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Cooling in Traps

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Abstract

Some recent achievements and possible experiments on cooled and trapped ions and atoms are summarized. Particular emphasis is given to a discussion of cooling limits in traps, recent advances of neutral atom trapping, cooling by velocity selective optical pumping, condensation and ordering in ion traps and possible future applications of confined cold particles.

1. Introduction

Trapping and cooling of ions and atoms has been a subject of particular interest for about one decade now. Although trapping of ionized atomic particles [1–3] has been utilized for even longer times, its advantages became apparent for the first time with the high precision experiments (microwave spectroscopy) performed on trapped $^3He^+$ particles [4]. The benign environment in an ion trap which is characterized by virtually infinite interaction times between ions and fields applied for spectroscopy, controllable or negligible shifts by the trapping fields, and the absence of collisions with walls or buffer gas atoms, led to proposals for its application in time and frequency standards experiments. Beyond its advantages in the microwave region, later proposals have been made to exploit its features in the optical domain, thus promising frequency stability and reproducibility of unprecedented values [5]. The need to overcome the ultimate limits set by the second order Doppler shift triggered the suggestion to apply radiative cooling to neutral atoms and trapped ions [6, 7].

The realization of single trapped particles [8, 28] and cooling to milli-Kelvin temperatures [9, 19] have been the milestones on the way to a wider applciation of cooling and trapping. Although cooling of trapped ions was realized almost a decade ago, it was not until recently that trapping of neutral atoms was successively achieved [10]. The reason for that, of course, is the very shallow well depth ($\simeq 10^{-4}$ eV) of neutral atom traps as compared to ion traps (several eV) makes it necessary that atoms be cooled before they can be trapped. However, after the cooling of atomic beams was successfully achieved [11, 12], different neutral atom traps have been realized.

Aside from the possibility of cooling ions in a trap by optical means, other methods have been investigated. Cooling by the viscous drag due to collisions with a cold background gas has been both suggested and successfully demonstrated [3]. Cooling of trapped ions may also be achieved by damping their induced currents [13]. Also, cooling and trapping of neutrals need not involve the mechanical forces of light [14]. However, only optical cooling proved to be able to reach very low (milli-Kelvin) temperatures and may be the preferred technique in certain experiments. Hence, the discussion throughout this paper will be devoted to optical cooling of trapped ions and atoms. By now, there are several extended reviews available on either subject of trapping [3, 15, 16] and cooling [17–20] so that we will not discuss general techniques and theories. The purpose of the present discussion is rather to provide a summary of certain interesting points in the field of cooling in traps, discussing state-of-the-art as well as discussing future techniques and possible applications.

This paper summarizes a panel discussion and consists of five sections which themselves may be read fairly independently. The organization is as follows: In Section 2, cooling limits of laser cooling in traps are discussed. It applies quite generally to any trap, although most of the discussion is done with ion trapping in mind. Section 3 summarizes the more recent achievements and results in neutral atom traps as well as the required cooling in order to fill these traps. Collisions of confined ultracold neutral atoms and their applications are discussed. In Section 4 a method is proposed to overcome the so called Doppler limit by means of velocity selective optical pumping [21]. This is done with particular consideration of a magnetic neutral atom trap. Section 5 gives some ideas about possible observation of ordering phenomena in ion traps. Special shapes of ordered structures are predicted by means of simulation calculations. The concluding Section 6 gives an overview of possible future applications of cooling in traps.

2. Laser cooling limits for trapped particles

Laser cooling of atoms trapped in a harmonic potential well, e.g., harmonic secular motion for ion traps, has been extensively treated in the literature [17–20]. When the oscillation frequency ω_v in the trap is much less than the radiative decay rate γ of the laser cooling transition, the minimum achievable temperature is given by [17–20]

$$T_D = \frac{\hbar\gamma}{2k_B} \text{ (the so called Doppler limit).}$$

Experimentally, laser cooling has been applied to trapped ions, in most cases single ions, as well as to confined atoms; however, only recently two experiments [23, 24] have reached the theoretical limit. Cooling of a single Hg^+ ion stored in a miniature RF-trap with laser light at 194 nm resulted in a temperature of about 1.7 mK [24]. This could be determined by observation of motional sidebands at the ion's secular motion (at optical frequencies) which also indicated that the ion was in the Lamb–Dicke regime. Another experiment, exploiting laser cooling on optically confined neutral Na atoms [23] resulted in an even lower temperature of 0.24 mK for a cloud of about 1000 atoms, being possible by the smaller decay constant γ of the Na transition.

In the limit where $\gamma \ll \omega_v$, the final temperature of con-

fined atoms or ions is determined by the "sideband" limit. In this case, the minimum kinetic energy achieved is often given in terms of the mean occupation number $\langle n_v \rangle$ of the harmonic oscillator state for the ion or atom in the well. Since laser cooling gives rise to a thermal distribution of occupation numbers [17], the final temperature in the sideband limit may be written as

$$T_S = \hbar\omega_v/(k_B \ln \langle n_v \rangle^{-1}). \quad (\langle n_v \rangle \ll 1)$$

The mean kinetic energy may be written as

$$\langle E \rangle = (\langle n_v \rangle + 1/2)\hbar\omega_v.$$

For the experiment in Ref. [24] on a single trapped Hg^+ ion this results in $\langle n_v \rangle \simeq 10$ indicating that even smaller kinetic energies may be possible.

There is usually a problem with r.f. ion traps in achieving low kinetic energies. Due to mutual Coulomb repulsion, the ions tend to be in trap regions where they experience strong restoring forces. In r.f. traps the ions' secular motion is strongly modulated by the trap drive frequency resulting in a micromotion limiting the final kinetic energy. It is the secular motion, at frequency ω_v, which is cooled by laser cooling. The kinetic energy in the micromotion is directly related to the kinetic energy in the secular motion [3, 16, 25, 26] but is not directly cooled by the laser. For more than one ion loaded into the trap the kinetic energy would be dominated by the r.f. motion even though very low temperatures of the secular motion could be achieved. In Penning traps the space charge leads to orbits away from the trap axis thus limiting the final kinetic energy by the resulting $\boldsymbol{E} \times \boldsymbol{B}$ rotation due to the presence of the magnetic field.

Hence, in order to achieve the ultimate cooling limit in an ion trap, it is necessary to experiment with single ions. Independently of the method used, for a single trapped ion or atom, cooling is "finished" when $\langle n_v \rangle \ll 1$, thus giving

$$E_{min} \simeq 1/2\hbar\omega_v$$

In order to reach the cooling limit $\langle n_v \rangle \ll 1$, a two stage cooling might be required. To approach the Lamb–Dicke limit, it may first be necessary to reach a kinetic energy provided by the Doppler cooling limit on a strongly allowed electric dipole transition. As an example of how such a two stage cooling might work, consider cooling in an r.f. trap. Assume the initial cooling is performed on a strong transition (transition 1) where $\gamma_1 \gg \omega_v$. The mean oscillation quantum number $\langle n_v \rangle$ can be derived in the Doppler limit from $(\langle n_v \rangle + 1/2)\hbar\omega_v = \hbar\gamma_1/2$ to be

$$\langle n_v \rangle = (\gamma_1/\omega_v - 1)/2$$

The Lamb–Dicke limit $(k(\hbar/2m\omega_v)^{1/2}\langle 2n_v + 1\rangle^{1/2} \ll 1)$ is usually closely approached in the Doppler cooling limit [27]. The step after reaching the Doppler cooling limit would be to drive a much weaker transition in the same ion (linewidth $\gamma_2 \ll \omega_v$) where the sideband cooling applies. This could equally be a very narrow Raman transition or a two-photon transition in the same system. Tuning the cooling laser to the first lower sideband of this transition allows one to achieve very low kinetic energies and finally $\langle n_v \rangle \ll 1$.

Perfect cooling, i.e., the arrival at the limit is verified by measuring the absorption spectrum of the sideband cooling transition. Since this corresponds usually to a very weak transition, a double resonance scheme (shelving method)

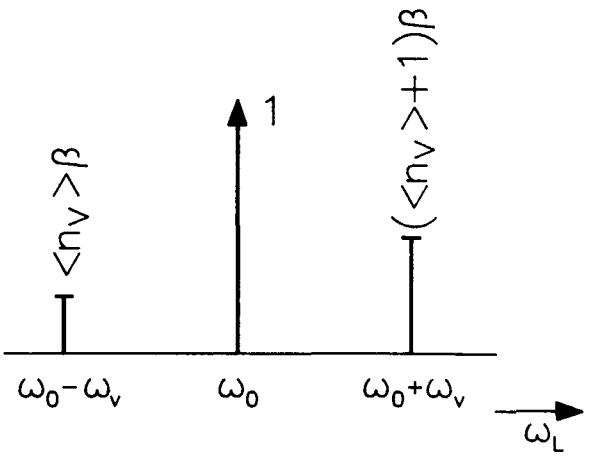

Fig. 1. Absorption spectrum of an ion in a harmonic potential for $\langle n_v \rangle \ll 1$ and $\beta \ll 1$.

[5, 28] may be conveniently used. Here, the fluorescence of a single trapped ion is observed on the transition used for Doppler cooling (transition 1), and absorptions made on transition 2 (used for sideband cooling) are detected by the absence of fluoresence on transition 1. Cycling between detecting and cooling allows the observation of the absorption spectrum on transition 2. As can be seen in Fig. 1, the strength of the lower sideband (assuming a carrier strength = 1) is $\langle n_v \rangle \beta$ and that for the upper sideband is $(\langle n_v \rangle + 1)\beta$ where β is given by the wavenumber k of the cooling light and the zero point amplitude at ω_v

$$\beta = (kx_0)^2 = \frac{\hbar k^2}{2m\omega_v}$$

From the difference in the absorption for the lower and upper sideband an estimate for an upper limit of $\langle n_v \rangle$ can be made.

Among the original motivations for laser cooling, the reduction of Doppler shifts and broadening in very high resolution spectroscopy was particularly attractive. Achieving the Lamb–Dicke regime essentially eliminates first order Doppler broadening effects since the intensity in the sidebands is very small. Second order Doppler shifts which are currently limiting the precision of high resolution experiments [29] can be made smaller than other systematic effects if the limits provided by sideband cooling can be realized. Even in the Doppler cooling limit for an allowed transition the second order Doppler shift could be extremely small. The typical magnitude of the resulting minimum second order Doppler shift per kinetic energy degree of freedom ε_{D2} is given by [27]

$$\varepsilon_{D2} = -\frac{\Delta\nu_{D2}}{\nu_0} = \frac{\hbar\gamma}{4mc^2} \simeq \frac{1.18 \times 10^{-18}(\gamma/2\pi)}{M}$$

where $\gamma/2\pi$ is in MHz and M is the ion mass in atomic mass units. In the sideband cooling limit, since $\langle n_v \rangle \ll 1$, the kinetic energy in the zero point oscillations $\hbar\omega_v/4$ for each degree of freedom causes the second order Doppler shift and is given by [27]

$$\varepsilon_{D2} = -\frac{\Delta\nu_{D2}}{\nu_0} = (2\langle n_v \rangle + 1)\frac{\hbar\omega_v}{4mc^2} \simeq \frac{1.18 \times 10^{-18}(\omega_v/2\pi)}{M}$$

where $\omega_v/2\pi$ is given in MHz.

The values of ε_{D2} can thus be made very small, however, the uncertainty in these values can be made even lower. This could result in an uncertainty in the second order Doppler shifts of approaching 1 part in 10^{24}. This precision is, of course, beyond all current limitations due to electric and magnetic field interactions and the spectral purity and amplitude stability of current laser sources. However, it is expected, that an accuracy and measurement imprecision at 1 part in 10^{18} or better will be achieved.

3. Laser cooling of trapped neutral atoms

The field of neutral atom traps has seen remarkable advances during the past few years. Magnetic traps, optical molasses and laser traps, using both "dipole" and "spontaneous" forces, have all been demonstrated, since 1985. The starting point for these developments was the laser cooling of atomic beams, a subject which is reviewed in Ref. [30]. A laser-cooled beam was the source for the nearly stopped Na atoms which were trapped for the first time, in a magnetic trap, at NBS in the 1985 [10]. That first neutral atom trap confined Na atoms with energies less than about 20 mK to a volume of 20 cm^3 at a density of about 10^3 atoms/cm^3, for times of about 1 s. The confinement time was limited by collisions with background gas.

At about the same time a laser cooled atomic beam was used to load the first optical molasses, at AT&T Bell Labs [31]. Optical molasses refers to atoms undergoing diffusive motion due to strong, three dimensional laser cooling. While not a true trap, in that there is no restoring force, optical molasses can provide long confinement times. The first experiments confined Na atoms in a volume of 0.2 cm^3 at a density of $10^6/cm^3$ for about 0.1 s. The energy of these atoms was measured to be about 240 μK, the theoretical limit of the laser cooling process. The limit on the confinement time was presumably from diffusion out of the molasses.

Although optical molasses is not a trap, it has great importance for traps, both as a way to cool atoms in the trap and as a source of cold atoms to load the trap. This was demonstrated in a subsequent experiment at Bell Labs in 1986 [23], where the first optical trap, using dipole forces, confined a few hundred atoms to a volume of about 10^{-9} cm^3 for times of a few seconds. The trap was embedded in optical molasses from which it received a quasi-continous supply of slow atoms. The molasses also supplied the cooling needed to overcome the natural heating of the trap, which would otherwise have "boiled" the atoms out. The trap depth in these experiments was about 5 mK, with a volume of $\simeq 10^{-7}$ cm^3; however, since the atoms are cooled by the molasses to about 330 μK, they occupy only a small fraction of the trap volume.

A dipole trap, though effective, is rather small and usually shallow. The dipole or "gradient" force relies on a large gradient in the optical field, and therefore requires small, tightly focussed laser beams. The spontaneous force, on the other hand, saturates at quite modest optical intensities. A trap using the spontaneous force could be large (cm size) and still deep (order of 1 K) since the force could be applied over a large distince. Unfortunately, the optical Earnshaw theorem [32] forbids a stable, static radiation pressure trap where the force is proportional to laser intensity.

Violations of the static [33] and proportional [34] conditions of the theorem have been proposed as ways of making radiation pressure traps. This year (1987) a collaboration of groups at MIT and Bell labs made the first such trap [35]. A special configuration of magnetic field and optical polarization ensures that the radiation pressure force is not simply proportional to the radiation intensity and provides a force that is always restoring. The resultant trap has an effective depth of about 1 K, a spatial extent of several millimetres and confines Na atoms at a density of $10^{12}/cm^3$ in a region of a few hundred micrometers in diameter. The temperature is presumably in the milli-Kelvin or sub-milli-Kelvin range. The very good vacuum and great depth of the trap in this experiment results in a trapping time of several minutes. At the highest densities achieved in this trap there is a faster decay which appears to be due to collisions between trapped atoms.

In other experiments this year at NBS, continuous loading of optical molasses has yielded densities of $10^8/cm^3$ in $\simeq 1$ cm^3 volume, with a confinement time more than 0.5 s [36]; at MIT, continuous loading of a cryogenic magnetic trap has confined about 10^9 Na atoms in a volume of about 100 cm^3, with lifetimes of several minutes [37]. Another group at MIT [14] has trapped refrigerator-cooled spin-polarized hydrogen, at densities greater than $10^{12}/cm^3$ and then evaporatively cooled them to 40 mK; a group at JILA has trapped Cs atoms in a radiation pressure trap using a different design from the MIT-Bell trap [38].

The high densities and low temperatures brought about by these recent achievements in cooling and trapping some unique opportunities for experiments. Among these is the possibility, studying collisions of ultra-cold atoms in traps.

Consider Fig. 2, which shows interatomic potentials and molecular energy levels for a pair of ground state atoms and for a ground-excited state pair. One could imagine performing bound-bound molecular spectroscopy on such a system, exploring transitions between the ground and excited molecular states. The resolution of such spectroscopy would be limited by the energy width of the excited states. Alternatively, one could perform free-bound spectroscopy between free ground state atoms and bound excited states. (Some excited states may only be accessible through such an excitation

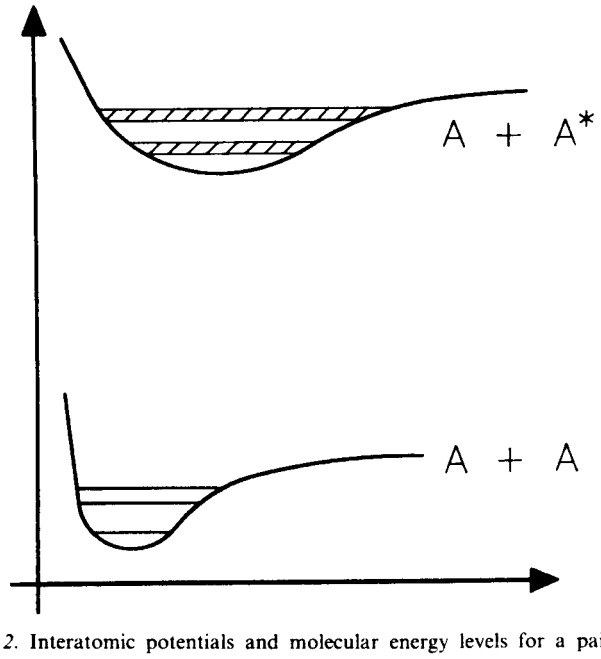

Fig. 2. Interatomic potentials and molecular energy levels for a pair of ground state atoms and for a ground-excited state pair.

process.) If the free atoms were at room temperature thermal energies, the energy spread of the free atoms would be about 10^6 times larger than the excited state linewidth, and the resolution of the free-bound spectroscopy would be limited by that large spread. However, if the free atoms were laser cooled to the Doppler cooling limit, their kinetic spread would be about the same as the excited state energy width, so free-bound spectroscopy would have the same resolution as bound-bound spectroscopy.

Consider also collisions between free atoms. At room temperature the atomic deBroglie wavelength is very small compared to the range of the interaction potential, and the collision process is described in terms of large numbers of partial waves. As a result it is possible to ascribe a semiclassical trajectory to the collision, and effects ascribed to a single partial wave will usually be washed out when all the waves are summed. Conversely if the atoms are at the Doppler cooling limit, the deBroglie wavelength will typically be larger or on the order of the interaction potential range. Only one or a few partial waves will contribute to the scattering and the collision will be highly quantum mechanical. This represents a new and virtually unexplored area of collision physics.

These concepts, as well as other ideas related to molecule formation with ultracold, trapped atoms, are discussed by Thorsheim, Weiner, and Julienne [39].

4. Cooling by velocity space optical pumping

The subject of this section is the discussion of some possibilities for cooling atoms to ultra low temperatures with the goal of refrigerating an atomic sample in a magnetic type neutral trap [37]. As has already been mentioned above, the nominal Doppler limit of the kinetic energy $k_B T = \frac{1}{2}\hbar\gamma$ [17–20] (we take here $k_B = 1$ so that temperature is specified in energy units). Can one really cool atoms to an arbitrarily low temperature by merely doing standard Doppler cooling with a sufficiently weak atomic transition? The answer is no; this theoretical limit fails for extremely weak transitions because in its derivation one averages over the discrete momentum kicks given an atom by the laser photons as they scatter. In fact, one runs into problems in trying to cool atoms far below the recoil energy, $E_{\text{recoil}} = \frac{1}{2}mv_{\text{recoil}}^2$, associated with the velocity kick given to an atom by a single photon, $v_{\text{recoil}} = \hbar k/m$, where k is the magnitude of the wave vector associated with the laser photons.

We can see the difficulty by considering the interaction of laser light with an arbitrarily narrow atomic transition. Take the laser to be tuned to the red wing of the transition and resonant with atoms that have a component of velocity, v_z, moving towards the laser – the standard arrangement for Doppler cooling. The mean net change in kinetic energy of an atom per scattering event may be calculated by considering the separate energy changes due to the absorption and reemission parts of a cycle. For absorption:

$$\langle \Delta E_{\text{abs}} \rangle = \tfrac{1}{2}mv_f^2 - \tfrac{1}{2}mv_i^2, \quad \text{where } \boldsymbol{v}_f = \boldsymbol{v}_i + \hbar\boldsymbol{k}$$

$$\langle \Delta E_{\text{abs}} \rangle = \left\langle \hbar \frac{\boldsymbol{k}\cdot\boldsymbol{v}_i}{m} + \frac{\hbar^2k^2}{2m} \right\rangle = -\frac{\hbar k v_z}{2m} + \frac{\hbar^2k^2}{2m}$$

Similarly, for the spontaneous emission of a photon with wave vector $\boldsymbol{k}'$, the mean change in the kinetic energy of an atom is:

$$\langle \Delta E_{\text{S.E.}} \rangle = \tfrac{1}{2}mv_f'^2 - \tfrac{1}{2}mv_i'^2 = \left\langle -\frac{\boldsymbol{k}'\cdot\boldsymbol{v}_i}{m} + \frac{\hbar^2k^2}{2m} \right\rangle = \frac{\hbar^2k^2}{2m}$$

We have used the face that the direction of the spontaneous emission photon is random and thus $\langle \boldsymbol{k}'\cdot\boldsymbol{v}_i \rangle = 0$. Adding these, the total mean change in energy per absorption-reemission cycle is:

$$\langle \Delta E_{\text{tot}} \rangle = -\frac{\hbar k v_z}{m} + \frac{\hbar^2k^2}{m}$$

This is less than zero – i.e., represents cooling – only if:

$$v_z > v_{\text{recoil}}$$

Therefore, regardless of how narrow our atomic transition is, standard Doppler cooling will not cool atoms to velocities below v_{recoil} or temperatures below E_{recoil}.

Can we use laser light in some other fashion to cool E_{recoil} in a magnetic type neutral trap? One approach is to tune the light to the first red motional sideband of a resonance as described above (cf. Section 2) for ions. However, it is an important difference between magnetic neutral traps and ion traps that characteristic ion trap frequencies are typically several MHz whereas neutral trap frequencies are usually more like tens to hundreds of Hz. Consequently, apart from the problem of coming up with a transition narrow enough that the motional sidebands do not overlap, even finding the first red motional sideband in a neutral trap may be very difficult.

Another approach to cooling below the recoil limit is to implement some form of velocity space optical pumping (VSOP). The idea behind VSOP is that we may tune the laser such that, though the net effect on an atomic sample is to heat it, occasionally a scattering even will produce a very cold atom. We want to arrange things such that the very cold atoms undergo no further scatterings (they are allowed to accumulate). We would, in addition, like to retain the atoms that were heated and give them more opportunity to scatter photons and wind up in the desired very low-speed region of velocity space. If all this can be done, we should be able to cool our atoms to below some target temperature $E_{\text{target}} = \varepsilon^2 E_{\text{recoil}}$, for $\varepsilon < 1$, i.e., the atoms hotter than the target temperature are the ones to be recycled; the cooler atoms are to be left alone.

We have modeled one implementation of VSOP which uses two near resonance laser beams. We picked $\varepsilon = \frac{1}{2}$. The two laser frequencies were taken to be red shifted from resonance such that the first was resonant with atoms having $v_z = v_{\text{recoil}}/2$, and the second for atoms with $v_z = 2v_{\text{recoil}}$. The thinking is that the first beam excites all atoms with energies $> E_{\text{recoil}}/4$ and occasionally produces a cold atom. The second laser, ten times more intense, cools the atoms which have been heated by the first one, and allows them to be recycled. A Monte Carlo computer simulation kept track of 1000 atoms in the laser beams. For ease of computation, the interactions between the lasers and the atomic transition were described by square lineshapes: for each laser, atoms with "z" velocities in bands about the nominal resonant velocity scattered photons at a rate, R, proportional to the intensity of the

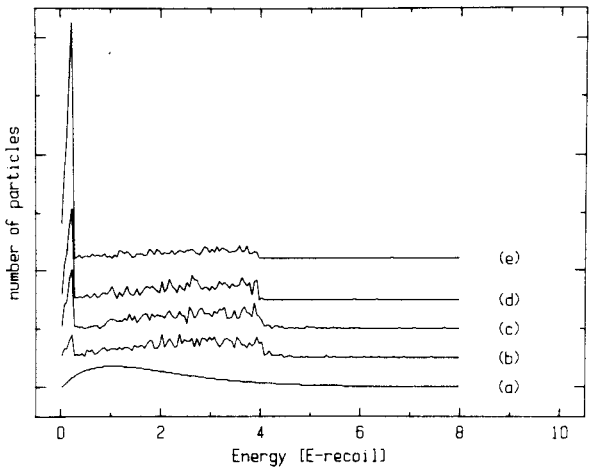

Fig. 3. Plots of energy distribution of atoms undergoing velocity space optical pumping. (Lasers tuned to $0.5v_z$ and $2.0v_z$ and relative intensity 1/10). (a) original distribution. After (b) 3100, (c) 15600, (d) 24700, (e) 66200 laser excitations.

laser beam. Atoms with "z" velocities located outside of the bands did not scatter photons. In particular, Lorentzian tails of the excitation function (which arise from both the atomic transition and possible power broadening by the laser) were not included in this simulation. Fig. 3 shows predictions of this model. The two beams do indeed lead to a net cooling of the atoms below the recoil limit with atoms accumulating at energies less than $E_{\text{recoil}}/4$.

For a specific system, in order to calculate reliable cooling rates and ultimate temperatures, it is certainly necessary to include the Lorentzian tails of the excitation functions [40]. However, one can approximate square shaped functions arbitrarily well and see that, in principle, the scheme should work. For example, one could work with a very weak transition with very small tails and broaden the excitation function by modulating the laser frequency with a noice source having a square spectrum. Note that, in our model, the ultimate temperature is independent of the absolute excitation rate of the atoms.

5. Ordered structures in ion traps

The realization of laser cooled trapped ions [8] and atoms [11, 12] and the subsequent demonstration of neutral atom confinement by optical [23] and magnetic [10] fields have raised the question of possible crystallization of trapped particles. Numerical simulations for the dynamics of cold one-component plasmas [41] have already indicated that such a so-called "Wigner-crystal" may exist. An essential parameter to describe such phenomena is the ratio of the nearest neighbour Colomb energy to the thermal energy of the particle [42]:

$$\Gamma = \frac{E_C}{E_{\text{kin}}}$$

With

$$E_C = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{r} \quad \text{and} \quad E_{\text{kin}} \simeq k_B T$$

we obtain

$$\Gamma = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{r k_B T}$$

where r is usually taken as the Wigner–Seitz radius derived from the particle density n

$$r^3 = \frac{3}{(4\pi n)}$$

When $\Gamma > 2$, the plasma should exhibit liquid like behavior and for $\Gamma = 178$ crystal like structures are predicted [41].

A beautiful experiment, performed almost 30 years ago, has shown that ordered structures of charged aluminium particles in an r.f. trap cooled by the viscous drag of the residual background gas are indeed observed [43]. This, of course, was possible due to the high charge of the aluminium dust particles, resulting in a high Γ value.

With the achievement of very cold trapped ions by means of laser cooling, similar structures may be observed with confined atomic particles. Until now, experimental evidence is still lacking, however, recently numerical investigations have been carried out [44–47] to calculate for ordering phenomena in small numbers of laser cooled ions. Quite generally, ordering (induced by laser cooling) may be observed much easier in Penning traps as in r.f. traps. The reason for this is the inherent time dependence of the trapping potential in Paul traps, which leads to a limitation of the kinetic energy of more than one trapped particle by the residual micromotion (cf. Section 2). Ion plasmas with a Γ of 100 and greater have already been achieved in Penning traps, however, direct observation of crystallization is still subject to further investigations [48].

Nevertheless, ordering in r.f. traps has been investigated numerically and several different structures have been predicted. According to these calculations, small numbers of ions should arrange in simple regular geometric patterns, e.g., four ions are predicted to arrange as a tetrahedron, six ions should be located in the corners of an octahedron. However, most of the calculations were performed by assuming the pseudopotential model, i.e., they consider the ions motion being governed by three secular frequencies in an harmonic potential. This leads to predictions of arrangements of e.g., 5 ions as being located in the corners of a tetrahedron and the fifth ion being at its center. In the same way, structures of seven and nine ions with one centered ion have been predicted [44, 45]. More recently, a calculation has been carried out [47], based on a Monte-Carlo simulation of the dynamics of small trapped ion clouds which accounts for the full time dependence of the trapping potential in r.f. traps and considers the stochastic processes imposed by the spontaneous emissions during the cooling process. In the simulation procedure, the mechanical forces acting on the ions are calculated and the equations of motion are integrated for time increments small enough to follow the trajectories in an r.f. trap adiabatically, i.e., the motion of the ions is considered to be free during these time intervals. This approximation makes possible to apply a simulation technique which has been shown to correctly describe laser cooling of free particles [49]. Comparison of simulation results with observed ion trajectories [43], experimentally determined cooling results of single trapped ions and observed statistical properties of ion clouds (like e.g., spatial and velocity distribution) show excellent agreement and give high confidence in its ability to predict ordering phenomena correctly. A typical example of these simulation results can be seen in Fig. 4 where structures of 5 ions in an r.f. trap are computed. The calculations show

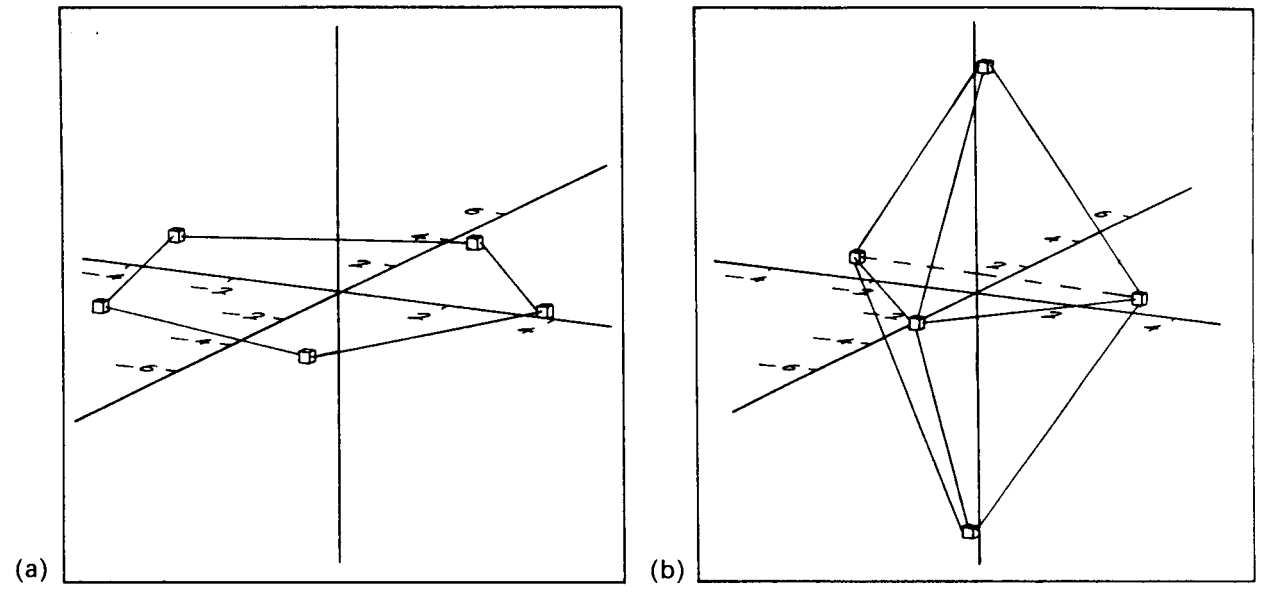

Fig. 4. Ordered structure of five optically cooled ions in an r.f. trap: (a) $\omega_r < \omega_z$, (b) $\omega_r = \omega_z$. The indicated scale is in μm.

a strong dependence of the shape of the "ion-crystal" on the symmetry of the trap potential. As can be seen in Fig. 4a for secular frequencies $\omega_r < \omega_z$, i.e., the restoring force in the x–y plane being smaller than the one in axial direction of the trap, the ions arrange in the shape of a pentagon in the x–y plane. Whereas for symmetrized conditions ($\omega_r = \omega_z$, leading to equal forces) the shape abruptly changes into a double tetrahedron structure, as can be seen in Fig. 4b. However, in either case no centered ion can be observed. This is in agreement with the result of Ref. [44] for their minimum kinetic energy of five ions but is at variance with the calculations of Ref. [45]. In the same way no stable configuration of seven and nine ions with one centered ion has been found in these calculations. The reason for such a behavior is apparently the presence of the micromotion and the fluctuations due to the random events occurring in spontaneous emissions, changing the momentum of the trapped ions.

Due to the inherent time dependence of the trap potential, a Γ factor similarly derived as above is also strongly time dependent and it is not very clear that its definition is still correct in the sense of a strongly coupled one-component plasma [50]. However, crystal like ordered structures can be obtained in r.f. traps, at least according to the calculations and their experimental verification is certainly a challenge.

As the calculations show, there will be certain problems in observing such arrangements in reality. Slight imperfections in the symmetry of the cooling laser with respect to the center of gravity of the ion cloud lead to rotations of the ordered structures. This difficulty might be overcome by observing the ion clouds with a stroboscopic method, i.e., one could excite (and cool) the ions with an amplitude modulated laser beam to produce a steady picture of even a rotating cloud. Of course, this requires a constant rotation which may not be granted under the influence of a cooling laser. Another method to prevent the ion cloud from rotating consists of applying an asymmetric trap potential, leading to totally different secular frequencies. However, this in turn would also influence the ordered ion arrangement, but this could be simulated as well [46]. A different, very elegant method to detect ordered structures would be to observe Bragg-scattering, a technique currently being investigated for trapped Be^+ ions confined in a Penning trap [48]. It is expected that the realization of such crystallization in ion traps as well as in neutral atom traps will give rise to the observation of novel phenomena and would allow experiments on collective interactions of light with a small number of nonmoving atoms [46].

6. Prospects for future experiments with cooled trapped particles

After the demonstrative first experiments on laser cooled and trapped particles, a wide field of possible applications has opened. Of course, since cooling in ion traps has been achieved earlier, its particular advantages have become clear already and impressive demonstrations of their applicability in the field of precision spectroscopy have been given [16, 51]. However, with the recently achieved trapped and cooled neutral atoms more species and experimental possibilities are available. As has been shown in the recent observation of quantum jumps [52, 53, 54], a major subject will be the investigation of quantum ensembles. A single particle confined in a trap represents an example of an isolated single quantum system. This enables us to determine not only the quantum mechanical averages, i.e., the quantum mechanical expectation values, but also the statistics of individual events making it up and thus gives access to all correlation functions and eventually their experimental verification. By repeatable preparation (e.g., by extreme cooling and/or applying quantum jumps) we can build up the quantum ensemble of measurements.

A second field, not yet explored in traps, is the investigation of coherent transients. Again, one is able to observe the transients built up from events either from a sample of atoms confined in a trap or ultimately from a series of events of a single trapped particle. This would allow to investigate relaxation mechanisms and their effects on quantum systems on a microscopic scale.

Quantum tunneling and the influence of relaxations on it is certainly a more advanced project, however, the experimental possibilities are available. In solid-state physics, Josephson-junctions, tunneling, relaxation and their quan-

tum limits have been discussed and recently a proposal was made [55] to exploit a double well trap to study possible phenomena of tunneling with trapped particles. Bringing two Bose condensates (consisting of very cold confined atoms/ions) close enough to each other, an oscillatory exchange of atoms between the traps has been predicted. This is the consequence of the spontaneous symmetry breaking associated with the Bose condensation. Thus, very fundamental aspects will be a motivation for further investigation of cooling in traps.

Extended application of the mechanical forces of light (in combination with cold beams e.g.) will be made in the field of atomic microscopy and, quite general, in atom optics and atom interferometry [56]. The precise manipulation of cold atoms and their large deBroglie wavelengths will be utilized to make diffraction experiments and interferometric measurements. Hence, the interaction of laser light with ultra-cold atoms, e.g., in ring like traps (confined atomic beams) will be a major subject for further investigation.

A different field has already been mentioned above (cf. Section 3): The application of cold trapped atoms/ions to chemistry. We can force atoms/ions towards each other in a trap very often and in this way "molecular orbitals" may be formed, resulting in quasimolecules. When this is done in a laser field, we can make a model of laser chemistry. Distances and directions can be measured, the dynamics of molecular bindings can be investigated in a very clean and reproducible environment.

Condensation and crystallization has been discussed above (cf. Section 5). Very cold particles may set up an ordered structure in traps and even in beams. In Paul and Penning traps the motion of ions may become correlated and exhibit cooperative frequencies. This is of particular interest, since it has been shown by Javanainen [46, 57] that it should be possible to cool also those vibrational modes, i.e., the cooling rate per particle in a crystal is about the same as for a single trapped ion. This would indeed allow to provide for temperatures low enough to lead to condensation, i.e., to a phase transition. Such a condensation breaks the symmetry and the question is, can we effect this by the geometry of the trap? For not too many particles the configurations (lattices) may take on the symmetry group of the trap geometry. Thus the same system may condense into different structures.

A future application of cold trapped particles is perhaps its use for catching and manipulating very big (biological) molecules. If a molecule has a symmetry (or certain geometry) a trap of this symmetry (geometry) may be able to confine the (ionized) molecule to a well defined position when cooled. This, of course, raises fundamental problems, not yet overcome: How do we really cool such big molecules? The recoil energy is very small and its level structure may be anything but advantageous. However, since it is trapped in a given geometry, the molecule could be affected by light of any desired geometric property. This would enable us to build molecular tweezers, very similar to an experiment of A. Ashkin who demonstrated this by confining and moving small (life) bacteria. An application to genetic manipulation seems to be of interest.

7. Conclusion

Cooling and trapping has been a field in atomic physics and quantum optics with many stimulating demonstrations for about one decade now. The very first experiments have been performed with trapped ions and first applications, in particular as time and frequency standards have evolved. After the successful achievement of atomic beam cooling also atom traps have been realized. This was summarized and possible applications have been discussed. Cooling limits have been indicated and possible ways to overcome them have been shown. Particularly interesting in this field are still the different techniques for cooling and trapping. Possible organization and condensation in traps is of interest for more fundamental reasons as well as for future applications for which a wide variety of possibilities has been discussed. It is expected that many of the ideas indicated will be realized in the near future.

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