Efficient transfer in a double magneto-optical trap system

T. B. Swanson*

Tri-Universities Meson Facility, 4004 Wesbrook Mall, Vancouver, British Columbia, Canada V6T 2A3, and Department of Chemistry, Simon Fraser University, Burnaby, British Columbia, Canada V5A 1S6

D. Asgeirsson, J. A. Behr, A. Gorelov, and D. Melconian

Tri-Universities Meson Facility, 4004 Wesbrook Mall, Vancouver, British Columbia, Canada V6T 2A3, and Department of Physics, Simon Fraser University, Burnaby, British Columbia, Canada V5A 1S6

Received April 14, 1998; revised manuscript received August 13, 1998

We demonstrate the transfer of potassium atoms from a vapor-cell type magneto-optical trap (MOT) to a second MOT up to 75 cm away with the use of a spatially narrow push laser that generates a 40-m/s atomic beam. By adding two-dimensional MOT's (atomic funnels) along the transfer path to generate transverse cooling and compression of the beam, we can consistently transfer 78±10% of the atoms. © 1998 Optical Society of America [S0740-3224(98)01711-1]

OCIS codes: 020.7010, 140.3320.

1. INTRODUCTION

Experiments involving the cooling and trapping of neutral atoms have matured to the point where the environment in which the atoms are initially confined can be incompatible with performing a high-precision experiment owing to the uncaptured and contaminant atoms in the trapping vessel. This has been recently shown with experiments involving Bose–Einstein condensates[1–3] and nuclear-decay experiments involving trapped radioactive isotopes[4–8] where the transfer of atoms to an ultrahigh vacuum (UHV) environment is necessary for these experiments to succeed.

Vapor-cell magneto-optical traps[9] (MOT's) load only the low-velocity tail of the Maxwell–Boltzmann distribution, typically less than 1% of the vapor present in the cell. Beam-loaded traps rely on Zeeman slowing[10] or chirped cooling[11] to slow atoms in a thermal atomic beam below the trap capture velocity, but even these methods do not slow the entire velocity distribution. These untrapped atoms are either present in the vapor and limit the trap lifetime and the trap population or they stick to the cell or chamber walls.

Transfer from the collection MOT to a second MOT in a UHV system allows for multiple loadings and higher populations. Long trap lifetimes and large trap populations are desirable for the start of the evaporative-cooling process leading to Bose–Einstein condensation. In radioactive-decay experiments, background signals are reduced with the absence of untrapped atoms, and long trap lifetimes increase the fraction of decays that occur from atoms in the trap. Transfer to a second, beam-loaded MOT adds distance from the radioactive source, allows for placement of shielding to further reduce backgrounds, and allows detection of the low-energy (~500-eV) nuclear recoils from β decay, which is incompatible with vapor-cell walls.

The transfer of atoms into a UHV MOT requires generation of a low-velocity, cold atomic beam passing through a tube or an aperture to allow differential pumping of the low- and high-vacuum sections of the system. For high efficiency the beam needs to have minimal transverse expansion during the transfer to maximize the number of atoms within the capture area of the second trap, so it is desirable to have atoms that are cold and traveling at close to the capture velocity of the second trap.

Several methods have been used to transfer atoms or to generate a suitable atomic beam. Cold atoms have been dropped vertically into a second MOT with ~20% efficiency.[12] Moving optical molasses in a MOT has been used to load a second MOT[13] and magnetic trap[14] and has also been used to generate slow, cold atomic beams by use of a two-dimensional MOT or an atomic funnel.[15,16] Transfer with a push beam that polarizes the atoms and uses magnetic confinement has been demonstrated with 90% efficiency with a 40-cm separation between traps.[17] Methods that use an unbalanced trapping beam to generate the transfer force have been demonstrated to generate a low-velocity atomic beam[18] and also in a pyramidal funnel used to transfer atoms to a UHV MOT with ~ 6% efficiency, over a 35-cm path.[19]

The geometry of our system (see Fig. 1) precludes copying the low-velocity intense source technique,[18] in which the push beam is derived from an unreflected portion of the trap beam and thus directed along a trapping-beam axis. Producing the fields required for magnetic confinement of the atomic beam presents possible limitation on the transfer. In Ref. 17, resistive heating of wires lim-

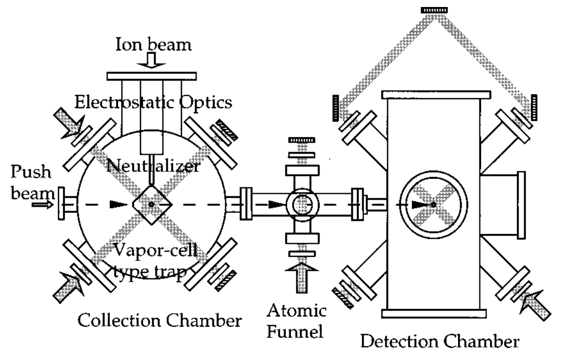

Fig. 1. Layout of the double magneto-optical trap system. With a single atomic funnel the separation between trap centers is 48 cm. This is increased to 75 cm with the addition of a second funnel.

ited the transfer rate to one load every ~2 s, which is far too long to be useful with short-lived radioactives. The duty cycle was improved by adding permanent magnets whose presence might unnecessarily complicate the polarization required in the planned study[6] of the β–ν correlation in ^{37}K. Adapting the pyramidal trap[20] into a funnel[19] requires special machining of mirrors. Here we describe our transfer system, using a push beam, easily implemented and with more flexibility than these other methods.

2. EXPERIMENT

The transfer tests were carried out with stable ^{41}K, generated as a 2.5–4-keV ion beam, neutralized[6] and coupled into a dry-film-coated cell. Our collection MOT is a standard six-beam trap[21] with three retroreflected 4.5-cm beams, ~140 mW per beam, detuning of -5Γ, and a magnetic-field gradient $dB/dz = 20$ G/cm, which traps $\sim 5 \times 10^5$ atoms. The cell is a 5-cm cube with 6-mm entrance and exit holes drilled into the edges with a narrow window located opposite the exit hole to accommodate the push beam. The second trap (detection MOT) uses two retroreflected beams, one each in the horizontal (15-mm) and vertical (20-mm) directions, with a total power of ~160 mW. The horizontal beam passes through both axes of the trap before being retroreflected, as shown in Fig. 1, and has a higher intensity (3:1) than the vertical. The beams are from a commercial Ar^+-ion laser-pumped Ti:sapphire ring laser locked to a D2 ($4S_{1/2} \rightarrow 4P_{3/2}$) Zeeman-dithered saturation spectroscopy signal[22] and frequency shifted with acousto-optic modulators (AOM's). To allow for flexibility in frequency selection, the beam is split, and independent pairs of AOM's shift the Ti:sapphire frequency to the trapping frequencies, as shown in Fig. 2. Because of the narrow (17-MHz) $4P_{3/2}$ hyperfine splitting of ^{41}K, the laser, which is tuned to the red of the $F = 2 \rightarrow F' = 3$ trapping transition, must be detuned to the red of all three possible ($F = 2 \rightarrow F' = 1, 2, 3$) transitions. This results in strong optical pumping to the $F = 1$ ground state and requires nearly equal power in both the trap ($F = 2 \rightarrow F' = 1, 2, 3$) and the repump ($F = 1 \rightarrow F' = 0, 1, 2$) beams, as demonstrated in Ref. 23.

The transfer of the atoms is generated by introducing a narrow push beam through the collection MOT and directed along the tube connecting the collection chamber and the detection chamber. The tube is 1 in (2.5 cm) in diameter at the inlet and the outlet with 1.5-in (3.8-cm)-diameter components along the transfer path. A few milliwatts of laser power is split off, frequency shifted, and then focused in a telescope to create a slowly diverging beam ~1 mm in diameter at the position of the first trap (~2-mm FWHM in size). The large imbalance in scattering rates is enough to force atoms out of the trap and create a low-velocity atomic beam that can be captured. The small size of the push beam imposes a geometrical limit to the divergence of the atomic beam so that atoms with large transverse velocities will move out of the push beam before exiting the trap volume in a fashion similar to that in Ref. 18. These atoms will interact with the trapping beams and continue to be confined, cooled, and available for transfer.

Because the push beam can disrupt loading of the second MOT, the push beam is intentionally misaligned a few millimeters so that it misses the center of the second MOT. The push beam was typically aimed above the center of the detection MOT so that gravity would tend to deflect the atoms back to the center of the trap. The gravitational drop in a 20-ms transit time is ~2 mm.

This basic method was shown to transfer atoms over a 48-cm path with a single-pulse transfer efficiency of a few percent. This is thought to be limited by deflection of atoms at the edge of the trap caused by intensity imbalances in the trapping beams and a large divergence angle arising from the low transfer velocity owing to the retarding forces of the trap beams at full intensity.

To improve the transfer efficiency, we operate the system in pulsed mode. The trap power is lowered to ~10% of normal during the push, which allows the transfer to behave more like a one-dimensional, single-beam push and minimizes any steering effects at the trap edge. In addition to lowering the intensity we shift the frequencies ~10 MHz closer to resonance in an effort (along with the intensity change) to lower the trap temperature and help counteract heating from the push beam. Another improvement is the addition of two-dimensional MOT's (atomic funnels) in the vacuum system along the transfer tube, which cause spatial compression and cooling of the atoms during the transfer.[24,25] We use 15-mm beams split from the detection MOT beams with an intensity of 3–10 mW/cm^2 for the funnel(s) with a 6-G/cm quadrupole

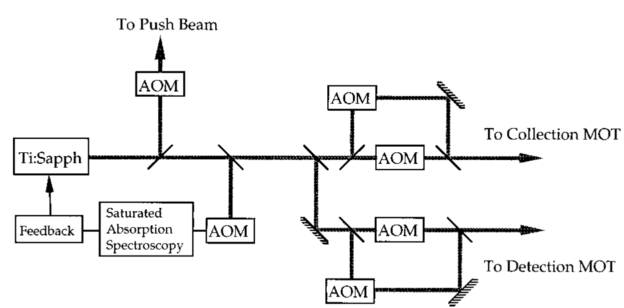

Fig. 2. Laser schematic. The beams for the first and the second magneto-optical traps (MOT's) and for the push are independently tunable with acousto-optical modulators (AOM's), which allow both the trapping and transfer efficiencies to be maximized.

magnetic-field gradient generated by rectangular anti-Helmholtz coils.

The narrow excited-state hyperfine structure that causes the strong optical pumping present in ^{41}K results in some behavior that would not be present in other alkali atoms. Our single-frequency push beam is detuned to the blue of the $F = 2 \rightarrow F' = 3$ resonance in order to minimize the rate at which pumping to the $F = 1$ ground state takes place. Even under these conditions the atoms still spend a considerable fraction of the time in the $F = 1$ ground state and the push requires more power than would be required for an atom where optical pumping was much weaker. Once the atoms leave the trapping region, the absence of the repumping frequency ensures that the push interaction switches off after only a few additional scatters. It was found that the detection MOT was more efficient in capturing atoms from the transfer beam with a larger amount of power (~2:1) in the $F = 2 \rightarrow F' = 3$ transition, unlike in the vapor-cell collection MOT.

Transfer efficiency of the system was measured by comparing the decrease in the population of the collection MOT with the population present in the detection MOT after a single transfer pulse of 20 ms, which couples ~50% of the trapped atoms into the transfer beam. Trap populations were measured by collecting fluorescence signals with charge-coupled device cameras shielded by a 1-nm FWHM interference filter. Results were compared with a model in which the atomic beam, assumed to have a two-dimensional Maxwell–Boltzmann distribution of velocities, expands over the transfer path. It is compressed and cooled in the presence of the atomic funnel(s), and the atoms are captured in the detection MOT if incident within the area of the trapping beams.

The mean velocity of the atoms during transfer was deduced with a time-of-flight measurement. With the detection MOT light turned off, the push beam was switched on for 5–10 ms. After a delay, the detection MOT was then turned on and the fluorescence was measured. Atoms that had already traversed the detection MOT region were not captured. These measurements of the detection MOT population were fit to a function that models the pushed beam of atoms as a series of point sources emitted for the duration of the push pulse. Each point in the beam has the same mean drift velocity and velocity spread.[16] The atoms are accelerated in the trap region and then drift to the detection MOT.

3. RESULTS AND DISCUSSION

Transfer efficiencies were measured for two different separations between the collection and detection MOT's. At a trap separation of 48 cm and without the atomic funnels the efficiency was measured to be 55%±9%. This is consistent with the 63% predicted by expansion of a beam at a temperature of 1 mK, the estimated transverse temperature of the atoms after interaction with the push beam. When the separation was increased to 75 cm, the efficiency dropped to 40%±5%, agreeing with the predicted 38%. With the push beam aligned to miss the detection MOT below trap center by 8 mm, the poor overlap of the atomic beam profile with the detection MOT reduced the efficiency to 21%±3%. The predicted efficiency in this alignment is 24%.

One of the effects of the funnels is to steer the atomic beam toward the center of the detection MOT, minimizing losses from large alignment offsets of the push beam. Another is the spatial compression and cooling of the atomic beam, predicted by calculating the spatial and the velocity compression time constants[26] and calculating the effect on the atomic-beam profile and temperature during the transit of the 15-mm funnel laser beams. At the 48-cm trap separation the addition of one funnel improved the efficiency of 78%±14%, with the model predicting 86%. Increasing the trap separation to 75 cm necessitated the addition of a second funnel to maintain performance. The transfer efficiency in this case was 78%±10%, compared with the predicted value of 77%.

Time-of-flight data were taken to determine the velocity of the atoms in the transfer beam. A sample fluorescence signal and the resultant fit from the model are shown in Fig. 3. The mean transfer velocity was determined to be 40±2 m/s with a velocity spread (1/*e* Gaussian width) of 6.7±1.4 m/s for the normal detuning of +47 ± 2 MHz and a push-beam power of 3.2 mW. The velocity spread is consistent with a one-dimensional push, where the atoms acquire a velocity distribution such that Doppler identification of the fast and the slow atoms in the beam is limited by Γ, the linewidth of the transition.[11] For the 6.2-MHz linewidth of K, one expects a velocity spread of order $\Delta v = \Gamma/k = 4.8$ m/s FWHM, where k is the wave number of the transition.

The variation of beam velocity with push power is shown in Fig. 4. Owing to saturation of the transition,

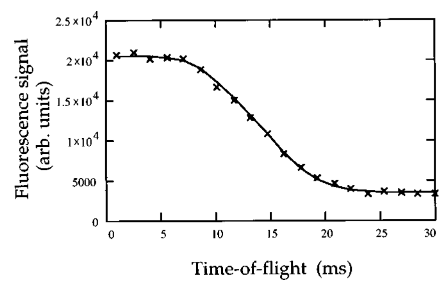

Fig. 3. Fluorescence signal from the detection trap used in time-of-flight analysis (×). The solid curve is a fit to the data that yields the mean velocity and the velocity spread.

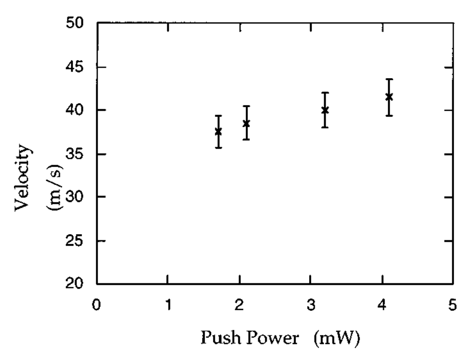

Fig. 4. Transfer-velocity variation with push-beam power at +47 ± 2 MHz detuning. Saturation of the transition reduces the effects of changes in power.

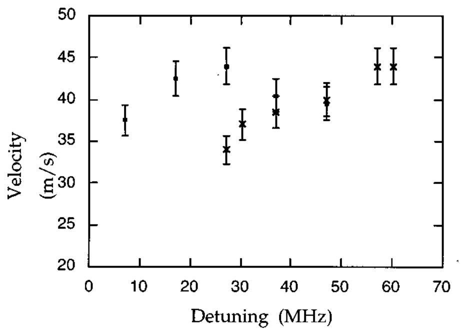

Fig. 5. Mean transfer-velocity variation with push detuning. The × symbol (● symbol) denotes helicity of circular polarization that matches (opposes) the helicity of the ingoing trap light. The push power is 3.2 mW.

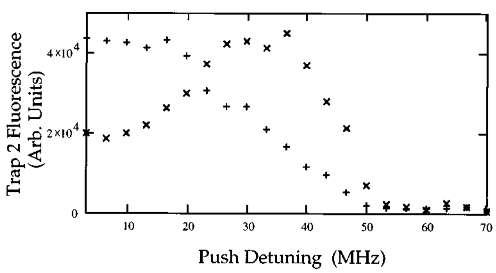

Fig. 6. Population-transfer variation with push-beam detuning. The × symbol (+ symbol) denotes helicity of circular polarization that matches (opposes) the helicity of the ingoing trap light with equal power in the trap and repump frequencies. The push power is 0.8 mW.

the scattering rate does not change significantly as power is increased, and little change in efficiency is seen with push powers above ~1 mW. The variation with detuning for both circular polarizations of the push beam, matching and opposing that of the trapping beams, is shown in Fig. 5.

For the push-beam helicity that matches the ingoing trap beams the slow variation of velocity with detuning is consistent with the 30-MHz broad (FWHM) transfer efficiency curve shown in Fig. 6. As the transfer velocity drops with smaller detunings the expansion of the transfer beam is consistent with the decrease in efficiency. With the higher speeds present at larger detunings some of the atoms should be traveling at speeds larger than the detection MOT is able to capture. Maximum efficiency occurs at different frequencies for the two polarizations owing to the Zeeman shifts present in the MOT.

4. CONCLUSIONS

We have demonstrated an efficient means of transporting atoms in a double-MOT system. Because the push-beam frequency can be tuned independently of either trap, it is possible to maximize the transfer efficiency without compromising the trapping efficiency of the vapor-cell collection MOT. This technique should prove useful where a multiply loaded UHV MOT is required for a successful experiment.

ACKNOWLEDGMENTS

This work was supported by the Natural Sciences and Engineering Research Council and the Tri-Universities Meson Facility. We thank O. Häusser and K. P. Jackson for their encouragement and G. Savard for useful discussions.

*Current address: U.S. Naval Observatory, 3450 Massachusetts Avenue, NW, Washington, D.C. 20392.

REFERENCES

1. D. S. Jin, M. R. Matthews, J. R. Ensher, C. E. Wieman, and E. A. Cornell, "Temperature-dependent damping and frequency shifts in collective excitations of a dilute Bose–Einstein condensate," Phys. Rev. Lett. **78**, 764–767 (1997).
2. C. C. Bradley, C. A. Sackett, and R. G. Hulet, "Bose–Einstein condensation of lithium: observation of limited condensate number," Phys. Rev. Lett. **78**, 985–989 (1997).
3. M. R. Andrews, C. G. Townsend, H.-J. Miesner, D. S. Durfee, D. M. Kurn, and W. Ketterle, "Observation of interference between two Bose condensates," Science **275**, 637–641 (1997).
4. Z.-T. Lu, C. J. Bowers, S. J. Freedman, B. K. Fujikawa, J. Mortara, S.-Q. Shang, K. P. Coulter, and L. Young, "Laser trapping of short-lived radioactive isotopes," Phys. Rev. Lett. **72**, 3791–3794 (1994).
5. J. E. Simsarian, A. Ghosh, G. Gwinner, L. A. Orozco, G. D. Sprouse, and P. A. Voytas, "Magneto-optic trapping of ^{210}Fr," Phys. Rev. Lett. **76**, 3522–3525 (1996).
6. J. A. Behr, A. Gorelov, T. Swanson, O. Häusser, K. P. Jackson, M. Trinczek, U. Giesen, J. M. D'Auria, R. Hardy, T. Wilson, P. Choboter, F. Leblond, L. Buchmann, M. Dombsky, C. D. P. Levy, G. Roy, B. A. Brown, J. Dilling, and J. Deutsch, "Magneto-optic trapping of β-decaying ^{38m}K, ^{37}K from an on-line isotope separator," Phys. Rev. Lett. **79**, 375–378 (1997).
7. Z.-T. Lu, K. L. Corwin, K. R. Vogel, C. E. Wieman, T. P. Dinneen, J. Maddi, and H. Gould, "Efficient collection of ^{221}Fr into a vapor cell magneto-optical trap," Phys. Rev. Lett. **79**, 994–997 (1997).
8. X. Zhao, S. J. Brice, S. G. Crane, A. Goldschmidt, R. Guckert, A. Hime, D. W. Preston, V. Sandberg, M. J. Smith, D. Tupa, and D. J. Vieira, "Trapping radioactive ^{82}Rb Atoms for a β decay asymmetry measurement," Bull. Am. Phys. Soc. **42**, 928 (1997); R. Guckert, X. Zhao, S. G. Crane, A. Hime, W. A. Taylor, D. Tupa, D. J. Vieira, and H. Wollnik, "Magneto-optical trapping of radioactive ^{82}Rb atoms," Phys. Rev. A **58**, R1637–R1640 (1998).
9. C. Monroe, W. Swann, H. Robinson, and C. Wieman, "Very cold atoms in a vapor cell," Phys. Rev. Lett. **65**, 1571–1574 (1990).
10. T. E. Barrett, S. W. Dapore-Schwartz, M. D. Ray, and G. P. Lafyatis, "Slowing atoms with σ^- polarized light," Phys. Rev. Lett. **67**, 3483–3486 (1991).
11. W. Ertmer, R. Blatt, J. L. Hall, and M. Zhu, "Laser manipulation of atomic beam velocities: demonstration of stopped atoms and velocity reversal," Phys. Rev. Lett. **54**, 996–999 (1985).
12. A. Steane, P. Szriftgiser, P. Desbiolles, and J. Dalibard, "Phase modulation of atomic de Broglie waves," Phys. Rev. Lett. **74**, 4972–4975 (1995).
13. K. Gibble, S. Chang, and R. Legere, "Direct observation of *s*-wave atomic collisions," Phys. Rev. Lett. **75**, 2666–2669 (1995).
14. E. A. Cornell, C. Monroe, and C. E. Wieman, "Multiply loaded, ac magnetic trap for neutral atoms," Phys. Rev. Lett. **67**, 2439–2442 (1991).
15. E. Riis, D. S. Weiss, K. A. Moler, and S. Chu, "Atom funnel for the production of a slow, high-density atomic beam," Phys. Rev. Lett. **64**, 1658–1661 (1990).
16. T. B. Swanson, N. J. Silva, S. K. Mayer, J. J. Maki, and D. H. McIntyre, "A rubidium atomic funnel," J. Opt. Soc. Am. B **13**, 1833–1836 (1996).
17. C. J. Myatt, N. R. Newbury, R. W. Ghrist, S. Loutzenhiser,

and C. E. Wieman, “Multiply loaded magneto-optical trap,” Opt. Lett. **21**, 290–292 (1996).

18. Z.-T. Lu, K. L. Corwin, M. J. Renn, M. H. Anderson, E. A. Cornell, and C. E. Wieman, “Low-velocity intense source of atoms from a magneto-optical trap,” Phys. Rev. Lett. **77**, 3331–3334 (1996).
19. R. S. Williamson III, P. A. Voytas, and T. Walker, “A magneto-optical trap loaded from a pyramidal funnel,” Opt. Express **3**, 111–117 (1998).
20. K. I. Lee, J. A. Kim, H. R. Noh, and W. Jhe, “Single-beam atom trap in a pyramidal and conical hollow mirror,” Opt. Lett. **21**, 1177–1179 (1996).
21. E. L. Raab, M. Prentiss, A. Cable, S. Chu, and D. E. Pritchard, “Trapping of neutral sodium atoms with radiation pressure,” Phys. Rev. Lett. **59**, 2631–2634 (1987).
22. U. Tanaka and T. Yabuzaki, “Simultaneous improvement of short- and long-term frequency stability of a laser diode,” Proc. SPIE **1837**, 70–80 (1992).
23. R. S. Williamson III and T. Walker, “Magneto-optical trapping and ultracold collisions of potassium atoms,” J. Opt. Soc. Am. B **12**, 1393–1397 (1995).
24. J. Nellessen, J. Werner, and W. Ertmer, “Magneto-optical compression of a monoenergetic sodium beam,” Opt. Commun. **78**, 300–308 (1990).
25. J. Yu, J. Djemaa, P. Nosbaum, and P. Pillet, “Funnel with oriented Cs atoms,” Opt. Commun. **112**, 136–140 (1994).
26. P. D. Lett, W. D. Phillips, S. I. Rolston, C. E. Tanner, R. N. Watts, and C. I. Westbrook, “Optical molasses,” J. Opt. Soc. Am. B **6**, 2084–2107 (1989).