Beating the density limit by continuously loading a dipole trap from millikelvin-hot magnesium atoms

M. Riedmann, H. Kelkar, T. Wübbena, A. Pape, A. Kulosa, K. Zipfel, D. Fim, S. Rühmann, J. Friebe, W. Ertmer, and E. Rasel
Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover, Germany
(Received 18 May 2012; published 10 October 2012)

We load 10^5 magnesium atoms in a dipole trap from a millikelvin-hot magneto-optical trap (MOT) using a continuous-loading scheme. Light-assisted two-body processes limit the maximum achievable density in a MOT, resulting in a reduced transfer efficiency into a dipole trap when using the conventional sequential scheme. It is overcome in a continuous-loading scheme where a loss channel is opened in the MOT. This allows the accumulation of atoms in the dipole trap over the trap lifetime, determined by collisions with the background gas. This results in a significantly higher number of trapped atoms even at a lower steady-state peak density in the MOT.

DOI: 10.1103/PhysRevA.86.043416 PACS number(s): 37.10.−x, 67.85.−d, 06.20.−f

Confinement of neutral atoms in a trap based on the optical dipole force has become a widespread tool for Bose-Einstein condensation [1], condensed matter studies in lattices [2], performance of high-resolution spectroscopy [3], and many other studies. Compared to magnetic traps, dipole traps provide higher trapping frequencies and the possibility to trap nonmagnetic states. Usually, the depth of these traps is below 1 mK with trapping volumes far below those of magnetic traps. Loading atoms into such traps requires efficient cooling techniques and high atomic densities as starting conditions. Continuous-loading schemes have proven useful in several cases where these conditions cannot be met.

Here, we demonstrate a continuous-loading scheme for a more efficient loading of magnesium atoms in a dipole trap from a millikelvin-temperature magneto-optical trap (MOT). Our scheme generates a continuous flux of atoms in a dark state that is insensitive to MOT light and magnetic fields. The dipole trap overlapped with the MOT acts like an energy filter and continuously captures the low-energy tail of the flux. The scheme allows loading times up to the background-gas collision-limited trap lifetime. We compare this approach to a stepwise-loading scheme and show that a significantly higher number of atoms can be trapped using the former approach. The latter is severely restricted by density-limiting processes occurring in the MOT.

Related schemes have been applied to calcium [4] and strontium [5]. In the case of calcium, a reservoir of atoms in a metastable state was created to fill the dipole trap by spatially selective depumping. The number of captured atoms in this case is limited by the size of the reservoir. In the case of strontium, the atoms from the MOT were drained into a metastable dark state using two additional laser beams overlapped with the MOT. The optimization possibilities offered by our scheme (as discussed in later sections) are not possible in that case since the MOT configuration of [5] cannot be simultaneously optimized for a higher number of atoms and efficient loading of the dipole trap. The two processes are inherently coupled. Continuous-loading schemes have been used to load magnetic traps as well [6–8]. The continuous accumulation of atoms in a magnetic trap was the key to achieving Bose-Einstein condensation in ^{84}Sr [9,10] which has a natural abundance of only 0.56%.

The working principle of the sequential- and continuous-loading schemes can be understood from the ^{24}Mg energy levels shown in Fig. 1. In both schemes, atoms are captured in a MOT operating on the closed singlet transition $^1S_0 \rightarrow {}^1P_1$ (S-MOT). A narrow-linewidth pump laser is used to transfer the population from the singlet to the metastable (triplet) manifold via the $^1S_0 \rightarrow {}^3P_1$ intercombination transition. The atoms in the $^3P_1$ state are pumped to the $^3P_2$ state and loaded into a second MOT operating on the closed triplet $^3P_2 \rightarrow {}^3D_3$ transition (T-MOT). In the stepwise scheme, the atoms in the $^3P_2$ state are then transferred to a dipole trap overlapped with the T-MOT. However, in the continuous scheme, the $^3P_0$ state is *not* repumped while all the other lasers and the dipole trap are operated continuously. Off-resonant excitation to other ^3D states results in a significant population decaying to the dark $^3P_0$ state. In steady-state operation, this generates a constant flux of $^3P_0$ atoms that are captured in the dipole trap.

The experimental details of the two MOT stages are described in [11]. In short, 3×10^9 atoms of ^{24}Mg are loaded from a thermal beam into the S-MOT at a temperature of 3 mK, slightly above the Doppler limit of 1.9 mK. The light for addressing the intercombination transition is provided by an amplified and frequency-doubled diode laser which is stabilized to a high-finesse resonator giving a laser linewidth below 100 Hz. Addressing the intercombination transition while the atoms are stored in the S-MOT opens a loss channel due to the relatively long lifetime of the $^3P_1$ state (4.4 ms [12]). This allows the atoms to leave the capture radius of the S-MOT. This loss is used to measure the efficiency of excitation into the metastable state. Despite the narrow-linewidth transition, transfer to the triplet system is possible within 10 ms. The dependency of transfer time on laser frequency is shown in Fig. 2. The broadening of the intercombination transition is mainly due to the inhomogeneous magnetic field of the MOT coils (1.3 T/m). The Doppler broadening is smaller than this by more than a factor of 2. Once the atoms in the metastable manifold are pumped to the $^3P_2$ state, they are captured in the T-MOT. Due to off-resonant excitations to other ^3D states, two repumpers on the $^3P_1 \rightarrow {}^3D_2$ and $^3P_0 \rightarrow {}^3D_1$ transitions are needed to pump atoms back into the cooling cycle (see Fig. 1). Both repumpers are used for T-MOT operation and stepwise loading, whereas only the $^3P_1 \rightarrow {}^3D_2$ repumper is

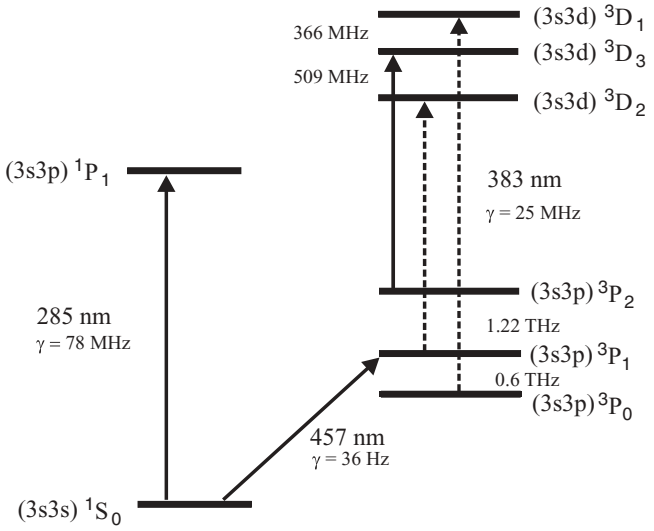

FIG. 1. Partial energy diagram of ^{24}Mg with the transitions relevant for the operation of a dual MOT in our experiment. (Dashed) arrows indicate transitions driven by (repump) lasers. The S-MOT operates on the singlet ($^1S_0 \rightarrow {}^1P_1$) transition while the T-MOT operates on the triplet ($^3P_2 \rightarrow {}^3D_3$) transition. The ($^1S_0 \rightarrow {}^3P_1$) transition is used to transfer atoms to the triplet manifold.

applied for continuous dipole trap loading. The light to address these three transitions is generated by three amplified and frequency-doubled diode lasers at 766 nm.

The number of atoms loaded into the dipole trap is strongly influenced by the properties of the T-MOT. Hence, we study the T-MOT with respect to lifetime, number of atoms, and temperature by first loading the S-MOT followed by a 30 ms transfer to the triplet manifold via the intercombination transition. After the transfer, the atoms are captured in the T-MOT. The S-MOT and the T-MOT both use the same magnetic quadrupole field of 1.3 T/m in the strong direction. The

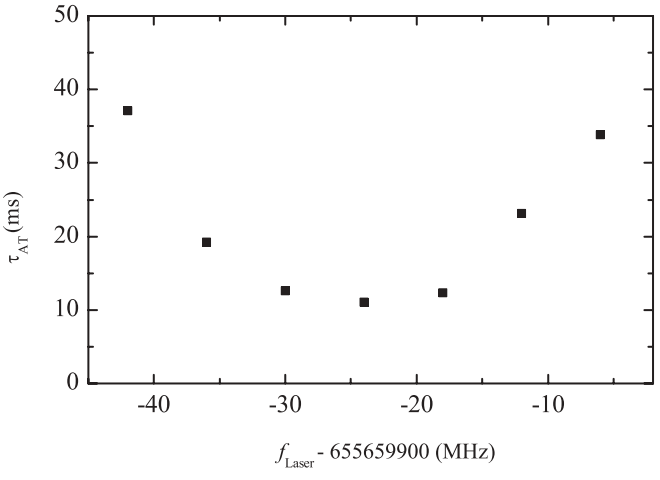

FIG. 2. Transfer time τ_{AT} for atoms in the S-MOT to be transferred to the triplet system via the $^1S_0 \rightarrow {}^3P_1$ intercombination transition in a sequential manner. The loss of atoms from the S-MOT is used to measure the transferred population. The transfer laser intensity is 3.9 kW/m^2. The absolute frequency is measured with a high-precision wave meter.

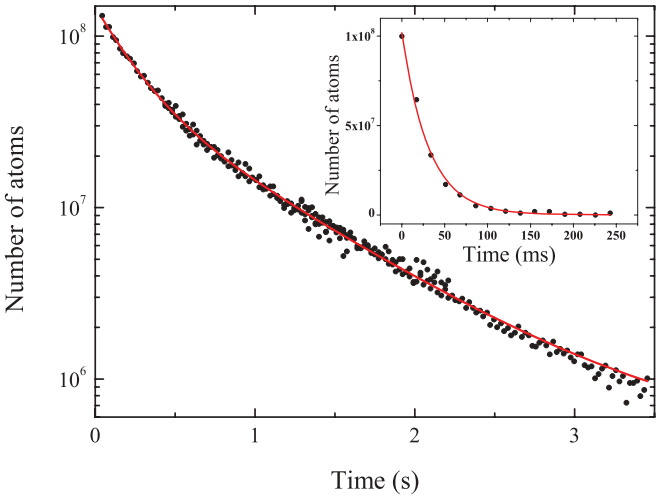

FIG. 3. (Color online) Evolution of the number of atoms in the T-MOT. The fast decay for short times is attributed to binary collisions, whereas the exponential decay for longer times (with a time constant of 0.9 s) is due to insufficient repumping of the $^3P_1$ state. In comparison, the background-gas collision-limited lifetime (observed for the dipole trap) is 5 s. The (red) curve is a theoretical fit of a two-body loss equation to the experimental data using the model in [13]. The fluorescence of the T-MOT is detected by a CCD camera. Inset: T-MOT decay with the repumper for the $^3P_0$ state switched off. The decay has a time constant of 30 ms.

T-MOT is imaged onto a CCD camera to measure the number of atoms and atomic cloud size. Figure 3 shows the number of atoms in the T-MOT as a function of time. In this case, the saturation parameter for the cooling transition is 0.1, the detuning is one natural linewidth and the spatial extension of the T-MOT is independent of the number of atoms (hence the MOT is not in the density-limited regime). The data show strong losses for short times (large numbers of atoms) due to inelastic binary collisions between trapped atoms. The decay of the number of atoms can be analyzed in a straightforward analytical way as is done in [13]. The (red) line in Fig. 3 is a theoretical fit of the rate equation including the two-body collisional loss rate. For longer holding times, the number of atoms in the T-MOT decays exponentially with a time constant of 0.9 s. This is much faster than the S-MOT decay and occurs due to insufficient repumping, followed by subsequent decay of the $^3P_1$ state. For a smaller detuning of the cooling laser (half a linewidth), a density limitation due to photon reabsorption can be observed for 10^8 atoms in the T-MOT.

The T-MOT cooling transition has a linewidth of 25.6 MHz and thus shows a lower Doppler limit than the S-MOT. At a detuning of half a linewidth, the T-MOT has a temperature of $T_{\mathrm{MOT}} = 1$ mK and a root mean square size of $\sigma_{\mathrm{MOT}} = 280\ \mu$m, which are both smaller than those for the S-MOT which are 3 mK and 600 μm, respectively. For larger detuning of the cooling light, the cloud size increases. The atoms from the T-MOT are loaded into a dipole trap created by a 1064 nm laser beam. The light for the dipole trap is provided by a fiber laser with an output power of 50 W and is focused to a $1/e^2$ radius of $w_0 = 53\ \mu$m at the position of the atoms. The trap has a maximum depth of $U_0/k_B = 260\ \mu$K for the $^3P_0$ and $^3P_2$

states and a trap frequency of 1.8 kHz in the radial direction (measured using the release-recapture method [14]).

We investigate a continuous-loading scheme for the dipole trap and compare it to a conventional stepwise one. In the stepwise scheme, atoms are first loaded into the T-MOT as described above. The dipole trap is then switched on, followed by switching off the T-MOT. The temporal overlap of the two traps, in principle, has an effect on the number of captured atoms [15]; however, we operate in the shallow-trap regime $[q = U_0/(k_B T_{\mathrm{MOT}}) = 0.25]$ where it can be neglected. In this scheme, the atoms captured in the dipole trap are in the $^3P_2$ state.

In the continuous loading scheme, the dipole trap, S-MOT, T-MOT, and transfer laser are all operated simultaneously, while the repump laser addressing the $^3P_0$ state remains off at all times. This results in a flux of $^3P_0$ atoms, of which the low-energy ones are captured continuously in the dipole trap. The large fine-structure splitting of the ^3P states prevents the captured $^3P_0$ atoms from being excited by the T-MOT light. In this scheme, the atoms in the dipole trap are in the $^3P_0$ state.

The loading curves for both schemes are shown in Fig. 4. The loading time for the stepwise scheme is given by the S-MOT loading time. For short times, the two curves are identical, implying a similar loading rate. Continuous loading saturates at about 5 s, which is also the lifetime of the dipole trap. In the stepwise scheme, the number of atoms saturates much earlier at a lower level due to density limitation. In this case, the density is limited due to photon reabsorption. The continuous-loading scheme results in about a factor of 5 higher number of atoms in the dipole trap compared to the stepwise scheme.

The reason for this enhancement can be understood qualitatively using the following model. The sequential scheme

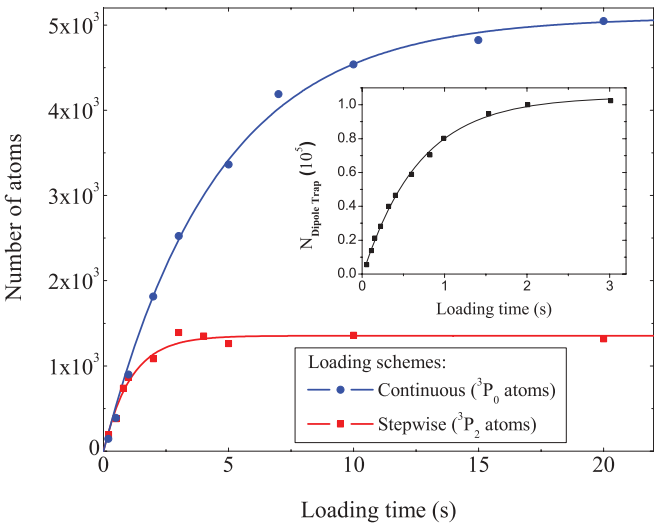

FIG. 4. (Color online) Loading the dipole trap using stepwise (red line with squares) and continuous (blue line with circles) schemes. The loading time for the stepwise scheme is the S-MOT loading time followed by transfer to the metastable state and T-MOT cooling, which takes a total of 50 ms. The inset shows the loading curve of the dipole trap using the continuous scheme for an increased incoming atomic flux and higher T-MOT cooling light intensity.

results in the transfer of a small number of atoms into the dipole trap and is limited by two main effects. First, within the overlap region, only those atoms are trapped whose kinetic energy is smaller than the dipole trap depth during T-MOT turnoff. Second, atoms outside the dipole trap volume are lost and since the T-MOT volume is larger than that of the dipole trap, the density of atoms in the overlap region can be assumed to be homogeneous. In this case, the number of atoms N_S transferred to the dipole trap can be expressed as

$$N_S = n_0 V_{\mathrm{DT}}. \tag{1}$$

Here, n_0 is the peak density of atoms in the $^3P_2$ state in the T-MOT and V_{DT} is the effective volume of the dipole trap. The trapped number of atoms can also be calculated by integrating the phase-space density distribution in the presence of the dipole trap over regions where the kinetic energy is smaller than the trapping potential. O'Hara *et al.* [15] derived an expression for the number of captured atoms from which the effective volume in the case of a shallow trap ($q < 1$) can be described as

$$V_{\mathrm{DT}} = \pi^{3/2} w_0^2 R q^2 \int_0^1 v(-\ln v)\exp(-qv)dv. \tag{2}$$

Here, w_0 is the waist of the dipole trap and R is the radius of the MOT. For given dipole trap parameters, a higher number of atoms can be captured by increasing n_0 until the density-limited regime is reached.

In the continuous-loading scheme, the lack of the repumper for the $^3P_0$ state introduces a dominant loss channel and reduces the lifetime τ of the T-MOT (see Fig. 3). This reduced lifetime is used to calculate the flux of atoms in the $^3P_0$ state and is equal to n_0/τ. Here we take into account that the T-MOT lifetime without the $^3P_0$ repumper (30 ms) is much smaller than that in its presence (0.9 s). Our model also assumes that the loading rate of the T-MOT is high enough to ensure that it remains density limited with the same peak density even in the presence of the loss channel (this regime is not reached in the experiment and is discussed below). Furthermore, our model supposes that the phase-space distribution of the $^3P_0$ atoms immediately after production is identical to that of the $^3P_2$ atoms. Hence, the loading rate into the dipole trap is given by

$$L_C = \frac{n_0}{\tau} V_{\mathrm{DT}}. \tag{3}$$

If the dipole trap has a lifetime of t_{DT} then the maximum number of captured atoms N_C is

$$N_C = L_C t_{\mathrm{DT}}. \tag{4}$$

The enhancement factor for the number of captured atoms by the continuous loading scheme is then given by

$$\frac{N_C}{N_S} = \frac{t_{\mathrm{DT}}}{\tau}. \tag{5}$$

For typical experimental parameters, the T-MOT lifetime τ without the $^3P_0$ repumper is 30 ms (inset of Fig. 3). This is also verified by calculations using the branching ratios for the transitions, and $t_{\mathrm{DT}} = 5$ s, limited by collisions with the background gas. This gives a potential enhancement factor of 165.

In the experiment, the density limit is easily reached for the stepwise scheme. However, reaching the density limit

for the continuous scheme requires a much higher flux of incoming atoms which actually could not be achieved. Hence, the observed enhancement of 5 is much smaller than the calculated value of 165.

The continuous-loading scheme offered further possibilities for optimization which were not applicable to the stepwise scheme. The flux of incoming atoms was increased by more than one order of magnitude by raising the temperature of the oven by 40 K to 733 K. This resulted in a reduced dipole trap lifetime due to a higher pressure of the background gas but in a gain in the overall number of captured atoms. Even under these conditions, the T-MOT without the $^3P_0$ repumper was not density limited. A further enhancement in the flux is possible by implementing a Zeeman slower. The transfer of atoms from the T-MOT to the dipole trap is strongly affected by the spatial overlap of the two traps. A better mode matching was achieved by reducing the T-MOT beam waist by a factor of 3, which resulted in ten times higher intensity and reduced the T-MOT diameter by about a factor of 4 to $\sigma_{\mathrm{MOT}} = 70\ \mu$m. Overall, we could increase the dipole trap loading rate by two orders of magnitude and capture 10^5 atoms in the dipole trap. The loading curve after these optimizations is shown in the inset of Fig. 4. The dipole trap depth determines the temperature and number of trapped atoms. For the full trap depth of 260 μK, we observe a temperature of 100 μK by time-of-flight expansion. As shown in Fig. 5, a lower trap depth results in atomic ensembles at lower temperatures but also in a reduced number of captured atoms. The dipole trap waist was 72 μm for this data set. For a small number of atoms the measurement of temperature by the time-of-flight method has a large error due to a poor signal-to-noise ratio. In these cases, the temperature is measured more reliably by first pumping the atoms to the $^1S_0$ state and then exciting them to the $^3P_1$ state via the narrow intercombination transition. For the pumping process, atoms are excited from $^3P_0$ to $^3D_1$, followed by spontaneous decay first to the $^3P_1$ and then to the $^1S_0$ state. The excited atoms are captured in the T-MOT and their fluorescence is used to determine the number of atoms in the excited state. The excited fraction is measured for different detunings of the $^1S_0 \rightarrow {}^3P_1$ laser. The width of the distribution is attributed to Doppler broadening from which the temperature of the ensemble is deduced. The flexibility to produce ensembles

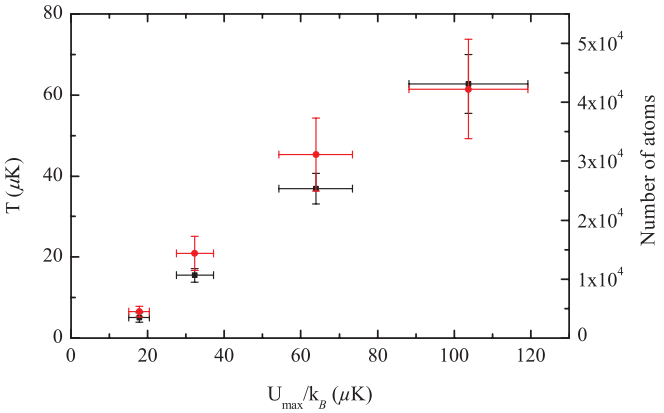

FIG. 5. (Color online) Temperature (black squares) and number (red circles) of atoms captured in the dipole trap for different trap depths. The dipole trap waist was 72 μm. Temperatures as low as 5 μK were observed.

of different temperatures is especially useful in experiments where lower temperatures are more important than a higher number of atoms as in the case of neutral atom optical clocks which are currently not limited by signal-to-noise ratio. At lower trap depths, we were able to capture 5000 atoms at a temperature of 5 μK.

In summary, we have demonstrated continuous loading of a dipole trap for magnesium atoms from a millikelvin MOT. The method allows us to capture a significantly higher number of atoms from an otherwise density-limited atomic sample. Magnesium is a promising candidate for a neutral atom optical frequency standard with calculations predicting very low uncertainties due to room-temperature blackbody radiation [16]. The low-temperature regime for loading will serve as a starting point for a magnesium optical clock and for achieving quantum degeneracy.

We thank the Deutsche Forschungsgemeinschaft for funding the Cluster of Excellence QUEST (Center for Quantum Engineering and Space-Time Research) supporting our experiments. This work was also supported by Sonderforschungsbereich 407. T.W. acknowledges financial support by QUEST.

[1] M. D. Barrett, J. A. Sauer, and M. S. Chapman, Phys. Rev. Lett. **87**, 010404 (2001).
[2] M. Greiner, O. Mandel, T. Esslinger, T. W. Hänsch, and I. Bloch, Nature (London) **415**, 39 (2002).
[3] M. Takamoto, F.-L. Hong, R. Higashi, and H. Katori, Nature (London) **435**, 321 (2005).
[4] C. Y. Yang, P. Halder, O. Appel, D. Hansen, and A. Hemmerich, Phys. Rev. A **76**, 033418 (2007).
[5] P. Lemonde, Eur. Phys. J. Spec. Top. **172**, 81 (2009).
[6] J. Stuhler, P. O. Schmidt, S. Hensler, J. Werner, J. Mlynek, and T. Pfau, Phys. Rev. A **64**, 031405 (2001).
[7] P. O. Schmidt, S. Hensler, J. Werner, T. Binhammer, A. Görlitz, and T. Pfau, J. Opt. B: Quantum Semiclassical Opt. **5**, S170 (2003).
[8] S. B. Nagel, C. E. Simien, S. Laha, P. Gupta, V. S. Ashoka, and T. C. Killian, Phys. Rev. A **67**, 011401 (2003).
[9] Y. N. Martinez de Escobar, P. G. Mickelson, M. Yan, B. J. DeSalvo, S. B. Nagel, and T. C. Killian, Phys. Rev. Lett. **103**, 200402 (2009).
[10] S. Stellmer, M. K. Tey, B. Huang, R. Grimm, and F. Schreck, Phys. Rev. Lett. **103**, 200401 (2009).
[11] J. Friebe, M. Riedmann, T. Wübbena, A. Pape, H. Kelkar, W. Ertmer, O. Terra, U. Sterr, S. Weyers, G. Grosche, H. Schnatz, and E. M. Rasel, New J. Phys. **13**, 125010 (2011).
[12] P. L. Hansen, K. T. Therkildsen, N. Malossi, B. B. Jensen, E. D. van Ooijen, A. Brusch, J. H. Müller, J. Hald, and J. W. Thomsen, Phys. Rev. A **77**, 062502 (2008).
[13] J. Weiner, V. S. Bagnato, S. Zilio, and P. S. Julienne, Rev. Mod. Phys. **71**, 1 (1999).

[14] H. Engler, T. Weber, M. Mudrich, R. Grimm, and M. Weidemüller, Phys. Rev. A **62**, 031402 (2000).

[15] K. M. O'Hara, S. R. Granade, M. E. Gehm, and J. E. Thomas, Phys. Rev. A **63**, 043403 (2001).

[16] T. Rosenband, W. M. Itano, P. O. Schmidt, D. B. Hume, J. C. J. Koelemeij, J. C. Bergquist, and D. J. Wineland, in *Proceedings of the 20th European Frequency and Time Forum, 2006* (EFTF, Braunschweig, 2006), p. 289.