Laser-free slow atom source

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A slow atom source, which does not rely on lasers, has been developed and characterized. The device, acting as an atomic low-pass velocity filter, utilizes permanent magnets to passively select the slow atoms present in a thermal atomic beam. Slow atoms are guided along a curved, conduction-limited tube by an octupole magnetic field, while fast atoms, unable to follow the curved trajectory, strike the tube wall and are removed from the beam. The performance of the device is demonstrated by loading a magneto-optical trap. Approximately 2×10^8 lithium atoms are loaded with a rate of $\sim6\times10^6$ atoms/s, while maintaining a background gas pressure of $\sim10^{-11}$ torr. This loading technique provides an exceptionally simple, economical, and robust alternative to laser cooling methods. [S1050-2947(99)00411-4]

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Sources of slow atoms are integral components of numerous atomic physics experiments, including investigations of Bose-Einstein condensation of atomic gases, high precision spectroscopy of trapped atoms, and ultracold collision studies. Given their widespread importance, much effort has been dedicated to improving slow atom sources, and especially to their simplification. In this paper, we describe a simple slow atom source and report its performance for loading a magneto-optical trap (MOT) [1] with ^{6}Li atoms.

The most common use of slow atom sources is for loading atom traps. Trap loading methods that rely on laser slowing an atomic beam can achieve high load rates and low background pressures, resulting in long trap lifetimes. Zeeman slowing [2] is the most successful of these techniques, providing typical load rates of 10^8 atoms/s into a MOT. Under optimum conditions, rates as high as 10^{11} atoms/s have been attained [3]. Unfortunately, this method is complex and expensive since it usually requires acousto-optical and/or electro-optical modulators, and significant laser power. MOTs have also been directly loaded from the slow atoms present in a vapor cell [4]. The main advantage of vapor loading lies in its simplicity since no additional laser beams, other than those used for trapping, are required. Load rates as high as 10^{11} atoms/s have been achieved in vapor cells [5], though the relatively high background gas pressure results in reduced trap lifetimes that prove unsuitable for many experiments. This limitation encouraged the development of the double-MOT scheme. In this technique, the trapped atoms from a vapor-loaded MOT are transferred to an ultrahigh-vacuum (UHV) chamber using magnetic guiding, providing load rates of $\sim10^8$ atoms/s [6]. The main disadvantage of this method, as for Zeeman slowing, is the degree of complexity and expense. MOTs have also been loaded directly from a thermal atomic beam [7], achieving load rates of $\sim10^7$ atoms/s from an oven located 20 cm from the trap [8]. Although simple, this method suffers from reduced trap lifetimes resulting from the proximity of the hot atomic source. Applications that require less than maximal load rates, but must be UHV-compatible, may benefit from a simple technique that does not involve lasers, such as the one described here.

In our experiment, the slow atoms present in a thermal lithium beam are magnetically transported to a MOT, using a device we call the ‘‘skimmer.’’ Related devices for transporting and focusing beams of slow atoms have been previously demonstrated [6,9]. The skimmer, however, operates as a low-pass velocity filter for the thermal beam. The atoms are transported through a curved, conduction-limited tube, allowing the trap chamber to be differentially pumped to UHV pressures. As shown in Fig. 1, permanent rare-earth magnets are placed around the tube to establish an octupole magnetic guiding field leading from the atomic source to the MOT. The low-field seeking atoms in the thermal beam are attracted to the magnetic field minimum at the tube center, and the field gradient provides the centripetal force needed to guide the atoms around the curve. Atoms that are slower than a threshold velocity, dictated by the magnetic field gradient and the radius of curvature of the tube, are successfully guided. Faster atoms, however, strike the tube wall, and are lost from the beam. Removing the fast atoms is beneficial, since they can lead to loss of trapped atoms through collisions.

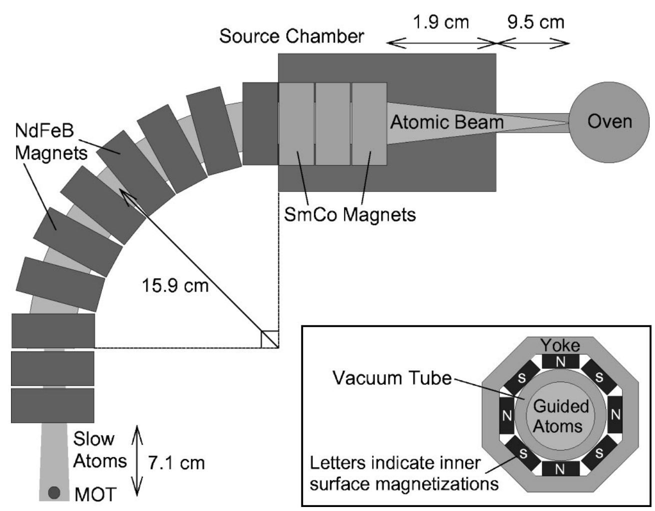

FIG. 1. Schematic drawing of the skimmer. The inset displays a cross section of the octupole magnet yokes. The SmCo magnets ($1.4\times4.8\times32$ mm) and NdFeB magnets ($2.5\times5.1\times18$ mm) are magnetized along the smallest dimension.

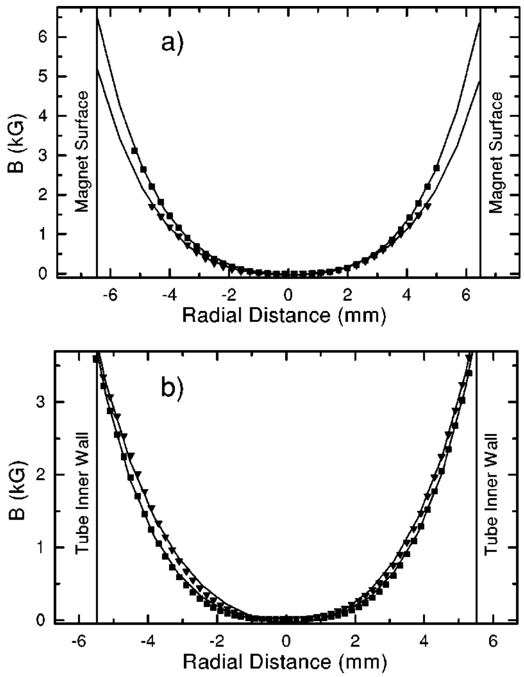

FIG. 2. Total magnetic field along radial lines at two different azimuthal angles inside (a) SmCo and (b) NdFeB octupoles. The square symbols correspond to a line between centers of two opposite magnets, while the triangles correspond to a line from the edge where two adjacent magnets meet at the opposite edge. For each line, two perpendicular field components were measured separately, from which the total magnetic field is calculated. The fourth-order polynomial fits, the average of which is used in the trajectory simulations, are shown as solid curves. For the SmCo octupoles, the motion of the atoms is constrained by the magnet surfaces, while inside the NdFeB octupoles, the atoms are limited by the curved vacuum tube. Inner faces of the SmCo magnets (residual induction, $B_r = 10.6$ kG) are at ± 6.4 mm. Inner faces of the NdFeB magnets ($B_r = 12.1$ kG) are at ± 6.7 mm, and the tube inner diameter is 11 mm.

A prototype of this guiding system was built and tested with a quadrupole field [10]. Comparison of the experimental results with a simple transport model indicated that a higher-order field would increase the flux of slow atoms. For the quadrupole design, most atoms entering the guiding tube suddenly experience a large magnetic field. For atoms that are close to the tube walls, the magnetic field might be sufficiently large to repel them from the tube entrance, preferentially removing the slowest atoms. Figure 2 shows the measured field profiles for the current octupole design. The field profile is flat over a larger range near the tube axis and has a higher gradient near the tube walls. The nearly uniform, low-field region near the axis allows a larger fraction of the slowest atoms to enter the skimmer, while the higher gradient near the walls leads to a higher threshold velocity for guiding. The octupole field was produced by sets of eight commercially available, homogeneously magnetized, rectangular magnets. Although using a small number of rectangular magnets weakens the octupole strength, introduces higher-order multipoles, and disturbs the cylindrical symmetry of the field profile, these effects can be tolerated to maintain simplicity and economy. Figure 2 shows that the dependence of the field on the azimuthal angle is minimal for the present configuration.

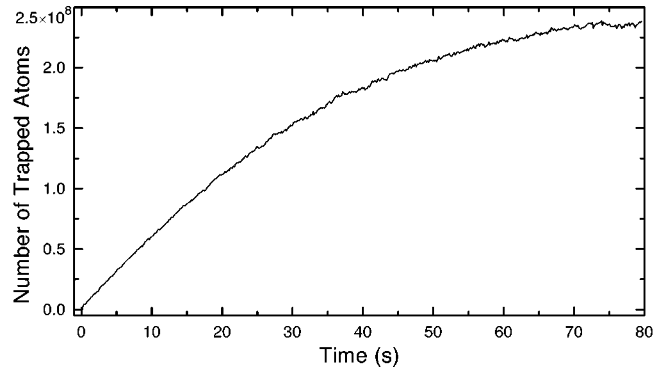

FIG. 3. Typical fluorescence data. The atomic beam is suddenly unblocked at time = 0, and the load rate is given by the increase in signal in the first few seconds.

The octupoles around the curved tube are constructed from NdFeB magnets, since this material provides the largest fields. The tube inner diameter is 1.1 cm and the total arc length is 25 cm, corresponding to a conduction of ~ 0.4 L/s. Although a larger tube diameter may produce a higher flux of slow atoms, a smaller diameter more completely isolates the source chamber from the UHV chamber. The entrance solid angle for the thermal beam is improved by extending the octupole field inside the source chamber. The additional octupoles are made from SmCo magnets, because their relatively high Curie temperature allows them to be vacuum baked with the chamber. As shown in Fig. 1, each octupole set of magnets is mounted inside cylindrical housings composed of a material with a high magnetic permeability, 400 series stainless steel in this case. These yokes shunt the field lines, which reduces stray fields that might perturb the MOT. They also flatten the magnetic field profile, thereby widening the entrance for slow atoms. Other benefits of the shunt yokes include enhancing the magnetic field strength ($\sim 50\%$ increase in the present geometry) and providing a surface for the magnets to be conveniently affixed in the appropriate positions.

The six MOT laser beams are derived from three circularly polarized, retroreflected, mutually orthogonal beams. The beams are produced by a frequency-stabilized dye laser that is locked to a saturated absorption feature in ^{6}Li. Optical pumping is prevented by simultaneously driving transitions from both ground-state hyperfine levels. The power in each frequency is the same, typically 60 mW in three beams. The $1/e^2$ intensity radii of the beams are 1.1 cm, and the beams are apertured to diameters of 1.8 cm. The detuning from resonance is 7.5Γ, where $\Gamma = 5.9$ MHz is the natural linewidth of the $2S$-$2P$ transition. A pair of anti-Helmholtz coils generate the MOT quadrupole magnetic field with an axial gradient of 32 G/cm.

The number of trapped atoms is determined by observing the excited state fluorescence with a photodiode. The load rate is measured by first emptying the MOT of all atoms and then observing the increase in fluorescence during the first few seconds after the atomic beam is unblocked. A typical data set is shown in Fig. 3. Load rates of $\sim 6 \times 10^6$ atoms/s and peak numbers of $\sim 2 \times 10^8$ atoms are obtained. The systematic uncertainty in the number of atoms is $\sim 40\%$, and is primarily due to measurement uncertainties in the beam intensities and laser detuning. The load rate dependence on the

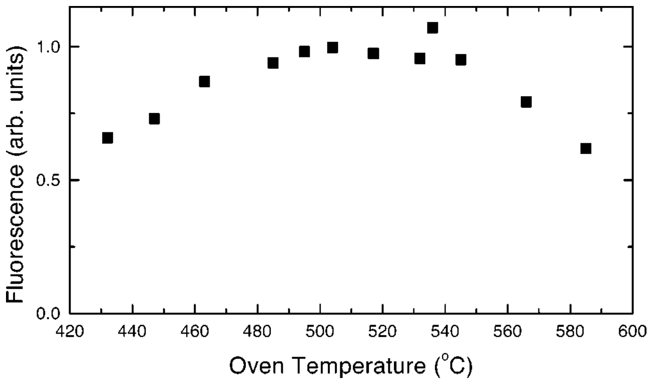

FIG. 4. Peak number of trapped atoms vs oven temperature. The overall systematic uncertainty in the number of atoms is ~40%.

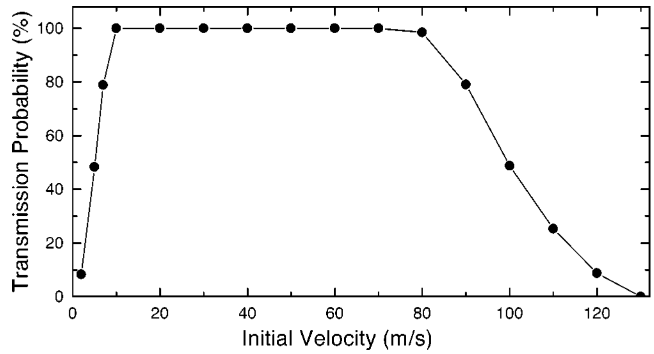

FIG. 5. Simulation of the transmission probability as a function of the initial atomic velocity.

oven temperature is displayed in Fig. 4. At lower oven temperatures, the number of trapped atoms rises with temperature as the number of available slow atoms increases. At higher temperatures, however, collisions in the beam reduce the flux of slow atoms into the skimmer. The trap lifetime is measured by blocking the oven and observing the decay in trap fluorescence. The decay is dominated by the losses due to inelastic collisions between trapped atoms. The lifetime due to background gas scattering is ~ 10 min, corresponding to a background gas pressure of $\sim 10^{-11}$ torr, which is below the sensitivity of our pressure gauge.

We have performed a Monte Carlo calculation to model the efficiency of the skimmer. The trajectory of an atom through the skimmer is calculated to determine whether it is transmitted to the exit. The initial position and velocity of each atom are chosen to be consistent with the recirculating atomic beam oven design and a Maxwell-Boltzmann velocity distribution [11]. The oven reservoir containing the lithium is maintained at $\sim 500\,°\mathrm{C}$, and is connected to the source chamber via a 9.5-cm-long nozzle with an inner diameter of 0.36 cm. The atomic source, therefore, is modeled as a thin-walled aperture located at the nozzle entrance that is collimated by the nozzle exit. The angular spread of the thermal beam is ~ 0.037 rad, so we neglect the transverse component of atomic velocity. The presence of shunt yokes and the close proximity of the nozzle exit to the skimmer entrance reduce the fringing fields seen by the atoms, so in the model the atoms are assumed to suddenly experience the octupole field upon entering the skimmer. Since the SmCo portion of the skimmer is straight and the transverse velocity of atoms is ignored, we assume that the spatial and velocity distributions are unchanged in this section. After entering the curved tube, the force on an atom is calculated from the measured magnetic field profile [12], according to which the trajectory is integrated. Atoms that strike the tube wall are assumed lost. An atom can also be removed from the beam by moving through the magnetic field zero so quickly that its magnetic moment does not follow the field direction, and the atom suddenly becomes high-field seeking. The Majorana criterion [13] is imposed at all integration steps to include this loss in the model.

The fraction of atoms expected to be transmitted through the skimmer is thus determined for each initial atomic velocity. The results are plotted in Fig. 5. The reduced efficiency at very low velocities is due to atoms that are rejected at the skimmer entrance, while atoms faster than the threshold velocity are unable to follow the guiding field. A rough estimate for the threshold velocity, v_{th}, can also be obtained by equating the magnetic force with the centripetal force necessary for atoms to traverse the curve, $\mu\nabla B = m(v_{\mathrm{th}}^2/R)$, where μ is the atomic magnetic moment, m is the atomic mass, and R is the radius of curvature of the guiding tube. If ∇B is taken to be half the gradient at the tube wall, $v_{\mathrm{th}} \approx 110$ m/s, in agreement with the Monte Carlo model. This simple calculation, however, was not as applicable to our earlier studies using a quadrupole guiding field. In this case, the Monte Carlo calculation gives a transmission probability that is not flat-topped as in Fig. 5 but, rather, slowly decreases from a peak velocity that is significantly below v_{th}. The reduced efficiency at large velocities is a consequence of the large fraction of atoms that enter the skimmer at a high field, for which the guiding is less effective. To calculate the expected MOT load rate, the magnetic field is assumed to suddenly go to zero at the skimmer exit and the atomic trajectories are extended to the trap region. Atoms that pass through the trap volume with speeds less than or equal to the capture velocity are assumed trapped. Using previous calculations of Li atom trajectories in a MOT [14,15], we estimate the capture velocity to be 30–40 m/s for the present trap parameters. This velocity range corresponds to load rates between 2×10^6 and 7×10^6 atoms/s, which is consistent with the measured load rate of $\sim 6\times10^6$ atoms/s.

The performance of the skimmer is not completely characterized by this experiment, because the predicted threshold velocity is greater than the capture velocity of the MOT. It has been shown that the capture velocity can be increased to ~ 150 m/s by broadening the frequency spectrum of the MOT laser beams [8]. In addition to verifying the performance of the skimmer, implementation of this scheme should produce a large increase in the load rate. The flux of slow atoms in our experiment could also be increased by using a less collimated atomic beam that would completely fill the entrance solid angle of the skimmer.

This guiding system can be viewed as an atom optical element that performs as a low-pass velocity filter. With suitable modifications, it should be possible to build a band-pass filter for delivery of a monoenergetic beam of atoms for applications such as atom lithography [16]. This device might also be promising for directly loading a magnetic trap based on permanent magnets [17] since its capture velocity is much greater than that of a MOT. Since the skimmer is simple and robust, it may be well-suited for space-born applications. Furthermore, the apparatus is inexpensive; the total cost of magnets [18], custom shunt yokes, and curved vacuum tube was less than \$3500. The performance of this guiding system represents a significant improvement in the design of slow atom sources.

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