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Observation of individual neutral atoms in magnetic and magneto-optical traps

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Abstract. – We have identified and photographed individual cesium atoms in a magneto-optical trap with steep magnetic gradients. By switching off the trapping light fields, single atoms were released to a bound state of the magnetic potential. A storage time of 38 s was measured for purely magnetic trapping, whereas a storage time of 147 s was observed in the corresponding magneto-optical trap.

Individual particles have been an important concept since the advent of microscopic physical theories. The cloud chamber invented by Wilson [1] in 1987 was the first instrument providing a direct macroscopic record of an individual microscopic particle. Much later, scanning-probe-microscopy techniques allowed to detect atoms or molecules bound to a surface with atomic resolution.

Charged or polarizable particles can be confined with electromagnetic fields [2], and concepts for detecting single particles were designed by Dehmelt [3]. Electromagnetic potentials for charged particles easily overcome thermal energies, and the once inconceivable preparation of a single particle visible in a microscope, the *artificial, hypothetical atom and molecule* of Mach [4], was realized in a radiofrequency trap for Ba^+ ions by Neuhauser *et al.* [5] in 1980 when they reported the first photographic recording of one or more individual barium ions.

Experiments with single ions allowed to actually realize "Gedanken Experiments" in the laboratory, for instance quantum jumps [6] or antibunching in resonance fluorescence [7]. Another interesting effect is the modification of the fluorescence rate when two or a few particles are closer together than the resonant wavelength (Lamb-Dicke regime). Recently, DeVoe and Brewer have reported variations at the per cent level for the fluorescence rate from two Ba^+ ions in a miniaturized Paul trap [8]. In order to observe stronger modifications the ion-ion distance has to be reduced substantially below 1 μm, which is, however, difficult due to their strong mutual Coulomb repulsion. A more promising route to such experiments may be given by neutral atoms. Confinement of neutral atoms is more cumbersome, however, since magnetic-dipole or induced electric-dipole potentials are too shallow for atoms at thermal energies.

Laser cooling has charged this situation, and traps for neutral atoms are now commonplace in many laboratories. The most successful storage device is the magneto-optical trap

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(MOT) [9], where more than 10^{10} atoms can be trapped in a volume of less than $1\,\mathrm{cm}^3$ [10]. Also trapping of laser-cooled atoms in purely magnetic traps of the quadrupole [11], [12] or Joffe type [13], [14] has been demonstrated.

Evaporative cooling in such devices has recently led to the generation of atomic samples at extreme phase space density where quantum effects become important [15]-[17]. It may be interesting to approach this quantum limit also with a few, *e.g* two particles which could allow to study interactions again at the microscopic level.

Recently, Hu and Kimble [18] have observed discrete levels of the fluorescence intensity from individual atoms stored in a standard MOT. We have taken another step towards these goals by tightly confining individual neutral cesium atoms in suitable magneto-optical and magnetic traps with strong magnetic gradients.

We used a vapour cell MOT in the standard $\sigma^+\sigma^-$ polarization configuration with three orthogonal pairs of counterpropagating laser beams. The trapping beams were derived from a slightly modified commercial Ti: sapphire laser with a linewidth of a few kHz only and an excellent long-term stability with respect to the $F = 4 \rightarrow F' = 5$ cooling transition in cesium [19]. Depopulation pumping to the $F = 3$ ground state was compensated by a beam from a diode laser stabilized to the $F = 3 \rightarrow F' = 4$ transition and superimposed with two pairs of the trapping beams.

The quadrupole distribution of the magnetic flux density was produced by two opposing stacks of permanently and axially magnetized NdFeB disks (diameter 50 mm, inner bore 10 mm, height 20 mm) mounted outside the vacuum vessel so that it could be baked. The minimum achievable distance of 57 mm gives a maximum gradient of 800 G/cm along the symmetry axis with the magnets used. In an earlier experiment [12], we have demonstrated that the main influence of a steep gradient is a significant reduction of the capture rate, while the temperature of trapped atoms is comparable to a low-field MOT and therefore leads to a stronger localization.

This situation is ideal to perform the experiments mentioned above with a few atoms only. A strong reduction of the capture rate R is, in fact, essential since the average number $\overline{N}$ of atoms in a typical low-density MOT is given by

$$\overline{N} = R\tau_\mathrm{s}\,, \tag{1}$$

with τ_s the mean time between collisions of trapped atoms with atoms from the background gas that kick an atom out of the trap. For experiments with individual atoms long storage times and hence very good vacuum conditions are essential. In our stainless steel chamber a residual pressure in the 10^{-10} mbar range was maintained by an ion pump and a closed-cycle cryopump. A cesium reservoir was cooled to $T = -3°\mathrm{C}$ and the atomic flux to the experimental region was controlled by means of a gate valve.

Alignment of laser beams, magnetic fields, and photodetectors was facilitated by first loading a large number of atoms into the magneto-optical trap. In order further reduce the capture rate R, the trapping beam diameters then were reduced by means of iris diaphragms until discrete steps became observable in the fluorescence intensity.

We have used two independent detectors to monitor the fluorescence from trapped atoms. For photon-counting purposes a Hamamatsu S2381 avalanche photodiode (APD) was operated in Geiger mode with passive quenching circuitry. The resulting current pulses were counted over a 100 ms time interval by a multichannel scaler. A lens mounted inside the vacuum chamber collected the fluorescence from a solid angle of 5.3%. In order to suppress background light, the image was first spatially filtered by $100\,\mu\mathrm{m}$ pinhole and then focused onto the detector.

Measurements on individual atoms were performed at three different gradients (25, 258, and 434 G/cm). The inset of fig. 1 shows a 12 minute section of the measured pulse rates. Arrival (loss) of individual atoms becomes visible by the corresponding sharp increase (decrease) of

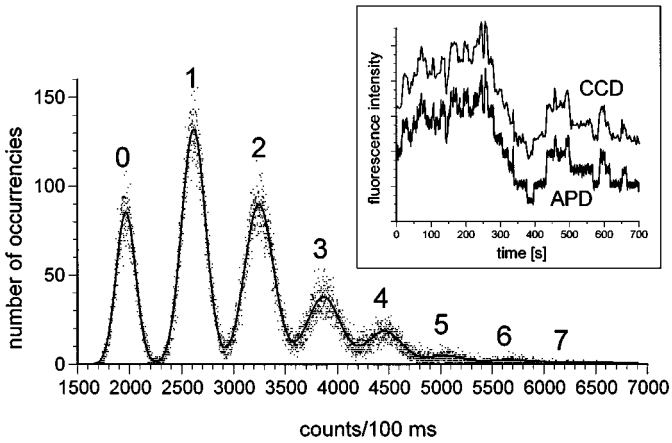

Fig. 1. – Distribution of fluorescence count rates from a three hour data run at 25 G/cm. The solid line is a fit to the data consisting of the sum of 8 Gaussians. Inset: fluorescence from trapped atoms, measured simultaneously by the avalanche photodiode and the CCD camera with integration times of 100 ms and 2.36 s, respectively.

pulse rates. The distribution of these rates (fig. 1) from an uninterrupted data run of more than three hours shows well-separated peaks corresponding to $N = 0, 1, 2 \ldots$ atoms and clearly reveals the discrete steps in the fluorescence rates. Each peak is wider than expected from Poisson statistics which is due to the APD circuitry. The increase in count rates by loading one more atom into the trap was a factor of 7 lower than expected from our experimental parameters. Background counting rates are mainly due to residual stray light falling onto the lens inside the vessel.

In table I we have collected results of uninterrupted measurements, each one extending over several hours. The average number $\overline{N}$ is given along with the inverse capture rate R^{-1} and the average storage time τ_{s}. The atomic-number distribution is Poissonian which shows that intratrap collisions are negligible and thus the use of the simple model (eq. (1)) is justified. To determine the lifetime even in situations with more than one atom in the trap, we use an algorithm which yields all possible combinations of distributing the atoms among the measured loading and loss times. From the resulting probability distribution the average τ_{s} is calculated. Note that the large differences between lifetimes are strictly correlated with different background pressures during measurement. The determined capture rates are just the inverse of the mean time between subsequent loading events. When assuming a constant deceleration of incident atoms throughout the capture volume and neglecting losses during the capture process, the loading rate can be calculated:

$$R = \frac{n_{\mathrm{Cs}} S \bar{v}}{8\sqrt{\pi}} \left(\frac{v_{\mathrm{cap}}}{\bar{v}}\right)^4 \tag{2}$$

TABLE I. – *Experimental parameters and results. Δ: detuning of the trapping laser, $s_0 = I/I_0$: resonant saturation parameter, r: radius of trapping beams, p: background pressure in* 10^{-10} mbar, *$\overline{N}$: mean number of atoms in the* MOT, *R: loading rate, τ_{s}: lifetime of atoms in the* MOT. *Errors are due to statistical uncertainty.*

$\partial B/\partial z$ (G/cm)	Δ/Γ	s_0	r (mm)	p	$\overline{N}$	R^{-1} (s)	$\sigma_{R^{-1}}$ (s)	τ_{s} (s)	$\sigma_{\tau_{\mathrm{s}}}$ (s)
25	−1.9	46	0.5	4.0	1.7(0.1)	42.5(2.6)	39	72(4)	76
258	−5.1	39	1.5	2.0	1.3(0.3)	122(24)	101	147(29)	158
434	−5.5	32	2.5	3.2	0.75(0.08)	131(14)	165	97(11)	91

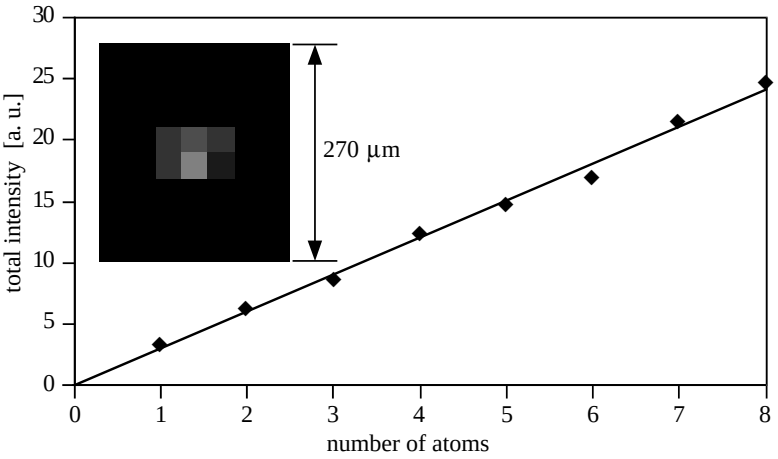

Fig. 2. – CCD picture of a single atom. The graph shows the total fluorescence intensity of 1 to 8 trapped atoms.

with $S = 4\pi r^2$ the surface of the irradiated volume and $\bar{v} = \sqrt{2k_{\mathrm{B}}T/m_{\mathrm{Cs}}}$. At 25 G/cm the influence of the magnetic field on the capture velocity can be neglected in our case and a capture velocity is calculated as $v_{\mathrm{cap}} = \sqrt{4ar} = 9.4$ m/s where $m_{\mathrm{Cs}}a$ is the scattering force. Thus the density n_{Cs} of cesium atoms in the background gas is of order $100/\mathrm{cm}^3$ corresponding to a partial pressure of $4{\cdot}10^{-15}$ mbar only. Similar values were reported by Hu and Kimble [18]. From the estimated density and the measured loading rates we now can determine capture velocities of 2.9 m/s and 1.6 m/s for 258 G/cm and 434 G/cm, respectively.

We have also evaluated the rms deviations $\sigma_{R^{-1}}$ and $\sigma_{\tau_{\mathrm{s}}}$ which are expected to equal the average values for perfectly random distributions. While $\tau_{\mathrm{s}} \simeq \sigma_{\tau_{\mathrm{s}}}$, there is a deviation for R^{-1} and $\sigma_{R^{-1}}$. The latter may be caused by sudden burst of atoms emitted from the cesium reservoir that cause the loading rate to increase temporarily without changing the storage time very much. In addition to the avalanche photodiode we have also employed a CCD camera collecting light from a 0.72% solid angle for spatially resolved images (reduction 1.5) of individual trapped atoms. The total fluorescence seen by the CCD camera exhibits the characteristic steps (inset fig. 1), which are half as high as expected from a camera calibration measurement.

Using the APD detector to monitor the number of atoms during the exposure time, we have taken pictures of 1 to 8 trapped atoms at 258 G/cm. The integrated intensity shows excellent linearity, as can be seen in fig. 2. The 34 µm width (HWHM) of the fluorescence distribution is independent of the number of atoms. It is limited by the spatial resolution of the imaging system and would correspond to a temperature $E_{\mathrm{kin}}/k_{\mathrm{B}}$ of a few hundred µK. However, temperatures in a MOT with steep gradients have been measured as low as 10 µK [12]. At such low energies one might expect to find atoms localized to better than 6 µm, only one order of magnitude above the Lamb-Dicke regime.

Camera measurements at higher gradients are currently plagued by stray light, since the laser beam diameters have to be enlarged to compensate for the reduction of the capture rate. We have nevertheless observed (many) magneto-optically trapped atoms at 800 G/cm with our CCD camera before the insertion of the lens into the vessel.

At 258 G/cm the magnetic-dipole force is 10 times larger than gravity for cesium atoms with magnetic moment $|\mu| = \mu_{\mathrm{B}}$, so that purely magnetic trapping of laser-cooled atoms is possible. After a single atom was detected in the MOT, we switched off the repumping laser which caused the atom to be pumped to the $F = 3$ ground state within a ms. Then all trapping lasers were switched off within 100 µs. After a variable time delay t_{off} light fields

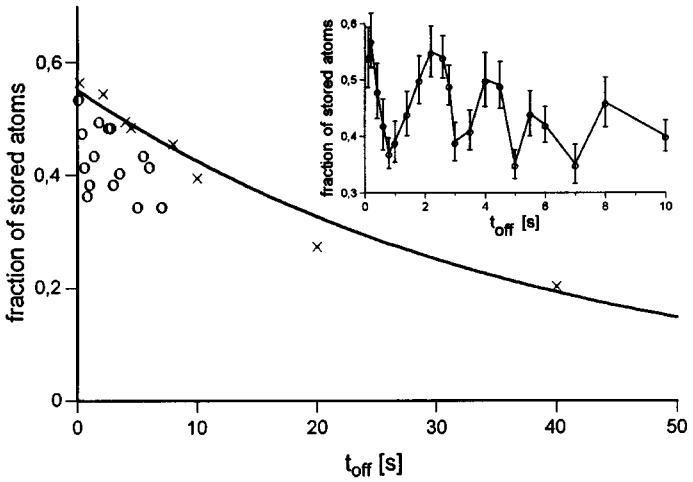

Fig. 3. – Magnetic storage of individual atoms. Each data point is the result of more than 100 measurements with single atoms and represents the fraction of atoms detected after the corresponding time with trapping lasers off. The solid line is an exponential fit to the (×) data points with time constant $\tau = 38\,\mathrm{s}$. Inset: apparent oscillating storage probability. Error bars indicate statistical uncertainty.

were switched on again. Survival or loss of the atom in the magnetic trap was detected from the fluorescence level immediately after switch-on. The probability of capturing a different atom during the detection procedure was less than 4% and has been subtracted from the data. Only single-atom events have been systematically studied, but magnetic storage of two atoms simultaneously has also been observed.

The result of the measurements is shown in fig. 3 *a*). Following an initial drop of about 50%, a slowly decaying probability of recapturing the magnetically trapped atom into the MOT is observed. The initial drop is a result of the preparation process, which does not select a specific m_{F}-level, so that roughly half the population is ejected from the trap. Since the loss process is irreversible, the observed 30% modulation of the decay probability (fig. 3 *b*)) must be a property of the dynamics of the detection process: in the shallow-magnetic-trapping potential atoms can venture beyond the detection volume and, due to small laser misalignments, may actually be ejected instead of detected by the trapping laser light. The measured period is about 2s, which is not compatible with a typical trap oscillation period of 10 ms. We have, however, theoretically found such low frequencies in the slow rotation of nearly closed orbits with angular momentum $L_z \neq 0$. For an estimate of the storage time we have therefore used only measurements yielding a monotonically decreasing function of time. The resulting storage time of 38 s has to be compared with the measured 147 s lifetime in the corresponding MOT with identical background pressure.

Reduced storage times in magnetic-quadrupole traps with high atomic density have been attributed to losses through non-adiabatic spin-flips near the zero point of the magnetic field. In our case, however, the trajectory of the trapped atom remains non-ergodic even when gravity is included. Since trajectories passing through the critical volume of about $1\,\mu\mathrm{m}^3$ near the origin constitute only a tiny fraction of the phase space that can be populated when the trapping laser are switched off, losses through spin-flips can be neglected.

Instead, collisions, with the background gas become dominant. Due to the detection mechanism the effective trap depth in our experiment is determined by the volume irradiated by the laser beams, yielding approximately 0.4 mK–1.3 mK for the magnetic trap, depending on the orientation of the atom, compared with 46 mK for the magneto-optical trap as determined

from the corresponding capture velocity. Therefore, even very weak grazing collisions with the background gas can eject atoms from the magnetic trap. Since we do not know the composition of the background gas, the cross-section for ejection due to collisions was calculated for helium. From a classical model [20] assuming van der Waals interactions, we find an increase from $\sigma = 6.5 \cdot 10^{-15}\,\mathrm{cm}^2$ in the MOT to $\sigma = (1.38, 1.43, 1.50) \cdot 10^{-14}\,\mathrm{cm}^2$ in the magnetic trap, corresponding to a storage time of (69, 67, 64)s for $m_\mathrm{F} = -3, -2, -1$, respectively. The weak influence of the magnetic sublevel on the cross-section thus justifies the use of a single exponential fit. Since multiple collisions, each with energy transfer less than the trap depth, can occur, the calculated storage times have to be interpreted as an upper limit.

We have shown that a small number of individual neutral atoms can be captured, stored and photographed. Atoms are entering and leaving the MOT at approximately random times. In the magnetic trap the storage time is significantly shorter than in the MOT because of the reduced binding potential. With an optimized detection system and improved stray-light suppression magneto-optical trapping of a few atoms at even higher gradients should be feasible. The experiment could open a route to investigate the radiative properties of two or more atoms at very small separation below the resonant wavelength.

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