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Magnetic trapping of atomic chromium

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Ground-state ^{52}Cr atoms have been magnetically trapped using buffer-gas loading. The atoms are produced by laser ablation of solid ^{52}Cr, thermalized by collisions with a cryogenically cooled helium buffer gas, and trapped by an anti-Helmholtz quadrupole magnetic field. The atoms are detected by absorption spectroscopy on the $a^7S_3 \leftrightarrow z^7P_3$ transition at 427.6 nm. Using this technique, approximately 10^{11} atoms are loaded into the trap in a single ablation pulse. Loading has been demonstrated at temperatures from 0.3 to 1.4 K. [S1050-2947(98)50205-3]

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Recently we demonstrated the technique of buffer-gas loading of neutral species by using it to load a magnetic trap with europium atoms [1,2]. The atom density achieved in that experiment ($n \sim 10^{12}$ cm^{-3}) is comparable to the highest densities achieved in magneto-optical traps, and the number trapped ($N \sim 10^{12}$) is an order of magnitude higher than can currently be obtained with light-force traps [3]. The buffer-gas method promises the extension of magnetic trapping and evaporative cooling to species other than alkali atoms, and should open the way for producing ultracold, dense samples in a variety of atomic and molecular species.

Herein, we report the magnetic trapping of atomic chromium via buffer-gas loading. Chromium has many properties of interest. It is a metal dissimilar to europium; trapping it further demonstrates the generality of buffer-gas loading. Chromium's large magnetic moment of 6 μ_B (Bohr magneton) allows for trapping at elevated buffer-gas temperatures, opening up the possibility to trap it with a simple pumped liquid helium cryostat. Study of chromium is also motivated by its applications in atom lithography [4,5]. As it has four naturally occurring isotopes, three bosons and one fermion, trapping could open the door to the study of chromium Bose-Einstein condensates or degenerate Fermi gases [6–9].

The principles of buffer-gas loading and the specifics of our apparatus are outlined in previous papers [1,2]. We give a brief description below. Our magnetic trap is a linear quadrupole field formed by two anti-Helmholtz coils. The trapping region is filled with helium buffer gas. The buffer gas is maintained at cryogenic temperatures by a dilution refrigerator. The species of interest (atomic chromium in this case) is introduced into the trap, where it diffuses through the helium gas and quickly thermalizes with it via elastic collisions. The atoms in the weak-field-seeking magnetic states are contained by the magnetic fields, but as the atoms are thermally distributed, they evaporate from the trap at a rate determined by η, the ratio of the trap depth to the temperature of the atoms. For a sufficiently large η, this evaporation is slow enough that a large fraction of the atoms may be held for a long enough time that the (nonmagnetic) helium gas can be (cryo-)pumped out of the trapping region. This leaves a thermally isolated, trapped sample. Because this technique relies only on elastic collisions with the buffer gas and on the magnetic state of the species, it should be applicable to any magnetic species that can be cleanly introduced into the cryogenic environment.

In our experiment, Cr atoms are produced, thermalized, and trapped within a copper cell. There is a fused silica window on the bottom of the cell to permit optical access (for detection and ablation) and a mirror on the top of the cell to retroreflect the probe beam for absorption spectroscopy of the trapped sample. Resistance thermometry is used to determine the cell temperature. Additional resistors attached to the cell are used as heaters. The cell is filled with either ^{3}He or ^{4}He buffer gas. A sufficient amount of ^{3}He (^{4}He) is present so that at temperatures above 0.3 K (0.9 K) the density is approximately 10^{17} cm^{-3}. Below these temperatures, the density is determined by the helium vapor pressure. The Cr atoms are brought into the gas phase by single pulse laser ablation of a solid sample of isotopically pure ^{52}Cr. The solid ^{52}Cr is positioned at the edge of the trapping region inside the cell. A doubled yttrium-aluminum-garnet laser with typical ablation pulse energy of 25 mJ at 532 nm is used for ablation. The atoms are detected by laser absorption spectroscopy on the $a^7S_3 \leftrightarrow z^7P_3$ transition at 23 386 cm^{-1} [10,11]. This probe beam is produced by doubling the output of a continuous-wave titanium-sapphire laser with a $KNbO_3$ crystal. The typical probe power used is $\sim 10^{-7}$ W.

Using the above apparatus, we were able to produce, thermalize, and trap neutral, ground-state ^{52}Cr atoms. Two methods were used. In the first method, designated as ''normal loading,'' the temperature of the cell is raised prior to ablation. The cell is heated to a temperature where the cell has the desired density ($\sim 10^{17}$ cm^{-3}) of helium buffer gas. Then the ablation laser is fired, producing chromium atoms that diffuse through the buffer gas and thermalize with it. After ablation, the cell temperature is lowered. This cryopumps the helium gas to the walls of the cell. In the second method, ''cold loading,'' the cell is not heated prior to ablation. The cell is cold ($\sim$100 mK) and, therefore, a negligible amount of helium is in the gas phase before the ablation laser is fired; it is condensed as liquid on the interior of the cell. However, atoms are successfully loaded into the trap. We believe cold loading works because the ablation pulse not only produces chromium atoms, but simultaneously evaporates helium into the gas phase. After the pulse, buffer-gas loading proceeds as usual. The advantage of cold loading is a faster cooling of the cell, as it is not heated prior to ablation. If we infer the helium pressure from the cell temperature,

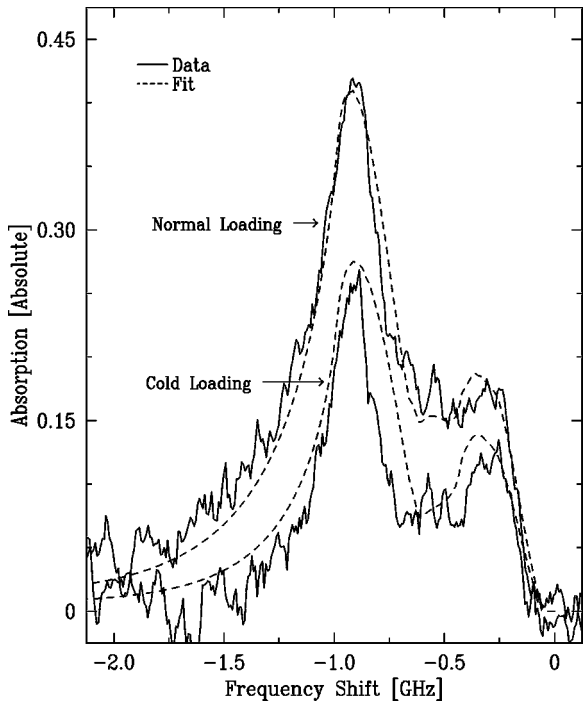

FIG. 1. Absorption spectra of trapped ^{52}Cr obtained by scanning over 4 GHz in 100 ms. Spectra taken 2 s after the ablation pulse. Broadening is primarily due to Zeeman shifts. The double-peaked structure is due to the probe beam passing through the cloud-trapped chromium atoms twice, at two different distances from the trap center. The frequency zero is the location of the field-free line center.

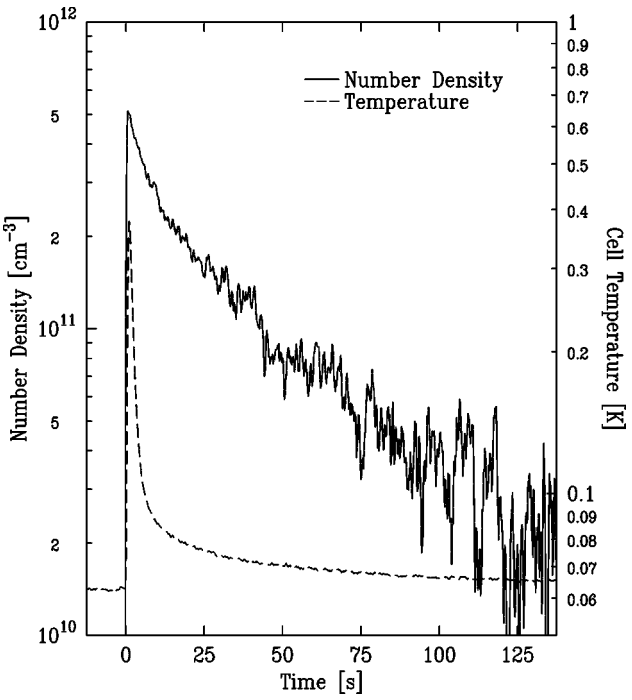

FIG. 2. Atoms trapped via ^{4}He cold loading in a 2.4-T trap. Measurement of the cell temperature is limited by the slow time response of our resistive thermometry. Due to this, temperature readings from 0 to ~3 s are of limited accuracy.

then within 5 s of the ablation pulse, the background pressure of ^{4}He is less than 10^{-18} Torr [12].

Shown in Fig. 1 are spectra of the trapped chromium taken 2 s after ablation, using ^{4}He as the buffer gas and a trap depth of 2.4 T. Also shown are simulations of the spectra, calculated assuming a thermal distribution of atoms within our trap. The $m_J=3$ ($6\,\mu_B$) state of ^{52}Cr is trapped. The number density of atoms within our trap was obtained from these spectral simulations. In the case of cold loading, the temperature was determined from this fit as well. With normal loading, we were able to load in 1×10^{11} chromium atoms into our trap, with a peak density of 5×10^{11} at a temperature of 1 K. With cold loading, slightly fewer atoms were trapped: two seconds after loading, 4×10^{10} atoms at a density of 4×10^{11} were trapped. Quoted atom numbers and densities are accurate to within a factor of 2. No significant attempt was made to increase the number of trapped atoms by optimizing the loading procedure.

The decay of the trapped chromium is shown in Fig. 2. It was obtained by monitoring the Cr absorption at a fixed frequency. The number density was calculated from this absorption and a spectrum taken at a short time. If we fit the decay to purely one-body loss (exponential decay) we find a time constant of 44 s. If we fit to purely two-body loss ($\dot{n}=-g_{\rm eff}n^2$), we find $g_{\rm eff}=2\times10^{-12}$ cm^{-3} s^{-1}. Fitting to combined one- and two-body loss ($\dot{n}=-n/\tau-g_{\rm eff}n^2$) gives $\tau=76$ s and $g_{\rm eff}=7\times10^{-13}$ cm^{-3} s^{-1}.

While the pure one-body fit provides a better fit than the pure two-body fit, it is not clear what could be causing one-body decay in our sample. Suspect mechanisms are the evaporation of atoms over the trap edge, Majorana transitions at the low-field trap center, and optical pumping by the probe beam. However, our sample is at a sufficiently high η ($\gtrsim$13) that evaporative losses should be negligible. Our trap parameters are such that Majorana losses would take place on a much longer time scale [13,14]. Optical pumping was ruled out by varying the probe power over a wide range and observing little effect in the time scale of the absorption signal.

One possible explanation of the apparent one-body loss in our trap is the inaccuracy in our calculation of the chromium density. We compute the density at a given time from the absorption at a single frequency at that time and a spectrum of the atoms taken at a fixed time. It is assumed that the distribution of atoms is not changing over the trap lifetime. However, if the distribution (and hence spectrum) changes over time due to cooling or heating in the trap, this would distort the calculation. This could make the fitting process inconclusive as to the exact nature of our loss.

We also loaded ^{52}Cr into our trap using ^{3}He as a buffer gas. The advantage of loading with ^{3}He is that its higher vapor pressure allows buffer-gas loading at lower temperatures than ^{4}He. With ^{3}He buffer-gas and normal loading, we loaded 5×10^{11} Cr atoms at a temperature of 0.3 K into a magnetic trap of depth 0.7 T.

The $6\mu_{\rm B}$ magnetic moment of Cr allows loading of our trap at elevated temperatures. With the cell at 1.4 K, we were able to load ~10^{11} Cr atoms. This is of interest because temperatures below 1.3 K can be easily reached with a pumped ^{4}He cryostat. Such a cryostat is comparably simpler than the dilution refrigerator system we currently use. Cr and

other large magnetic moment atoms could be trapped using this simple cryostat. Although a pumped ^{4}He refrigerator cannot reach the cold temperatures necessary to lower the vapor pressure of liquid helium, it should be possible to remove the helium buffer gas from the cell by cryopumping it with charcoal [15].

In summary, we have magnetically trapped ^{52}Cr atoms using the buffer-gas loading technique. Loading at 1.4 K was also accomplished. This demonstrates that a simple pumped helium apparatus should be adequate for trapping high-magnetic-moment species ($\gtrsim 5\mu_B$) [16]. Loading using the rapid introduction and rapid removal of the buffer gas was demonstrated. The rapid removal of the buffer gas may lead to other rapid loading techniques that allow loading at reduced η's (lower trap depths and/or higher buffer-gas temperatures). The temporal decay of ^{52}Cr atoms from the trap was observed. Under the tentative assumption of fixed atom temperature, a combined one- and two-body decay fit of our data gives an effective two-body relaxation constant $\lesssim 7 \times 10^{-13}$ cm^{-3} s^{-1} at a temperature of 0.75 K.

Buffer-gas loading allows the loading of multiple isotopes [2], and should easily allow the loading of multiple species. For Cr this is particularly interesting because of the isotopes available. ^{53}Cr is a fermion (nuclear spin $=3/2$) and ^{52}Cr is a boson (nuclear spin 0). As evaporative cooling of fermions becomes inefficient at low temperatures [6], it may be necessary to employ sympathetic cooling with a bosonic species to bring fermions into the degenerate regime. Chromium offers the possibility of the easy loading of the necessary isotopes at high densities. It remains to be seen, however, whether the low-temperature elastic and two-body relaxation cross sections will be favorable enough for an approach into the quantum degenerate regime. Other extensions of this work include trapping molecules, the trapping of heavy atoms for permanent electric dipole moment searches, and the development of ultra-cold-atom sources.

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[1] J. M. Doyle, B. Friedrich, J. Kim, and D. Patterson, Phys. Rev. A **52**, R2515 (1995).
[2] J. Kim *et al.*, Phys. Rev. Lett. **78**, 3665 (1997).
[3] W. Ketterle, K. B. Davis, M. A. Joffe, A. Martin, and D. E. Pritchard, Phys. Rev. Lett. **70**, 2253 (1993).
[4] V. Sandoghar *et al.*, J. Mod. Opt. **44**, 1883 (1997).
[5] J. J. McClelland, W. R. Anderson, and R. J. Celotta, Proc. SPIE **2995**, 90 (1997).
[6] J. M. V. A. Koelman, H. T. C. Stoof, B. J. Verhaar, and J. T. M. Walraven, Phys. Rev. Lett. **59**, 676 (1987).
[7] J. M. V. A. Koelman, H. T. C. Stoof, B. J. Verhaar, and J. T. M. Walraven, Phys. Rev. B **38**, 9319 (1988).
[8] M. Houbiers *et al.*, Phys. Rev. A **56**, 4864 (1997).
[9] J. Javanainenand J. Ruostekoski, Phys. Rev. A **52**, 3033 (1995).
[10] C. E. Moore, in *Atomic Energy Levels as Derived from the Analyses of Optical Spectra, Volume II*, Natl. Bur. Stand. Ref. Data Ser., Natl. Bur. Stand. (U.S.) No. NSRDS-NBS 35 (U. S. GPO, Washington, DC, 1971).
[11] T. Reinhardt, J. Maichel, M. Baumann, and J. Krüger, Z. Phys. D **34**, 87 (1995).
[12] J. Wilks, in *The Properties of Liquid and Solid Helium* (Clarendon Press, Oxford, 1987). Vapor pressure of ^{4}He is determined from extrapolation of data present in this reference.
[13] W. Petrich, M. H. Anderson, J. R. Ensher, and E. A. Cornell, Phys. Rev. Lett. **74**, 3352 (1995).
[14] J. Kim, Ph.D. thesis, Harvard University, 1997 (unpublished).
[15] D. W. Sedgley, A. T. Tobin, T. H. Batzer, and W. R. Call, J. Vac. Sci. Technol. A **5**, 2572 (1987).
[16] Mn, Re, Tc, Mo, Cr, Eu, Gd, Fe, Os, Ni, Co, Rh, Ir, Ru, Er, Tb, Ho, and Dy all have maximum magnetic moments of $5\mu_B$ or greater.