic experimental set up. The power spectrum of the fluctuations of the photocurrent is the Fourier transform of the light intensity autocorrelation function. (b) and (c) Examples of spectra, for different atomic temperatures (28 μK and 16 μK respectively, corresponding to $v_{rms} = 5\,cm\,s^{-1}$ in the case of Rubidium). The broad pedestal corresponds to the Doppler broadening. The narrow peak is interpreted as due to a Lamb-Dicke effect, for atoms localised in the potential wells associated with the modulated light shifts in the cooling standing wave.

technical problem is the excellent spectral resolution which is required [29], better than 100 kHz. In order to achieve such a resolution, a heterodyning method has been successfully used [30].

More recently, we have developped another *in situ* non-destructive probe of cold atoms, based on the analysis of intensity correlations in the scattered light from cold atoms in an optical molasses [31]. The idea is that the atoms are moving at various velocities, so that the light elastically scattered from different atoms into a photodetector, has different Doppler shifts (Fig. 2). These different frequencies can beat against each other causing the photocurrent to fluctuate. If the scattering is purely elastic, the power spectrum of these fluctuations is simply related to the motion of the atoms.

Figure 2 shows examples of the photocurrent power. It shows a pedestal with a width reflecting the Doppler broadening due to the atomic velocity distribution. The observed width, in the 100 kHz range, is in reasonable agreement with the value expected from velocity measurements by a Time Of Flight method. In addition, we clearly see a narrow peak a few kHz wide, around the zero frequency. This narrow peak, already observed in the heterodyne experiment [30], has been interpreted as a Lamb-Dicke effect [32], due to the localization of atoms in the subwavelength sized potential wells associated to the modulation of the light-shifts in the standing wave of the molasses. As shown on Fig. 2, the localization peak is narrower and higher when the atomic temperature is lower.

This localization effect is in agreement with the theoretical prediction that the equilibrium kinetic energy may be of the order of the depth of the potential wells due to the modulated light shifts [10]. It is then possible to observe the vibrational levels of the atoms oscillating in the bottom of these potential wells, as shown by several experiments [33–36]. In addition, since the potential wells are produced by a standing wave light-field, there is a spatially organised periodic structure, corresponding to an "Atomic Lattice".

2.3. *Below the one photon recoil*

An important question is of course: What is the lowest temperature obtainable in optical molasses? Experiments as well as the theory of Sisyphus cooling yield an answer: the limit temperature is of the order of a few "recoil velocity"

$$v_R = \frac{\hbar k_L}{M}. \tag{3}$$

The recoil velocity v_R is the velocity change of an atom which absorbs or emits a photon.

It may seem difficult to go beyond and to reach velocities smaller than v_R, because dissipation – which appears essential for cooling – requires spontaneous emission to play a role. Since there is a fundamental randomness in the process of spontaneous emission, it does not seem possible to control the linear momentum exchanges between the atoms and the photons with an accuracy better than the photon momentum $\hbar k_L$.

However, a completely different method – Velocity Selective Coherent Population Trapping (VSCPT) – has allowed atoms to be accumulated in a velocity range narrower than the one photon recoil [37, 38]. This method does not rely on a friction force. It is based on the fact that atoms may be optically pumped into a "non-coupled-state", where they no longer interact with the laser beams because of a quantum interference effect. However, if the atomic velocity is different from zero, the non-coupled state is not an eigenstate of the hamiltonian (which has a kinetic energy term), and it will evolve into a coupled state so that the atom will resume exchanging photons with the laser beams and emitting fluorescence photons. Because of the corresponding recoils, the atom thus makes a random walk in the velocity space, until it eventually falls into a non-coupled state at zero velocity: such a state is a stationary state where the atom no longer absorbs or emits photons, and where it can remain trapped for a very long time. This mechanism thus accumulates more and more atoms in the not-coupled state at zero velocity $\psi_{NC}(p = 0)$: it is a cooling process.

In order to experimentally achieve such a cooling, it is necessary to accumulate atoms in $\psi_{NC}(p = 0)$ for a long enough time. The theory shows that in the case of metastable helium, on the 2^3S_1 to 2^3P_1 transition at 1.08 μm, a few hundred atomic lifetimes ($\Gamma^{-1} = 0.1$ μs) should be enough to achieve a velocity distribution narrower than the recoil velocity, with a density in the velocity space clearly above the initial density (this is the signature of a real cooling). The major difficulty of this experiment is to warrant that the trapping state $\psi_{NC}(p = 0)$ will really remain not coupled to the lasers. This entails stringent requirements, on the magnetic field, and on the coherence of the laser beams. First, the magnetic field must be exactly zero, otherwise $\psi_{NC}(p = 0)$ is not a trapping state because it is a superposition of two non-degenerate Zeeman sublevels, so that it is not a stationary state. Second, the relative phase of the two σ_+ and σ_- laser beams must remain perfectly constant.

In the first experimental demonstration of subrecoil cooling [37], we were able to apply a 1D-VSCPT scheme to He* atoms in an atomic beam for 30 μs. The transverse velocity distribution was observed to be compressed, so that it was narrower and higher. Its width of 6 cm s^{-1} (HWHM) was smaller than the one photon recoil velocity for helium (9 cm s^{-1} on this transition). In fact, the final velocity distribution is not gaussian, and it is not possible to speak of a real temperature. We can nevertheless convert the measured width into kelvins, and this leads to 2 μK, which is half of the one-photon recoil temperature T_R for helium (the relatively high value of the recoil temperature for helium is related to the small mass of this atom).

After this first demonstration, in good agreement with the theoretical predictions [38], several questions were still open. Was it possible to generalize the situation to two and three dimensions? What was the lowest temperature achievable? How efficient could the process be? (i.e. What fraction of the atoms can be cooled?)

The generalization of VSCPT to more than 2 dimensions was predicted to be possible in a $J = 1 \rightarrow J = 1$ transition [39], like in metastable helium. In order to answer the question of cooling efficiency and ultimate temperature at long interaction times, it has been necessary to switch from the purely microscopic approach [38] to a new statistical approach, allowing us to make predictions in the asymptotic regime [40]. This approach uses mathematical results derived for unusual statistical processes – the so-called "Lévy flights". It predicts that the cooling process should keep efficient in 2D and 3D. Moreover, it confirms that, as conjectured in references [37, 38], VSCPT cooling has no fundamental limit: the temperature of the cooled atoms is predicted to decrease as the inverse of the interaction time between the atoms and the lasers [41].

A second generation of VSCPT experiment has thus been designed to be able to apply the VSCPT scheme for longer times, and in two and three dimensions. Instead of working with fast atoms in an atomic beam, helium atoms are first accumulated in a magneto-optical trap [42], then they are precooled to a few v_R, and they are released in free fall. The VSCPT lasers can then be applied for several milliseconds in a volume smaller than 1 cm^3.

This scheme has first lead to 1D cooling to $v_R/4.5$, corresponding to a temperature 20 times smaller than the recoil temperature [43]. It has also been possible to obtain 2D VSCPT cooling, at the same subrecoil temperature of $T_R/20$ [44]. Experiments on 3D subrecoil cooling are in process.

Another method for subrecoil cooling has lead to a clear 1D subrecoil cooling [45] as well as to a marginally subrecoil 2D cooling [46]. This so-called "Raman Cooling" is specially interesting for level schemes in which VSCPT does not seem easily applicable.

3. Trapping of neutral atoms

Since trapping of charged particles had turned out to be a remarkable tool for high precision measurements, early efforts were made to achieve a similar result with neutral atoms. The first success was obtained with magnetic traps loaded with laser cooled atoms [6]. Then, a purely optical trap was demonstrated [47]. But the most popular trap nowadays is the so-called Magneto Optical Trap (MOT), which combines light and a magnetic field.

3.1. *Magnetic trap*

It has been demonstrated for neutrons [48], and for atomic hydrogen [49], that a paramagnetic particle with a permanent magnetic moment can be trapped in a minimum of magnetic field (Maxwell equations preclude the existence of a maximum), for states where the magnetic moment is antiparallel to the magnetic field. Such traps are quite shallow (less than 1 K in the case of hydrogen in a field of 1 tesla), so that the particles must be precooled to make the trapping possible. Hydrogen experiments use cryogenic cooling for this purpose.

A similar result has been achieved with atoms stopped and cooled by laser action, and trapped around the zero value of a quadrupolar magnetic field [6]. The problem of the loading (one must use a non-conservative process, in order to decrease the total mechanical energy to a value less than the traps depth) was solved by using a time sequence: the atoms are first stopped, and the trapping magnetic field is then switched on.

A more sophisticated arrangement using supraconductors [50] has demonstrated an analogous trap but with a minimum magnetic field different from zero, in order to avoid the occurence of Majorana transitions. The loading is continuous by use of an optical molasses to damp the atomic motion in the bottom of the trap.

It would be interesting to trap atoms in a maximum of the magnetic field, in order to avoid spin flipping collisions (which would require energy in such a situation, in contrast with the case of a minimum of magnetic field). It has been proposed that a dynamical trap based on an a.c. magnetic field may achieve this goal [51]. A trap in this spirit has been achieved for cesium atoms [52]. Since this trap is very shallow (12 μK) its success relies on the most efficient methods of laser cooling (Section 2) for providing cold enough atoms. In a similar spirit, an R.F. trap has also been demonstrated [53].

Efforts to improving trapping of atoms in purely magnetic traps are still going on, since these traps are not affected by the heating related to spontaneous emission that occurs unavoidably in all optical traps (see following section).

3.2. *Optical traps*

The possibility of using radiation pressure from light to confine atomic motion has been considered in the early seventies [54]. For a long time, it was not clear whether a stable optical trap was possible. A major difficulty encountered was the so-called "Optical Earnshaw theorem" which forbids many schemes using the resonant radiation pressure force [55]. Another very serious problem is the strong heating that may occur when one wants to use the dipole force which is not constrained by the Optical Earnshaw theorem. This heating is related to strong fluctuations of the force around its average value when spontaneous emission happens.

These difficulties have been successfully overcome by use of alternated periods of trapping and cooling. The first optical trap [47] used the dipole force to attract atoms to the focus of a strongly focused laser beam, detuned below resonance. Doppler molasses were periodically turned on to counterbalance the heating due to the fluctuations of the dipole force. Other schemes in the same spirit have been demonstrated [56].

More recently, with the availability of samples of ultra cold atoms, it has been possible to load very shallow Far-Off-Resonance-Traps [57] based on the dipole force, but with a laser detuning so large that the spontaneous emission rate is small enough to avoid the usual heating problems.

3.3. *Magneto optical trap*

It has been realized in 1985–86, that the Optical Earnshaw theorem only applies to the two-level atom model, and that it could be by-passed [58, 59] in situations where the many sublevels of real atoms may play a role. A quadrupolar magnetic field in conjunction with a well chosen polarization scheme constitutes the celebrated Magneto-Optical Trap (MOT). Figure 3 presents the simplest example of such a scheme, where an atom with a $J = 0 \rightarrow J = 1$ transition is immersed in a magnetic field linearly varied along Oz (quadrupolar field $B(z) = bz$). If the atom is irradiated by two quasi-resonant counterpropagating laser beams with the same frequency and opposed circular polarization, the resonance will happen at different points in space for the two waves, so that the atom will experience a force changing with z. For a negative laser detuning, the force is restoring towards the point $z = 0$. This scheme is readily extended to three dimensions by adding two other pairs of counterpropagating counterpolarized laser beams along two orthogonal axes.

This scheme has first been demonstrated with sodium atoms, on the $F = 2$ to $F = 3$ hyperfine component of the D2 line [60]. Many atoms can be trapped in a similar way, including rare or unstable species [61]. This type of trap has several advantages. First, its depth is larger than in most other schemes. Second, simple inspection of the situation shows that the force also depends on the atomic velocity just as in optical molasses, so that the atomic motion is very efficiently damped. MOT is thus a very robust trap, easy to load, and which provides additional cooling for the captured atoms. By carefully controling the parameters, sub-Doppler cooling has been demonstrated in such a trap [62].

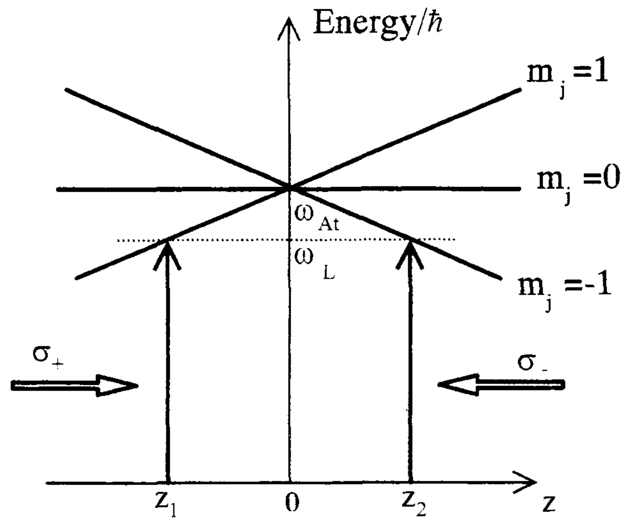


Fig. 3. Magneto Optical Trap. An atom moving towards the left part of the trap will interact around $z = z_1$ with the σ^+ polarized laser (propagating towards the right) on the $|J = 0, m_z = 0\rangle \rightarrow |J = 1, m_z = 1\rangle$ transition. The net force experienced by this atom will then push it back towards the centre of the trap. In the same way an atom approaching the right side of the trap will interact with the σ^- polarized laser (on the $|J = 0, m_z = 0\rangle \rightarrow |J = 1, m_z = -1\rangle$ transition, resonant for $z = z_2$) and it will be pushed back to the center of the trap. The net result is thus a restoring force towards $z = 0$ which leads to a spatial confinement of the atoms in the center of the magneto-optical trap. The scheme can be generalized to three dimensions. In addition to the position dependent restoring force, there is also a velocity damping force like in Fig. 1. The combination of trapping and cooling is the reason for the high efficiency of MOT.

A similar scheme can also be used to trap atoms inside a vapor cell at room temperature: it is then the low velocity part of the thermal velocity distribution which is captured [63]. This scheme is currently used in many laboratories.

In conclusion, Magneto Optical Traps constitute a very useful tool, and many of the applications of atom trapping have been realized in such traps. This scheme is also very efficient in a two-dimensional version that can transversely compress an atomic beam, both in space and in velocity: this is the so-called "atomic funnel" [64].

4. Collective effects

An often quoted, but highly speculative, application of laser trapping and cooling of neutral atoms, would be Bose-Einstein condensation. This phenomenon should happen when the atomic de Broglie wavelength becomes larger than the average interatomic distance. There is hope that laser trapping and cooling of atoms might eventually allow one to obtain the dense sample of cooled atoms required. However, in spite of the impressive results already achieved, this ultimate goal still looks far ahead.

On the other hand, several collective effects have already been reported. They rely on the achievement of high densities of cold atoms. Note that in a given trap, the spatial extension decreases with the temperature, so that cooling not only compresses the velocity distribution, but also it increases the density in real space.

For most of the phenomenons of this category, the laser light plays a role in the physical phenomenon itself, in addition to cooling and trapping. We will briefly give two examples.

4.1. *Collisions*

As soon as stable trap for cold atoms has been loaded, it is usually possible, for a large enough atomic density, to observe a non-exponential decay of the number of trapped atoms, superimposed on an exponential decay. The latter behaviour is clearly interpreted as due to losses by collisions with the background gas in the vacuum chamber. The former term is related to collisions between the trapped atoms themselves [65–67]. In some cases, the presence of light plays a major role. For instance, in the trap for (2^3S_1) metastable Helium [42], we find a He*-He* Penning ionisation rate higher than usual by more than one order of magnitude. We have shown experimentally that the corresponding unusually large collision cross section of $4 \cdot 10^6$ Å^2 is clearly related to the presence of the resonant laser light at 1.08 μm used for trapping. It can be interpreted as due to the long distance ($1/R^3$) dipole-dipole interaction between an excited and a ground state atom. Such a strong interaction exists in many optical traps, and can lead to various types of leaks. This is why, in view of obtaining large atomic densities, "dark spot" MOTs, with no light in the center, seem to be very efficient [68].

If collisions in a trap are obviously a serious problem if one's goal is to achieve densities as high as possible, they can also constitute a new field of study, since these cold atom collisions happen in a new regime. For instance, for slow enough atoms, the duration of the collision may become longer than the radiative lifetime of the excited state, leading to a completely unusual behaviour [69]. Also, if the de Broglie atomic wavelength is large enough, compared to the interatomic potential range, one may enter a quantum regime.

4.2. *Classical collective effects*

An example of classical collective effects is the onset of spatial structures that appear in magneto-optical traps, when one tries to increase the number of trapped atoms [70]. The explanation for these structures rely on long range repulsive forces (in $1/r^2$) due to radiation trapping: the scattered light may be reabsorbed, giving a radiation pressure force.

Although it has been observed with dielectric spheres, and not with atoms, it is also worth mentioning here the observation of a spatial pattern due to dipole-dipole interactions between glass spheres illuminated by laser beams [71]. Such interactions should play a role also in the case of atoms.

5. Atoms optics

As suggested by the title of this section, atom optics consists in acting on atoms, for obtaining effects analogous to what we know for light: reflection, focusing, diffraction, interference. The radiative forces from laser beams are a very important mean of action. It is also possible to use the diffraction of de Broglie atomic waves onto fabricated microstructures, which can be designed in a more and more precise way.

Although some demonstrations related to atom optics go back to the late seventies (see the review [72]), this field has recently taken a faster pace, with an explosion of new results [13]. We only give here examples of results in this field.

5.1. *Focusing*

The first demonstration of the focusing of an atomic beam, by the dipole force from a copropagating quasi-resonant laser beam detuned below resonance [73], goes back to 1978. Later, an atomic lens formed of counterpropagating gaussian laser beams has been used to image the two-point output of a double oven [74].

Multifocusing by the antinodes of a light standing wave has been shown to lead to the deposition of submicron size lines of atoms [75]. Recent success with chromium [76] open the way to useful applications in microlithography.

An other approach which has been successfully demonstrated, is the focusing by a free standing microfabricated Fresnel zone plate [77]. This approach is obviously related to the phenomenon of diffraction (Section 5.3).

5.2. *Reflection*

Mirrors have played a crucial role in the development of light optics. For instance Newton's telescope success is due to the absence of chromatic aberration in the concave mirror used as a focusing device. Also, most useful optical interferometers incorporate mirrors to separate or recombine the interfering beams. Inspired by this analogy, there is an active research to develop efficient atomic mirrors.

It has been realized in 1982 that the intensity gradient of an evanescent light wave, detuned above resonance, may be used to reflect atoms [78]. However, the maximum normal velocity that can be reflected is limited by the maximum value of the laser intensity on the surface, and it can hardly exceed a few meters per second. The first experimental demonstration consisted thus in reflecting a thermal atomic beam falling onto the evanescent wave at a grazing incidence, so that the normal component of the velocity was kept below 1 m/s [79]. Later on, atoms cooled in a trap and released above an evanescent wave have been shown to bounce, realizing an "atomic trampoline" [80]. However, because of the finite transverse velocity distribution, the atoms escape on the side after a couple of bounces, unless their motion is transversely confined, for instance by use of a concave mirror [81].

A crucial issue for atomic mirrors is their ability to preserve the coherence of the atomic de Broglie waves. It is then absolutely necessary to avoid spontaneous emission during the reflection on the evanescent wave detuned above resonance (the detuning $\delta = \omega_{\text{Laser}} - \omega_{\text{At}}$ is positive). Since the probability for spontaneous emission varies as δ^{-2}, while the reflecting dipole potential varies as δ^{-1}, a solution for limiting the spontaneous emission is to increase the detuning. However, the reflecting potential bareer is then lower, and the laser intensity must be increased accordingly. Several schemes have been considered for obtaining enhanced evanescent waves: surface plasmons [82], resonant dielecric wave-guides coupled by photon tunneling [83]. The success of such schemes is certainly a crucial issue for useful applications of atomic mirrors, for instance to atomic cavities [84] or to atomic beam focusing.

5.3. *Diffraction*

Diffraction of atomic matter-waves by a laser standing wave is attractive, because it provides a perfect periodic grating. However, such an effect can be observed only in conditions where no spontaneous emission can take place, and this puts stringent restrictions on the experimental conditions [85]. Similarly, one can also consider reflection gratings, based on modulated evanescent waves [86]. Experimental observation has turned out to be more difficult than anticipated [87], and it has been realized that an accurate understanding of such atomic reflection requires more than a simple generalization of a transmission grating [88]. The reason is that an atomic mirror is not based on a sudden boundary condition as in the case of light, but rather on a soft bareer, on which the normal velocity of the atom (in a semi-classical picture) is continuously decreased and reversed, on a scale large compared to the atomic de Broglie wavelength [89].

The problem of spontaneous emission does not happen with freestanding microfabricated gratings [90, 91], but it is difficult to have a perfect periodicity for these devices.

5.4. *Interferences*

For a long time, the achievement of an atomic interferometer has been considered a long term goal. It thus interesting that several interferometers have been demonstrated in a very short period of time [92–97]. The first one was a Young's double slit microfabricated structure. The second one was based on a triple grating configuration, also with microfabricated structures. Other schemes use the interaction of an atomic beam with transverse light beams: the separation between the two parts of the matter wave is realised through the momentum transfer $\hbar k$ from photons. The experiment of Ref. [96] uses a longitudinal Stern-Gerlach effect.

This wide variety of schemes already successful, shows that atomic interferometry will probably develop in many different directions. Several applications have already been demonstrated. Atom interferometers can be used for detecting inertial effects as rotations [93], or for measuring gravitation [94]. Dephasing associated to light-shifts, to collision with background atoms, or even due to topological effects (Aharonov-Bohm effect, Berry phase) have been observed. Many important achievements are expected.

6. Conclusion

What evolutions can we anticipate? First, there will probably be new advances in the domain of cooling and trapping. Sisyphus cooling definitely yield atoms in the regime where the atomic kinetic energy is smaller than the height of the potential barriers. We have indicated that the atoms may then be trapped in the corresponding potential wells, and that the quantization of the vibration levels plays a role. Because of the periodicity, one has in fact to consider a band structure of quantized levels [98]. Note that in these conditions, temperature has a different meanings no longer associated to the classical kinetic energy, but rather to the distribution of population among quantized energy levels.

The next goal in cooling is to go well below the one photon recoil temperature, in three dimensions. This may be possible either with the VSCPT method (Section 2.2), or by analogous schemes in the spirit of Velocity Space Optical Pumping [99], like Raman cooling already mentioned. An important progress would be to achieve subrecoil cooling in a trap.

Important applications in spectroscopy and metrology should florish. Already, a very narrow (2 Hz) linewidth of the Cesium atomic clock transition has been observed, thanks to the use of an atomic fountain using the most advanced techniques in laser cooling [100]. Several atomic clocks using this scheme are under construction, with an expected improvement of two orders of magnitude over existing clocks.

The quest of Bose Einstein condensation is still a very exciting goal, which will certainly prompt clever combinations of techniques, but it is difficult to tell the issue. Collisions and molecular effects may turn out to be an impossible to overcome mechanism of losses [101]. Note, however, that the experiments on magnetically trapped cryogenically cooled atomic hydrogen have been progressing regularly for many years [49, 102], and they are not far (one order of magnitude) from the critical conditions of density and temperature required for quantum statistical effects to show up [103]. Laser light is now used in the cryogenic hydrogen magnetic traps, and mixed schemes such as laser assisted evaporative cooling may help making the last step [104]. Note finally that another approach to quantum collective effects may be the accumulation of more than one atom per mode, in atomic cavities based on atomic mirrors [84].

At the opposite of these lines of basic research, laser manipulation of atoms offer the perspective of very useful applications, such as microlithography, or atomic microprobes. We thus think that, as many other discoveries in atomic physics and optics, laser manipulation of atoms will eventually become a standard tool, in addition to being an exciting domain of research.

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