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Efficient loading of a He* magneto-optic trap using a liquid He cooled source

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We report loading large numbers (up to 3×10^9) of metastable triplet helium atoms into a magneto-optical trap using an atomic beam derived from a liquid He (LHe) cooled dc discharge source. Moreover, we compare the effect of liquid N₂ cooling to LHe cooling the source and demonstrate that LHe cooling offers a significant increase in performance. © 2006 American Institute of Physics. [DOI: 10.1063/1.2190307]

INTRODUCTION

The ultimate aim of this experiment is to achieve Bose Einstein condensation (BEC) in metastable helium. The large internal energy of metastables makes them interesting candidates for BEC, allowing single atom detection with high spatial (micrometer) and temporal resolution (nanosecond). Recently, Schellekens *et al.* made use of this unique property to demonstrate the Hanbury Brown Twiss effect with He* atoms.¹ Another unique property of a He* BEC is that it produces ions due to Penning ionization. This process allows the experimenter a very sensitive tool, to nondestructively probe the condensate in real time. Seidelin *et al.* were able to map out the evolution of a BEC, from formation to decay, using this unique tool.²

The magneto-optical trap (MOT) is the standard tool for beginning the compaction in phase space towards BEC, hence the objective for many metastable rare gas experiments for many years has been building efficient MOT loading apparatus in order to start with the greatest number of trapped atoms.

The relative timing of successes in achieving BEC in alkali metals³⁻⁶ and metastable rare gases⁷⁻⁹ can largely be attributed to the difficulties in the laser manipulation of very light atoms, particularly helium, and the inherent limitations of metastables, for example, Penning ionization limited densities. As a result the evolution of He* experiments has witnessed many variations in the attempt to make a compact and efficient MOT loading metastable beamline. Problems to be overcome include the efficient production of large numbers of *manipulable* metastables, the probability of excitation into the 2^3S_1 metastable state is approximately 1 in 10^5 . This has the effect that along with the beam of metastables there is a significant amount of helium background gas that needs to be pumped away. In practice these background atoms are re-

moved through multiple differential pumping stages. Furthermore, the velocity of atoms out of the source is high relative to the recoil velocity of a helium atom. Thus to slow a helium atom down to a velocity where it can be caught by a MOT requires large slowing distances.

Previously some effort has been expended to produce simpler, shorter He* beamlines dedicated to MOT loading. In particular, the elimination of the atom optics required for slowing and beam brightening has been pursued by further cryogenic cooling of the source using liquid helium.¹⁰⁻¹² In principle these could produce effusive beams such that significant numbers of trappable He* atoms are in the lower end of the velocity distribution. However, to date these sources produce significantly lower flux compared to liquid N₂ (LN₂) sources such that even with enhancements of MOT loading rates using magnetic focusing and further slowing only small numbers of 10^4 and 10^6 atoms have been captured.^{10,11}

In this article we report on our own compact MOT loading apparatus, in which we consistently achieve 3×10^9 atoms. Moreover, we compare the effect of LN₂ cooling to liquid He (LHe) cooling the source and demonstrate that LHe cooling offers a significant increase in performance.

APPARATUS

The metastable source yields fluxes of approximately 2×10^{14} at./sr/s with a most probable velocity below ~ 700 m/s (Ref. 12) when cooled with liquid helium and about the same flux at ~ 1000 m/s when cooled with liquid nitrogen. One should note that this is not the highest flux obtainable from our source, however, for the purposes of loading a MOT it is the optimum. The source chamber is pumped by a 1400 l/s turbo pump, where the background helium pressure is $\sim 10^{-5}$ torr when using source pressures of ~ 0.25 torr. The metastable beam then passes through a skimmer, located 10 mm from the nozzle, into the the first chamber of the differentially pumped beamline which achieves a pressure below 10^{-6} torr.

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TABLE I. Detunings from resonance, light field dimensions (mm), and single beam intensities ($I_{\text{sat}}=0.16 \text{ mw/cm}^2$) used in our beamline. Note that although the laser beam used for Zeeman slowing starts at a size of 2.5 cm, it is focussed to a 1 cm spot at the entrance of the Zeeman slower.

Laser beam	$\delta_{\text{rel}}/\Gamma$	I/I_{sat}	Size
Collimator	-7.3	50	50×25
Push	-7.3	250	50×5
Slower	-400	30	$25 \text{ } \emptyset$
MOT	-19	85	$38 \text{ } \emptyset$

Immediately after the skimmer the He^* beam is first collimated in two-dimensional (2d) molasses with a 5 cm interaction length, using a recirculating, *in vacuo* mirror array. Collimation maximizes the flux through a 1 cm diameter aperture located 25 cm downstream from the source. Here the atomic beam is bent approximately 1.7° off axis by another 5 cm interaction zone. After 55 cm the metastable beam is 1 cm off axis where it passes into the Zeeman slower. The direct path for ground state atoms from the source is blocked, and they are pumped away. This chamber maintains a background pressure of a few 10^{-8} torr. Differential pumping through the Zeeman slower is enhanced by its length (0.75 m) and a 270 mm long tube 1 cm in diameter located in the slower's entrance. The Zeeman slower immediately loads the MOT chamber, so that the MOT center is 165 mm after the slower exit. Base pressure in the MOT chamber reaches a few 10^{-10} torr with baking. With the source operational, the typical partial pressure of helium in the MOT chamber is 5×10^{-9} torr. The collimator, bender, and MOT chambers are all pumped with 220 l/s turbo pumps.

The design of the Zeeman slower is detailed in Ref. 13. The detuning is set to the Doppler shift of an atom counter-propagating at 690 m/s and captures more than 80% of the flux below 700 m/s. A typical exit velocity is 70 m/s with a full width at half maximum (FWHM) of ~ 10 m/s.

To load large numbers of metastables into a MOT one requires not only an intense slow atomic beam, but also a trapping setup which maximizes loading out of the beam. To this end the MOT must be able to capture atoms with typical beam velocities, in our case of ~ 70 m/s. We achieve this capture velocity by using relatively high MOT magnetic field gradients ($\sim 20 \text{ G/cm}$) combined with large MOT laser beams ($\phi \sim 38 \text{ mm}$). This allows for Zeeman slowing inside the MOT itself, increasing the capture velocity of the MOT.

The three-beam MOT chamber has been designed specifically to maximize capture velocity, with reentrant ports in a 140 mm thick and 28 cm diameter chamber. This allows the magnetic coils to be located just 50 mm from the MOT center around large (38 mm) beam optics. The atomic beam enters the trapping region along a weak axis of the magnetic field at 45° between the laser beams.

BEAMLINER

A high flux of atoms into the Zeeman slower requires the efficient collimation and bending of the low velocity (below 700 m/s) component of the source flux. Both the collimator and bending stages are at the same detuning, see Table I. In

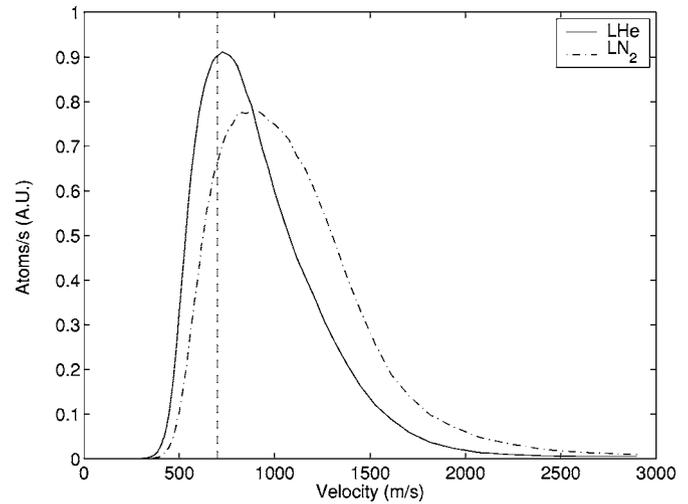


FIG. 1. Longitudinal velocity distributions of atoms emitted from the source when LHe cooling is used (solid line) and when LN_2 cooling is used (dashed dot line). The dashed vertical line indicates the 700 m/s capture velocity of our Zeeman slower.

practice the maximum signal was found for approximately equal powers of the collimation and bending laser beams. The metastable flux along the beamline can be measured by detecting the current from two stainless 1 cm diameter plates, located after the bending stage and after the MOT capture region. When the source is cooled with LHe these detectors measure an equivalent of $9 \times 10^{11} \text{ s}^{-1}$ typical flux in the bent beam and $2 \times 10^{11} \text{ s}^{-1}$ atoms detected at the end of the beamline. The current measured on these detectors is converted into an atomic flux using a 69% efficiency factor reported by Ref. 14.

The measured longitudinal velocity distribution of the He^* beam is shown in Fig. 1, showing the difference in cooling the source with LHe and LN_2 . The most probable velocity of the atomic beam is reduced from 880 ms^{-1} for LN_2 to 720 ms^{-1} for LHe cooling. This reduction in longitudinal velocity yields more atoms below 700 ms^{-1} , the capture velocity of our Zeeman slower, amounting to a two fold improvement in the number of capturable atoms. Moreover, since our source operates at low Mach numbers the transverse velocity distribution of the LHe cooled beam is narrower, due to the lower temperature, which allows more atoms to reach the MOT region. Combining these two effects gives an overall factor of ~ 6 in MOT loading rate, as shown in Fig. 2, for LHe cooling. We use fluorescence to determine the load rate into the MOT, measuring the load rate at early times when the density of the MOT is low and the atom number is linear with load rate.

MAGNETO-OPTIC TRAP

The limiting factor in trapping large amounts of He^* atoms is Penning ionization: two colliding He^* atoms have a combined internal energy of 40 eV which is sufficient to ionize one of the collision partners while transferring the other to the ground state. This process causes a large loss of atoms from the MOT, limiting the achievable atom density to $\sim 10^{10} \text{ cm}^{-3}$. Moreover, the dominant Penning ionization

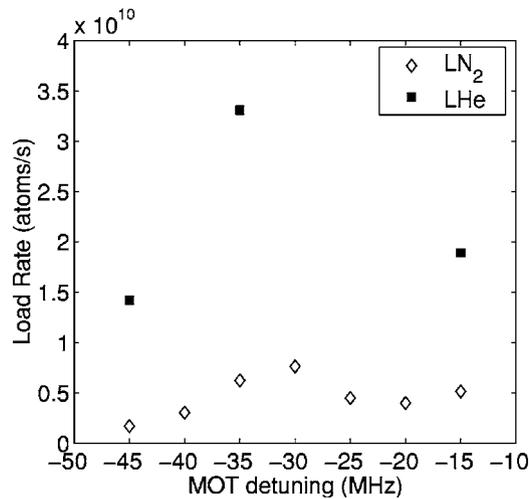


FIG. 2. Load rate of atoms into the MOT as a function of laser detuning. When LHe is used to cool the source a factor of ~ 6 increase in the achievable load rate is measured.

process is mitigated via a collision between an atom in the 2^3S_1 ground state and an atom in the 2^3P_2 excited state. Thus the route to large numbers of trapped He* atoms is to use far red-detuned light in conjunction with high magnetic field gradients.¹⁵ In such a setup, the volume of the atom cloud is large and the excited state population is low.

In order to measure the atom number in our MOT we use a saturated fluorescence method.¹⁶ The method relies on ramping our MOT laser beams to resonance with full power. In such case, the scattering rate of photons is simply $R = N\Gamma/2$, and one need only take into account the collection efficiency of the imaging system to determine the number of atoms. We confirm that the sample is saturated by increasing the power of the laser beams until no further increase in fluorescence is measured. We also use a high speed InGaAs photodetector capable of rise times of the order of 50 μ s. We estimate the error in such a measurement to be $\pm 15\%$, dominated by the reproducibility of our detuning ramp. Using this method we determine the atom number as a function of MOT laser detuning, for the case of LHe and LN₂ cooling.

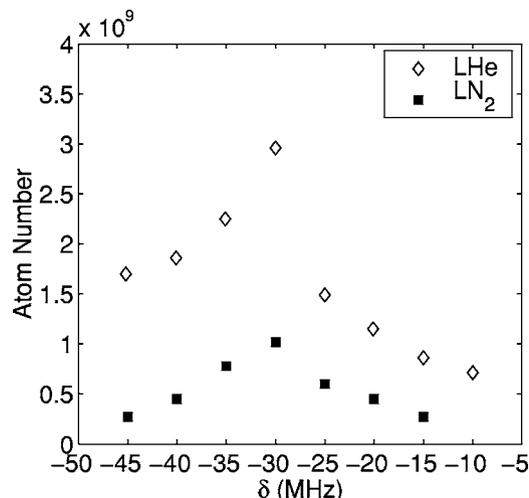


FIG. 3. MOT atom number as a function of laser detuning for both LHe and LN₂ cooling. An improvement of a factor of 3 is seen using LHe cooling.

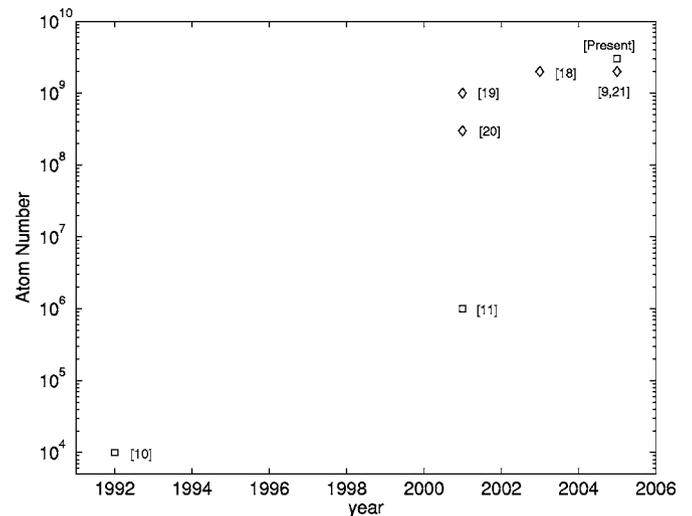


FIG. 4. Summary of He* MOTs, those using LHe cooled sources are shown with squares and those using LN₂ cooling are shown with diamonds.

Figure 3 shows the results of these measurements, and demonstrates the increase in MOT atom number that is achievable with LHe cooling. The maximum MOT number in both cases is achieved at a detuning of $\delta = -30$ MHz = -19Γ , a combined intensity of 82 mW/cm², and an axial field gradient of 8.7 G/cm. Note that the final MOT number scales as the square root of the load rate,¹⁷ and so a two and a half fold improvement in MOT number using LHe cooling is expected.

CONCLUSIONS

In this article we have shown that a LHe cooled source is an excellent starting point for creating a large number He* MOT. Previous attempts to use a LHe cooled source to load a He* MOT have resulted in at best 10⁶ trapped atoms, at least three orders of magnitude below that obtained here. In comparison with beamlines using LN₂ cooled sources, our compact MOT loading apparatus performs favorably against other leading experiments.^{9,18-21} The performance of our beamline compared to others reported in the literature is displayed in Fig. 4 and shows that our system achieves a higher MOT atom number than the 2×10^9 that has previously been reported.^{9,18,21}

Recently we have upgraded our beamline, installing a 15 cm long collimator section and replacing the single bending beam with a second collimation stage at the required bending angle. These modifications have improved our MOT loading rates to 2×10^{10} s⁻¹ for LN₂ cooling and 1.2×10^{11} s⁻¹ for LHe cooling. This LHe load rate implies a maximum MOT atom number of 5×10^9 .

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