

## Evaporative cooling of magnetically trapped atomic molybdenum

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We have magnetically trapped and evaporatively cooled atomic molybdenum. Using a cryogenic helium buffer gas,  $2 \times 10^{10}$  molybdenum atoms are loaded into a magnetic trap at an initial temperature of 500 mK. The molybdenum atoms undergo two-body decay with a measured inelastic rate constant of  $g_{\text{in}} = (1.2 \pm 0.6) \times 10^{-12} \text{ cm}^3 \text{ s}^{-1}$  for the initial conditions after loading. The molybdenum atoms are cooled by adiabatic expansion and forced evaporation to 200 mK.

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Cooling and trapping is the first step in the creation of ultracold and degenerate quantum gases. Atomic molybdenum has several features that make it an interesting candidate for an ultracold gas. Because of its large magnetic moment (6 Bohr magneton), the dipolar and van der Waals mean-field energies will be similar in a Mo Bose condensate, perhaps leading to new observable dipolar effects [1–5]. Mo has several stable isotopes, 2 fermions and 5 bosons. This opens the possibility for sympathetic cooling [6–8], of both Fermi and Bose degenerate gases, and interisotope comparisons. In addition, experimental studies of cold, trapped atoms at temperatures above degeneracy can shed light on collision and atomic structure theory [9]. Molybdenum is also important for a variety of studies including double beta decay [10] and biological proteins and enzymes. More detailed knowledge of molybdenum adds to our knowledge base of this element and could one day lead to a better understanding of the role of Mo in these processes.

The usual route towards magnetic trapping is laser cooling. It is, however, a technique that is most effective with atoms having energy levels leading to strong transitions at accessible wavelengths. An alternative method is buffer-gas cooling, which is effective in cooling atoms regardless of their internal level structure. In buffer-gas loading the species-to-be-trapped thermalizes with a cryogenically cooled gas of helium to temperatures below the depth of a magnetic trap.

Inelastic collisions limit the efficiency of evaporative cooling inside a magnetic trap. Static magnetic traps confine atoms in high-energy, low-field-seeking states. Inelastic spin-changing (i.e., Zeeman-state-changing) collisions lead to trap loss as less magnetic species are preferentially expelled from the trapping region. The dynamics of this loss also leads to heating [11]. It remains an open question as to whether quantum degeneracy can be reached in a magnetic trap with atoms having high magnetic moments as their inelastic spin-relaxation rates will, in general, be higher than for lower magnetic moment species (such as the alkali metal atoms). So far, only atoms with magnetic moments as high as  $2 \mu_B$  have been quantum condensed [12,13].

A promising route for reaching degeneracy with high magnetic moment atoms is to evaporatively cool them in a magnetic trap only down to a temperature that is low enough for them to be transferred to a microwave trap [14,15] or far off-resonance optical dipole trap (FORT) [16]. In these types

of traps they would be confined in the high-field-seeking, true ground state and evaporative cooling could be continued without inelastic loss. Buffer-gas cooling is well suited to the first stage of cooling and loading into a magnetic trap due to the resultant large numbers of trapped atoms.

In this Rapid Communication we report trapping of large numbers of Mo atoms, measurement of the inelastic Mo–Mo collision rate constant, and evaporative cooling of Mo. The experimental apparatus is described in detail elsewhere [17]. Briefly, Mo atoms are produced by laser ablation of a metal target inside a cylindrical double-walled plastic cell cooled by a dilution refrigerator (Fig. 1). The jacket formed by the concentric cell walls is filled with superfluid liquid helium that provides a thermal link between the cell and the mixing chamber of the refrigerator. Surrounding the cell is a superconducting anti-Helmholtz magnet which creates a spherical quadrupole trap with a depth of up to 7.2 K (2.3 T). The

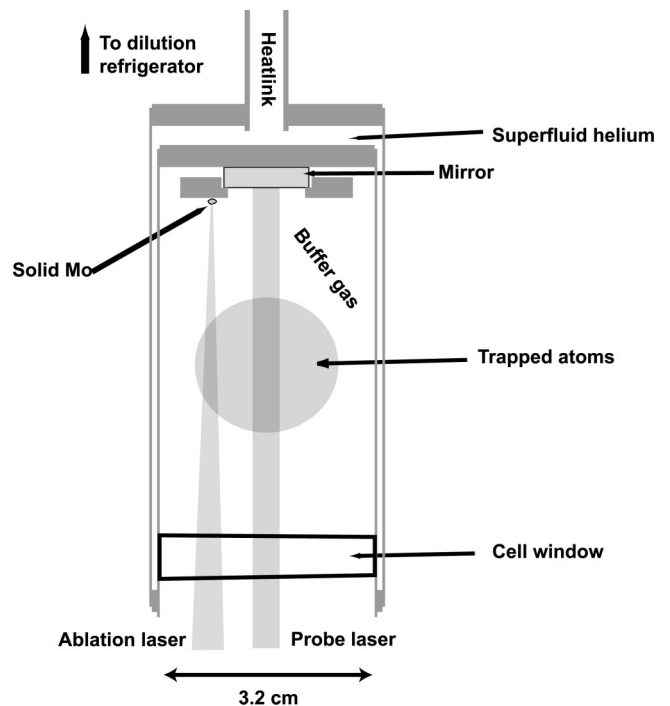


FIG. 1. The experimental plastic cell. The concentric cell walls are filled with superfluid liquid helium that provides thermal conductivity while being electrically insulating.

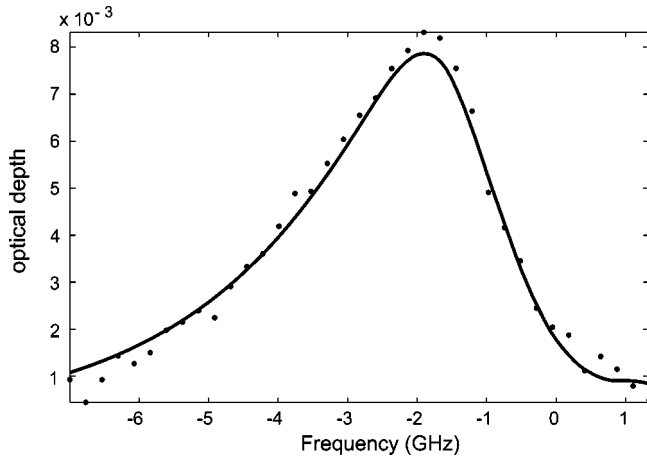


FIG. 2. Absorption spectrum of trapped Mo at the loading trap depth of 7.2 K (2.3 T). The data are shown as filled circles. The solid line is a simulation of a trapped thermal distribution of atoms with number and temperature as free parameters. The fit indicates  $2 \times 10^{10}$  Mo atoms trapped at a peak density of  $1 \times 10^{11} \text{ cm}^{-3}$  and a temperature of 500 mK. The frequency axis contains an arbitrary offset.

interior of the cell is filled with a fixed amount of  $^4\text{He}$  which serves as the buffer gas. The density of buffer gas in the cell is set by the vapor pressure of  $^4\text{He}$  and can be varied from  $<10^{12}$  to  $10^{17} \text{ cm}^{-3}$  by heating the cell from 0.2 to 1 K.

The loading procedure begins with a deep (7.2 K, 2.3 T) magnetic trap. The cell is heated to create a high density of buffer gas ( $10^{17} \text{ cm}^{-3}$ ) before firing a 15-mJ, 5-ns doubled Nd:YAG (532-nm) ablation pulse onto the Mo target. The target is a piece of natural isotopic abundance molybdenum metal. Roughly  $10^{12}$  molybdenum atoms are produced in the ablation. The Mo atoms quickly thermalize with the buffer gas. Low-field-seeking Mo atoms fall into the magnetic trap, while high-field-seeking Mo atoms are driven to the walls where they stick. The cell is cooled to below 0.2 K within 10 s, causing the buffer gas to liquify onto the cell walls, leaving a magnetically trapped, thermally isolated sample of Mo atoms.

Molybdenum atoms are detected via laser absorption spectroscopy on the  $a^7S_3 \rightarrow z^7P_2$  transition at 390 nm [18]. The  $\sim 2$  mm diameter probe beam is produced by passing the output of a Ti:sapphire laser through a resonant doubling cavity. Probe powers of 500 nW are typically used. We verify that the probe light does not affect the loss rate or temperature of the trapped atoms.

Zeeman broadening due to the inhomogeneous trapping field is the dominant broadening mechanism, allowing us to determine the spatial distribution of atoms in the cell from the spectra taken. Figure 2 shows a spectrum of trapped molybdenum atoms taken at the loading trap depth after cryopumping the buffer gas to the cell walls. The individual isotopes are unresolved due to the large magnetic broadening. A fit to the spectrum finds  $(2 \pm 1) \times 10^{10}$  trapped molybdenum atoms at a temperature of 500 mK.

We monitor the decay of the trapped atoms to determine the Mo-Mo inelastic collision rate (Fig. 3). The decay is fit to the expected functional form for two-body loss,  $dn/dt =$

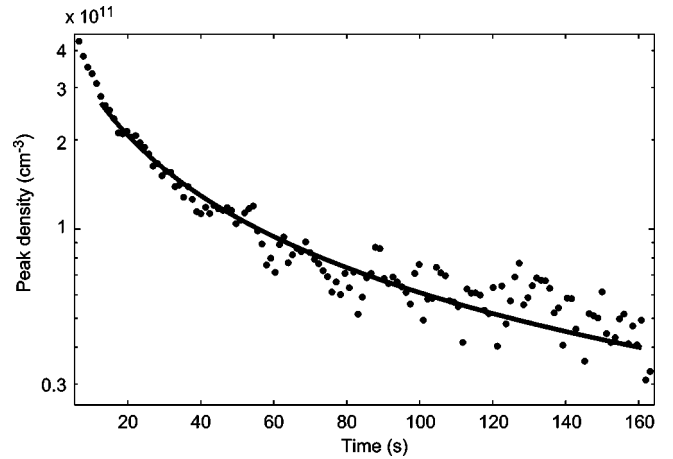


FIG. 3. Peak density as a function of time for trapped Mo atoms. The observed time profile (filled circles) is fit for two-body decay due to inelastic collisions,  $dn/dt = -1/8 g_{\text{in}} n^2$ .

$-1/8 g_{\text{in}} n^2$ , where  $g_{\text{in}}$  is the inelastic rate constant,  $n$  is the peak atom density in the cell, and the factor of 1/8 is a phase-space factor for our particular trapping geometry [11]. We find  $g_{\text{in}} = (1.2 \pm 0.6) \times 10^{-12} \text{ cm}^3 \text{ s}^{-1}$ . This is similar to the inelastic rate previously seen in Cr, which has the same valence electronic configuration and magnetic moment as Mo [19].

Once the atoms are loaded into the trap, the trapping fields may be reduced to force evaporation. The atoms are cooled both by the evaporation and by adiabatic expansion resulting from the reduced confinement. The electrically insulating plastic cell allows for fast ramping of the magnetic field without inducing eddy currents that would heat the cell. Figure 4 shows a spectrum taken after ramping the trapping fields to a depth of 0.9 K (0.3 T). Absorption lines are not observed for atoms in states other than the fully stretched state ( $|m_J=3\rangle$  for the five isotopes with zero nuclear spin,  $|m_J=3, m_I=5/2\rangle$  for the two isotopes with  $I=5/2$ ). Atoms

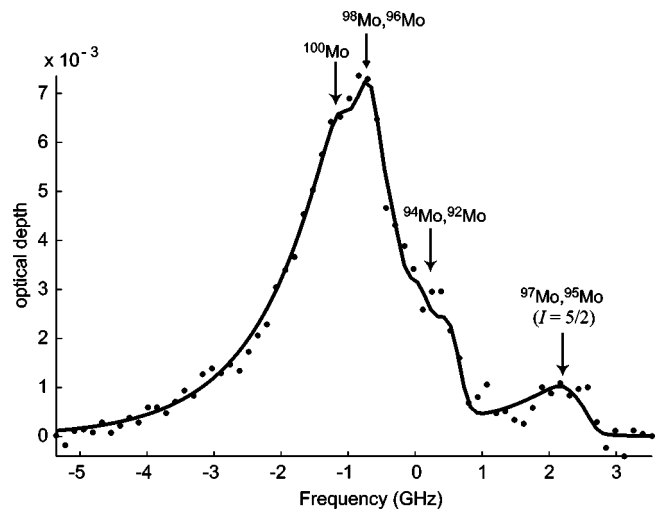


FIG. 4. Absorption spectrum of trapped Mo after forced evaporative cooling. The trapping fields are reduced to a final trap depth of 0.9 K (0.3 T) from the loading depth of 7.2 K (2.3 T). Multiple isotopes are resolved, as indicated.

with  $m_j \neq 3$  are less strongly confined and are quickly lost to evaporation. For those isotopes with nuclear spin, hyperfine states other than the fully stretched state are likely lost to spin-exchange collisions [11,20,21].

The observed spectrum is fit to find the temperature and number of atoms remaining. The fit shown determines  $8 \times 10^8$  atoms cooled to a temperature of 200 mK. Multiple isotopes are resolved. The known isotope shifts and relative natural abundances are used to fix the relative peak positions and heights for isotopes with zero nuclear spin [22]. The known isotope shifts and hyperfine constants are used to fix the positions of the  $^{95}\text{Mo}$  and  $^{97}\text{Mo}$  peaks [22–24], however their peak heights relative to the zero nuclear-spin isotopes are allowed to vary in the fit. One might naively expect the height of the  $^{95}\text{Mo}$  and  $^{97}\text{Mo}$  peaks to be reduced by a factor of  $2I+1$ , however we see a reduction only of a factor of 3. The fully stretched state population is enhanced after the ablation, likely due to spin exchange, as was seen previously with Cr [19]. The trap density is too low to allow for a measurement of the inelastic collision rate at this temperature.

Although temperatures as low as 2 mK were achieved previously for Cr using similar buffer-gas loading and evaporative cooling techniques [19], we were unable to detect Mo temperatures below 200 mK due to less efficient evaporative cooling resulting from a lower initial atom density, and to lower detection efficiency of the trapped atoms. The lower

initial density is expected since the higher boiling point for molybdenum (4639 °C compared to 2671 °C for Cr) should lead to a lower ablation yield [25]. While the resonant absorption cross section for the 390-nm transition used for Mo detection is twice that of the transitions used in Cr detection [18], the detection efficiency for Mo is lower due to its large number of significant, naturally occurring isotopes. The absorption signal is spread out over several resolved peaks corresponding to seven naturally occurring isotopes, each with a natural abundance of 9–25 %. In contrast, Cr has one isotope which is dominant ( $^{52}\text{Cr}$ , 84% natural abundance).

In conclusion, we have magnetically trapped all naturally occurring isotopes of molybdenum in large numbers and evaporatively cooled them to a temperature of 200 mK. The inelastic Mo-Mo collision rate is measured and found to be similar to that found in Cr-Cr collisions. Further cooling of molybdenum to temperatures lower than 200 mK would benefit from a technique such as cooling by evaporation via optical pumping [26], which avoids the decrease in trap densities associated with the lowering of the magnetic trapping field. Another possibility is evaporation by moving the cloud to the cell wall [27].

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