We have realized a scheme for continuous loading of a magnetic trap (MT). $^{52}$Cr atoms are continuously captured and cooled in a magneto-optical trap (MOT). Optical pumping to a metastable state decouples atoms from the cooling light. Due to their high magnetic moment ($6 \mu_B$), low-field seeking metastable atoms are trapped in the magnetic quadrupole field provided by the MOT. Limited by inelastic collisions between atoms in the MOT and in the MT, we load $10^8$ metastable atoms at a rate of $10^8$ atoms/s at 50-100 $\mu$K into the MT. After loading we can perform optical repumping to realize a MT of ground state chromium atoms.

Since their first realization [1], magnetic traps for neutral atoms have become important and powerful tools for many experiments in atom and quantum optics. Especially striking experimental results [2] have been achieved with Bose-Einstein condensates (BECs) that were realized by evaporatively cooling an atomic gas in a magnetic trap (MT) [3–5]. Up to the present, several groups have demonstrated pulsed [6,7], quasi-continuous [8] or continuous [9] outcoupling of magnetically trapped BECs. However, until now experiments suffer from the absence of a method for continuously loading atoms into the BEC. Hence to date a matter wave analogon to the continuous wave (cw) optical laser has not been realized. This cw atom laser is expected to extend limits of research and resulting applied technology. Although it is an important step towards the realization of a cw atom laser, continuous loading of a magnetic trap with laser cooled atoms that are decoupled from the cooling light has not been demonstrated to date. Alternatively, a cw atom laser based on magnetic guiding in combination with atomic collisions was suggested [10]. Continuous loading of optical traps with laser cooled atoms was proposed [11] and recently experimentally demonstrated [12].

In this letter we report on the first experimental realization of a continuous loading mechanism for a magnetic trap with laser cooled atoms that are decoupled from the cooling light. We show that atoms can be optically pumped from a chromium magneto-optical trap (MOT) [13,14] into a quadrupole MT. Metastable atoms in “dark” states are stored in the MT due to their high magnetic moment. We present results of systematic studies on the loading process and on the lifetime of the MT. This lifetime is limited by inelastic collisions between MOT atoms and atoms in the MT and by two-body collisions of magnetically trapped metastable atoms. We compare the temperatures of atoms in the MT with a simple theoretical model.

The basic idea of our continuous loading scheme for a MT consists of two steps that overlap in space and time. First a reservoir of cold and dense atoms is prepared by cooling and confining them in a MOT on a transition $|g\rangle \rightarrow |e\rangle$ (FIG. 1). A weak decay channel $|e\rangle \rightarrow |d\rangle$ allows the transfer of cold MOT atoms into an additional long lived state $|d\rangle$. The second step is to store atoms that have decayed into low field seeking Zeeman substates of $|d\rangle$ in the magnetic quadrupole field of the MOT. This loading scheme can be very efficient if $|d\rangle$-atoms are decoupled from the MOT light and have a large magnetic moment. A large decay rate branching ratio ($\Gamma_{ed}/\Gamma_{cd} \gg 1$) assures a steady state MOT in thermal equilibrium and is expected to greatly reduce re-absorption of transfer photons by atoms in the MT [15].

Chromium is an ideal candidate to explore this loading mechanism since it combines a realization of the desired level scheme in form of a $\Lambda$-system (FIG. 1, black levels $|g\rangle$, $|e\rangle$, $|d\rangle$).

![FIG. 1. Relevant part of the $^{52}$Cr level scheme. The MOT involves all levels and transitions, the continuous loading process of the magnetic trap (MT) relies on the $\Lambda$-system depicted in black (levels $|g\rangle$, $|e\rangle$, $|d\rangle$).](image_url)
425.6 nm, decay rate $\Gamma_{PS} = 3.1 \times 10^6$ s$^{-1}$, saturation intensity $I_s = 8.5$ mW/cm$^2$, FIG. 1). Two intercombination lines connect the excited $^3P_4$-state to the metastable states $^5D_4$ ($\lambda_{D4} = 658.3$ nm) and $^5D_3$ ($\lambda_{D3} = 649.3$ nm) [13]. Our measurements of MOT lifetimes give decay rates of $\Gamma_{PD4} = (127 \pm 14)$ s$^{-1}$ and $\Gamma_{PD3} = (42 \pm 6)$ s$^{-1}$ [21]. A repumper laser on the $^5D_3 \rightarrow ^5P_3$ transition plugs the $^7P_4 \rightarrow ^5D_3$ decay channel. By this method we effectively reduce the level scheme to the desired $\Lambda$-system ($|g\rangle = ^7S_3$, $|e\rangle = ^7P_4$, $|d\rangle = ^5D_4$, $\Gamma_{eg} = \Gamma_{PS}$, $\Gamma_{ed} = \Gamma_{PD4}$) with a branching ratio of 250:000. As long as no repumper laser is applied on the $|d\rangle \rightarrow |e\rangle$ transition atoms are optically pumped into the $|d,m_d\rangle$-substates ($m_d = -4, \ldots, 4$ denotes the magnetic quantum number) of $|d\rangle$ with a significant probability of ending in low field seeking ($m_d > 0$) states.

Our vacuum system consists of two vertically arranged chambers connected by a Zeeman slower. A high temperature effusion cell operated around 1700 K is attached to the lower chamber. Evacuation by an ion pump and a Ti-sublimation pump leads to residual gas pressures below $10^{-11}$ mbar in the upper chamber where the traps are located. Three pairs of retroreflected 1 cm diameter laser beams build up a standard six beam $\sigma^+ / \sigma^-$ light field for the MOT. A quadrupole magnetic field with gradients up to 20 G/cm is produced by two coils wrapped onto the chamber. The 4 mm diameter repumper laser beams pass the MOT and are retroreflected. We produce 1 W of blue laser light for the MOT and the Zeeman slower by frequency doubling a Ti:Sapphire laser using a LBO-crystal. Two grating stabilized laser diodes serve for repumping. One provides 7 mW at 654.3 nm to drive the $^5D_3 \rightarrow ^5P_3$ transition. The other is amplified by injection locking to obtain 12 mW at 658.3 nm for repumping on the $^5D_4 \rightarrow ^7P_4$ line ($|d\rangle \rightarrow |e\rangle$, FIG. 1).

In order to detect magnetically trapped metastable atoms we optically pump them within a few ms back into the ground state $|g\rangle$. Then $|g\rangle$-state atoms are resonantly excited with the MOT laser and their fluorescence is imaged onto a calibrated CCD camera. If we perform this repumping within the MT we prepare cold ground state chromium atoms in our magnetic trap. This is a powerful alternative to the method of buffer gas loading [22]. The optical transfer of metastable atoms into the ground state comes with a heating on the order of the recoil temperature ($T_r \approx 1 \mu$K) due to photon scattering. Optical pumping within the magnetic potential may change the mean magnetic moment of trapped atoms and alter their temperature due to a variation in potential energy. Both effects can be neglected within our experimental resolution since the temperatures exceed $T_r$ by more than one order of magnitude and the mean magnetic moment is much larger than its expected change [21].

We investigated the loading into the MT by performing the following experiments. First we prepare a steady state MOT with both repumper lasers on so that effectively no loading into the MT occurs. Then we switch off the $|d\rangle$ repumper laser and start cw-loading of the MT. After a variable time delay we detect magnetically trapped $|d\rangle$-state atoms. The resulting loading curves (number of magnetically trapped atoms versus loading time) show purely exponential loading. We extract the loading rates by fitting the loading curves to $N(t) = N_0[1 - \exp(-t/\tau)]$ (fitting parameters: steady state atom number $N_0$ and loading time constant $\tau$). The MT loading rate $R$ is given by $R = N_0/\tau$.

Fig. 2 shows loading rates obtained with three different detunings ($\Delta = \omega_{laser} - \omega_{atom}$) of the MOT light and a single laser beam intensity of 15 $I_s$ versus the steady state number of MOT atoms. During the loading process the number of MOT atoms was adjusted by varying the oven temperature and/or the efficiency of the Zeeman slower.

For given light field parameters $R$ depends linearly on the number of MOT atoms. In order to evaluate the transfer efficiency $\eta = R/(N_{MOT}P_c\sigma)$ of the loading process, the excitation probability $P_c$ was calculated using an averaged saturation intensity of $\langle I_s \rangle = \frac{3}{2}I_s$ as in [14,23]. We find $\eta = (32 \pm 5)\%$, $(25 \pm 4)\%$ and $(16 \pm 4)\%$ for $\Delta = -2, -5, -8\Gamma_{eg}$. Loading the MT at rates up to $R = 10^6$ atoms/s, we are able to accumulate $10^8$ atoms. The atom density in our quadrupole MT decreases exponentially from the trap centre. We observe peak densities of $n_0 = 10^{10}$ atoms/cm$^3$. Typical $1/e$-radii of the MT are $r \approx 800 \mu$m while the radii of the Gaussian shaped MOT are $\sigma \approx 200 \mu$m.

The maximum number of atoms in the MT is limited by the loading time constants of $\tau = 1$ s we observe when the experiment is operated at high loading rates. FIG. 3 shows the inverse loading time constants for the experimental parameters described above. The decay rates $\Gamma = 1/\tau$ are corrected for “dark” collisions with residual gas and the thermal chromium beam. This correction

![FIG. 2. Loading rates of the MT for MOT laser detunings of $\Delta = -2\Gamma_{eg}$ (circles), $-5\Gamma_{eg}$ (squares) and $-8\Gamma_{eg}$ (diamonds) as a function of the number of atoms in the MOT. The lines are linear least square fits to the data. The marker size represents the accuracy of our measurements.](image-url)
between excited atoms in the MOT and shows that if both traps are overlapped inelastic collisions of a thermal atom ensemble in a quadrupole magnetic field. We fit this density distribution to that dimensional velocity of $\sigma/r$ on the right hand side of Eq. (1) of 0.5-0.8 depending on the number of excited MOT atoms per volume of the MOT [24]. The finite MOT size would give a correction factor only at the trap centre and $|d\rangle$-state atoms are plotted in FIG. 3 linearly. This value is comparable to the two-body loss rate coefficient in a Cr-MOT [14]. $\sigma_{cd}$ is about one order of magnitude larger than the values observed in mixtures of two different alkalis [25,26]. Light-assisted collisions with the thermal chromium beam result in a non-vanishing decay rate at very low MOT densities.

If the MOT is much smaller than the MT collisions occur only at the trap centre and $n_e$ can be approximated by the number of excited MOT atoms per volume of the MT [24]. The finite MOT size would give a correction factor on the right hand side of Eq. (1) of 0.5-0.8 depending on the trap size ratio $\sigma/r$. We assume an average collisional velocity of $v \approx \sqrt{(T_{MOT} + T_{MT})3k_B/m_C}$, where $m_C$ is the chromium mass. We extract $\sigma_{cd} \approx 10^{-15} \text{ m}^2$ by fitting the data in FIG. 3 linearly. This value is comparable to the two-body loss rate coefficient in a Cr-MOT [14]. $\sigma_{cd}$ is about one order of magnitude larger than the values observed in mixtures of two different alkalis [25,26]. Light-assisted collisions with the thermal chromium beam result in a non-vanishing decay rate at very low MOT densities.

In order to estimate phase-space densities of atoms in our MT temperature is measured in the following way. We pump $|d\rangle$ atoms back into the ground state $|g\rangle$ with the magnetic field on. Then the density distribution of $|g\rangle$-atoms is imaged immediately after switching off the magnetic field. We fit this density distribution to that of a thermal atom ensemble in a quadrupole magnetic field including gravity. The three-parameter fitting function [21] gives the peak density, the temperature and the mean magnetic moment $\mu$. We typically measure $\mu = g_\sigma m_\sigma \mu_B = (4.5-6)\mu_B$ corresponding to $m_\sigma = 3-4$.

The temperature of atoms in the MT and in the MOT are plotted in FIG. 4 versus $I/\Delta$.

The MOT temperature is measured by ballistic expansion of the cloud and shows the expected linear increase with increasing light shift parameter $I/\Delta$ [27]. In the MT we observe temperatures down to 50 $\mu$K and phase space densities of $3 \times 10^{-7}$ assuming a totally polarized cloud. MT atoms are usually colder than atoms in the MOT. This can be understood by using the Virial Theorem and assuming that the transfer of MOT atoms occurs at the centre of the MT with negligible potential energy. The initial kinetic energy $E_i$ of MOT atoms is converted into final kinetic energy $E_f$ and potential energy $V_f$ (for a linear potential $V_f = 2E_f$) of MT atoms:

$$\frac{3}{2}k_B T_{\text{MOT}} = E_i = E_f + V_f = 3E_f = 3\frac{3}{2}k_B T_{\text{MT,th}}.$$  (2)

Including additional initial potential energy due to the finite size of the MOT one gets for the theoretical temperature $T_{\text{MT,th}}$ of atoms in the MT:

$$T_{\text{MT,th}} = \frac{1}{3}T_{\text{MOT}} + \Delta T.$$  (3)

We calculate $\Delta T$ for a transfer from an isotropic MOT with size $\sigma$ into an isotropic MT with mean magnetic field gradient $b$. If $m_\sigma$ is the mean magnetic quantum number of atoms in the MT, $\Delta T$ is given by

$$\Delta T = \frac{8}{9\sqrt{2\pi}} \frac{\mu_B}{k_B} g_\sigma m_\sigma b \sigma$$  (4)
and is about one order of magnitude less than $T_{\text{MOT}}$. Inserting the measured values $T_{\text{MOT}}$, $\sigma$, $b$ and $m_d$ in Eqs. (3) and (4) we evaluate $T_{\text{MT,th}}$ (circles in FIG. 4). Although taking our temperature resolution (about 10%) into account, atoms in the MT are hotter than theoretically predicted. This effect is more pronounced at low light shift parameters and can be explained by a heating mechanism in the MT. Trapped $|d\rangle$-state atoms are heated by 10-50 $\mu$K depending on the amount of time spent in the MT and the heating rate described below.

After stopping the cw-loading the number of atoms in the MT decays non-exponentially indicating inelastic two-body collisions between $|d\rangle$-state atoms. In addition we observe enlargement of the trapped cloud caused by a heating of more than 10 $\mu$K/s. In contrast, the MT with $|g\rangle$-state atoms decays purely exponentially ($N(t) \propto \exp(-t/t_0)$) with a lifetime $t_0$ of up to 60 s and shows heating rates of only 1 $\mu$K/s. In order to distinguish between the effect of heating and two-body losses in the $|d\rangle$-state MT the standard time derivative of the atom density is modified by a term taking the enlargement of the cloud into account:

$$\frac{dn_0}{dt} = -\frac{n_0}{t_0} - \beta n_0^2 - \frac{n_0}{V} dV, \quad (5)$$

where $n_0$ is the peak atom density, $V$ the MT volume and $\beta$ the two-body loss rate coefficient. We analyse our data in the following way. The increase of the MT volume ($V = V(t)$) due to heating is fitted linearly. After inserting this $V(t)$ and $t_0$ of the ground state MT we solve Eq. (5) for $n_0(t)$ and fit the resulting function (fitting parameter $\beta$) to the peak density of atoms in the MT. This results in $\beta \approx 7 \times 10^{-17}$ m$^3$/s leading to a cross section $\sigma_{\text{ed}}$ which is about one order of magnitude less than $\sigma_{\text{ed}}$. The inelastic $|d\rangle-|d\rangle$ collisions do not limit the loading process but possibly the phase space densities achievable by further cooling of the cloud. Experiments with a totally polarized cloud are under way and may lead to a reduction of $\beta$ as predicted for He* in [28].

In summary we have realized a continuous optical loading scheme for magnetic traps with light decoupled atoms by operating a magneto-optical trap and a magnetic trap overlapped in space and time. The loading rates up to $10^8$ atoms/s depend linearly on the number of excited MOT atoms. We continuously load up to $10^8$ atoms into the MT, limited by collisions with excited MOT atoms. The lifetime of metastable atoms in the MT after switching off the MOT is limited by inelastic collisions of trapped atoms. These are strongly suppressed in the ground state MT that can be loaded by repumping metastable atoms within the MT. In future experiments, the continuous loading of different kinds of magnetic traps (TOP [29] - and optical plug [5] trap) will be investigated. Our results of initial phase space densities encourage work towards Bose-Einstein condensation in ground state chromium atoms.