

# A magneto-optical trap loaded from a pyramidal funnel

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**Abstract:** We have demonstrated the transfer of  $^{39}\text{K}$  and  $^{40}\text{K}$  atoms from a magneto-optical funnel (a hollow pyramidal mirror) through a low (0.05 l/s) conductance hole and into a conventional magneto-optical trap (MOT) 35 cm away, with an efficiency of approximately six percent. This simple scheme should be useful for experiments requiring high loading rates with minimal contamination from hot untrapped atoms.

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Optical cooling and trapping techniques are becoming increasingly prevalent in a variety of physics experiments and are continually being adapted to fit an ever-broader range of experimental needs. Of current interest, experiments in Bose-Einstein condensation [1–3] and trapping radioactive isotopes [4, 5] both require particularly efficient loading of atoms into an ultrahigh-vacuum magneto-optical trap (UHV MOT) with a long trap lifetime. In this paper we describe an apparatus that accomplishes these goals with a simple magneto-optical funnel coupled to a UHV MOT through a low conductance hole.

Two popular methods for loading a MOT are capturing directly from an atomic vapor [6] and using a thermal atomic beam and Zeeman slower [7]. These methods introduce a large number of uncaptured atoms into the chamber, raising the pressure, depositing untrapped atoms on the chamber walls, or both. An increase in the pressure is undesirable when experiments require UHV conditions for trap lifetimes in the tens or hundreds of seconds. Deposition of radioactives on the chamber walls is problematic when measuring nuclear decay processes since it increases the background signal. In this work we overcome these difficulties by loading a UHV MOT from a collimated low-velocity beam of atoms which originates in a region of higher pressure and passes through a low-conductance hole into the UHV trap.

There are several methods to efficiently transfer slow atoms into a MOT. Gibble, Chang, and Legere [8] loaded a second trap using moving optical molasses. Myatt *et al* [9] demonstrated transfer between two traps using magnetic confinement and a push beam during transport. A simpler alternative method is to use an "atomic funnel" to produce a slow, collimated atomic beam. Although a number of funnels and funnel-related devices [10–14] have been demonstrated, the only funnel suitable for low-conductance transfer into a MOT is the Low-Velocity Intense Source (LVIS) scheme of Lu *et al* [14]. The LVIS funnel consists of a MOT with a hole drilled in one return  $\lambda/4$  plate. This produces an intensity imbalance that pushes atoms out of the MOT and through the hole, producing a cold atomic beam that could be used for loading into a second MOT with a much larger trapping lifetime.

We have transformed the pyramidal trap design of Lee *et al* [15] into a funnel that produces a cold atomic beam suitable for loading a UHV MOT. Our funnel consists of a hollow, four-sided pyramidal mirror whose sides form a  $90^\circ$  included angle, with a small hole drilled at the apex (Fig. 1). A large-diameter circularly-polarized beam is incident axially on the entire pyramid. Each of the mirror segments reflects a quadrant of the beam toward the axis, and the opposing segment reflects it a second time back toward the original beam direction. Each of these reflections approximately reverses the helicity of the light (whose sense is shown by small black arrows in Fig. 1). When combined with an appropriate spherical quadrupole magnetic field (shown by the arrows in inset of Fig.1), the correct MOT forces [16] are generated everywhere inside the pyramid except along the central cylindrical region, where there is no retroreflected light due to the hole in the pyramid apex.

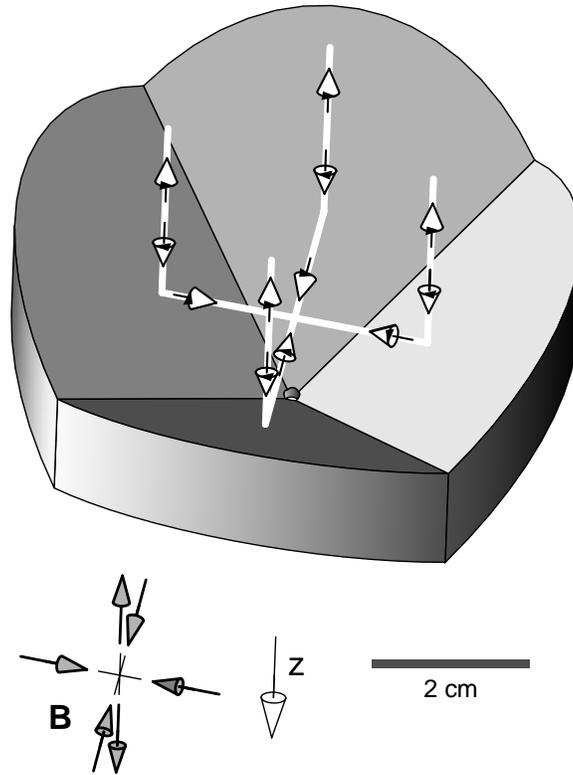


Figure 1. Pyramidal mirror used in the magneto-optical funnel. White lines indicate incident circularly polarized laser beam and its reflections. The helicities are indicated by small black arrows on the white arrowheads. The inset shows the configuration of the magnetic field in the funnel.

Atoms entering the funnel are slowed, cooled, and pushed towards the axis, where they are forced out of the pyramid by unbalanced radiation pressure. As they leave the funnel, they continue to be accelerated by the narrow light beam exiting the pyramid. Eventually the acceleration is reduced as the atoms Doppler-shift out of resonance by a few linewidths. The result is a slow, collimated atomic beam whose velocity is matched to the MOT capture range.

The funnel is constructed of four identical oxygen-free high-conductivity copper pieces, formed to make a hollow right pyramid inside and a 7 cm diameter cylinder outside. Results for two different pyramidal mirrors are discussed below. The mirrors were highly polished, gold electroplated, and evaporatively coated with  $\text{SiO}_2$ . Our first mirror had a 1 mm diameter hole of conductance  $\sim 0.05$  l/s through the apex. As a result of manufacturing difficulties, mirror 1 had poor surface quality so during tests with it we constructed a second mirror, with much better surface quality and a 2 mm diameter apex hole. Mirror 1 was supplied with potassium from bulk metal in a stainless steel side arm connected to the funnel. Mirror 2 was supplied with potassium by a system we intend to use to introduce  $^{37,38}\text{K}$  produced with our tandem accelerator. A potassium dispenser [17] was placed at the end of a Yttrium-lined, 15 cm long, 45 degree elbow, which was heated to about  $700^\circ\text{C}$ .

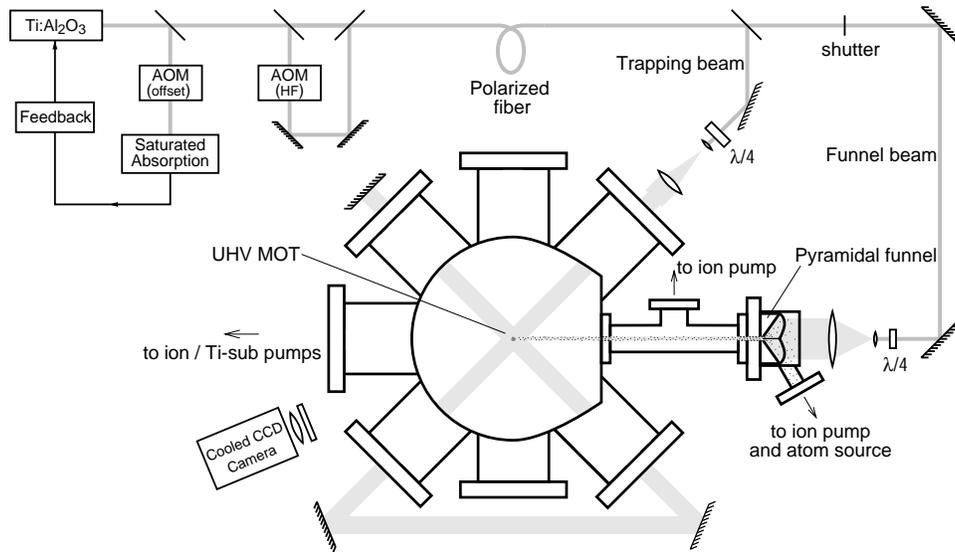


Figure 2. Schematic diagram of combined UHV MOT and funnel system. The arm of the UHV MOT which is perpendicular to the plane of the figure has been omitted for clarity.

Our integrated funnel/UHV MOT apparatus is shown in Fig.2. Potassium atoms that exit the funnel travel through a differentially pumped region and a 0.5 cm diameter orifice to the UHV MOT operated at a pressure of  $\sim 10^{-11}$  torr (trap lifetime, 150 s). The transport distance from funnel apex to UHV MOT is 35 cm. For all tests reported below, both the funnel and MOT are operated using the same Ti:Al<sub>2</sub>O<sub>3</sub> laser, acousto-optic modulator, and detuning  $\Delta$ . The UHV MOT is operated using the recirculated light method in which a single beam is directed along the three cartesian axes and then passed through a  $\lambda/4$  plate and retroreflected back along the same path. For the UHV MOT, we use light with a beam waist of  $w_0 = 2.8$  cm and a magnetic field gradient of  $dB/dz = 5$  G/cm. The funnel beam waist is  $w_0 = 3.0$  cm, and its magnetic field gradient is  $dB/dz = 4$  G/cm. For <sup>39</sup>K, the total intensity (split equally between the two ground state hyperfine levels [18]) at the trap center is 90 mW/cm<sup>2</sup>, and at the funnel center is 78 mW/cm<sup>2</sup>. For <sup>40</sup>K the UHV MOT total intensity is 100 mW/cm<sup>2</sup> and the intensity at the funnel center is 70 mW/cm<sup>2</sup>. In this case about 1/4 of the total intensity is at the  $F = 9/2 \rightarrow F' = 11/2$  transition and the rest at  $F = 7/2 \rightarrow F' = 9/2$ . We found that the transfer efficiency did not depend strongly on the distance from the apex to the magnetic field minimum in the funnel. For both isotopes we found that the laser light exiting the funnel tends to push atoms out of the UHV MOT. We avoid this by shimming the magnetic field so that the UHV MOT forms several mm away from the light from the funnel.

The pyramid, operating as a trap, is known to have a loading efficiency comparable to a standard MOT [15, 19]. The important parameters are the efficiency of transferring atoms from the funnel to the UHV MOT and the large pressure differential between the funnel and the UHV MOT. For <sup>39</sup>K we determine the efficiency by comparing the loading rate of atoms into the UHV MOT to the loading rate of atoms into the funnel operating as a trap. These rates were determined by measuring the fluorescence from the trapped atoms over time as the atoms loaded into an empty trap. To determine the loading rate into the funnel, we make the funnel into a MOT by retroreflecting the laser beam emerging from the funnel with a mirror and quarter-wave plate and shim the magnetic field so the trap is a few mm away from the axis. We measure the loading

rate into the UHV MOT and the ratio of this rate to the funnel loading rate gives the transfer efficiency, the maximum of which is 6%. We find that for  $^{39}\text{K}$ , the trap/funnel combination has a loading rate vs. detuning curve which is narrower and slightly shifted compared to both a vapor cell MOT and a collimated thermal beam loaded MOT. The maximum loading rate was obtained at  $\Delta = -43$  MHz. Here  $\Delta$  is the detuning from the highest energy hyperfine level of the  $\text{D}_2$  line [18]. The loading rate versus detuning data for both a collimated atomic beam and the funnel-produced beam are shown in Fig. 3.

The much lower number density of  $^{40}\text{K}$  in the presence of the substantial scattered light background in the funnel precluded a direct measurement of the funnel loading rate. However, we can compare the efficiency for transferring  $^{40}\text{K}$  to that of  $^{39}\text{K}$  by comparing the loading rate of the two isotopes in the UHV MOT. If the funnel loading rates and transfer efficiencies for the two isotopes are the same, we expect the loading rate in the UHV MOT to scale like the isotopic abundances. The ratio of the  $^{39}\text{K}$  UHV MOT loading rate of 5330 atoms/s to the  $^{40}\text{K}$  UHV MOT loading rate of 0.3 atoms/s is  $1.8 \times 10^4$ . The isotopic abundance ratio is  $8 \times 10^3$ . We infer from these results that the combined efficiency of the trapping and transfer process for  $^{40}\text{K}$  is within a factor of two of that for  $^{39}\text{K}$ .

To determine the frequency response of the system with  $^{40}\text{K}$ , we measured the number of atoms that accumulated in an initially empty UHV MOT during a four minute interval for a number of detunings. Here the detuning is measured from the nominal trapping transitions. The results (shown in Fig. 3) indicate that transfer and trapping of  $^{40}\text{K}$  occurs over a narrower range of detunings than  $^{39}\text{K}$ .

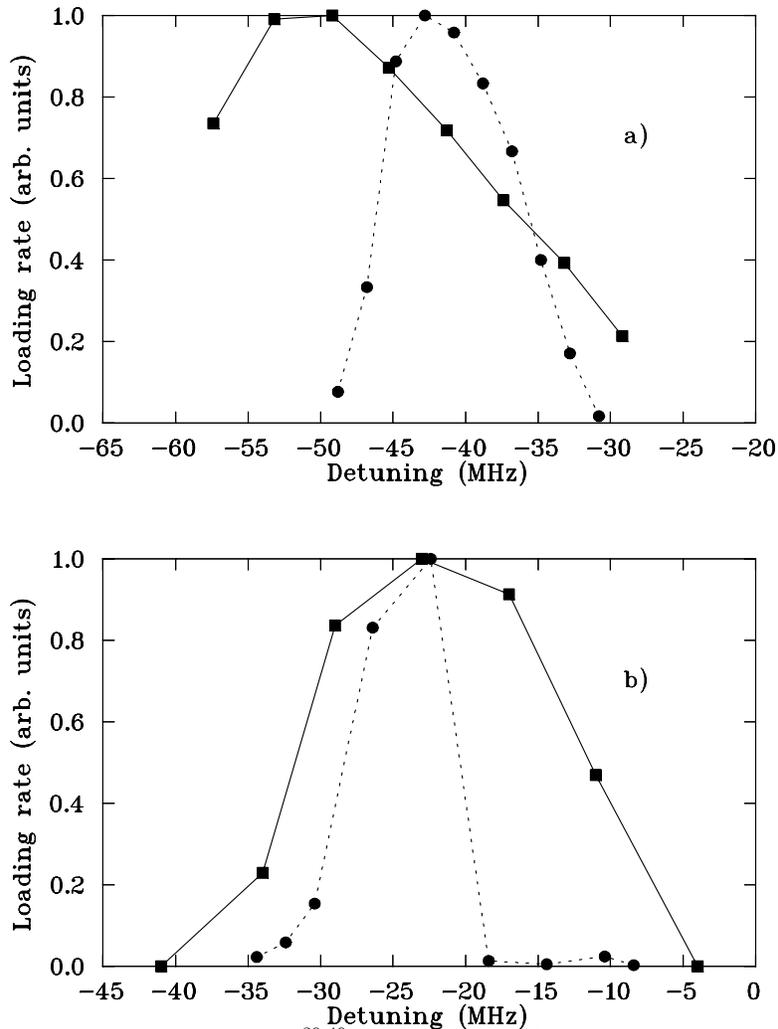


Figure 3. Detuning curves for  $^{39,40}\text{K}$  Shown in panel a) is the loading rate vs. detuning of  $^{39}\text{K}$  atoms into the UHV MOT from a collimated thermal beam (squares) and from the magneto-optical-funnel produced beam (circles). Panel b) shows similar curves for  $^{40}\text{K}$ . All curves are normalized to their maximum values in order to compare shape differences. The maximum value of the  $^{40}\text{K}$  curve corresponds to a funnel-loaded trap with about 7000 atoms.

The low conductance of the apex hole allows a large pressure drop to the MOT chamber. Operating the funnel with mirror 1 at pressures of  $10^{-6}$  torr  $\text{H}_2$  (instead of the typical  $\sim 10^{-9}$  torr) reduced the loading rate by only a factor of five. At  $6 \times 10^{-6}$  torr the loading rate dropped an additional factor of ten. At these high funnel pressures the UHV MOT lifetime was reduced by only a factor of two. It should therefore be possible to operate the funnel at potassium pressures of  $10^{-6}$  torr, increasing the loading rate by more than two orders of magnitude above that of a typical  $10^{-10}$  torr vapor cell MOT with a lifetime of tens of seconds.

With mirror 2 we see no significant difference in the transfer efficiency despite the improved surface quality of its mirrors and dri-film coating. We have no method to separately determine the incoming potassium flux and the number of bounces an atom undergoes before it is lost from the funnel. The larger hole should result in worse collimation, but it is more cleanly drilled which may offset this effect.

We have demonstrated loading with 6% efficiency of a MOT in a UHV chamber from a pyramidal funnel. The efficiency appears to be insensitive to mirror quality and dri-film coating of the interior of the funnel. The low conductance from funnel to UHV MOT allows loading rates corresponding to direct capture from an atomic vapor of  $10^{-8}$  torr in a  $< 10^{-10}$  torr UHV MOT. To compare these results with the LVIS we note that the LVIS efficiency of transfer into the atomic beam is 70%, though the atoms in the beam have not yet been trapped in a MOT. Despite the lower transfer efficiency, we believe the simple and compact design of our single-beam pyramidal funnel makes it attractive for loading magneto-optical traps in an ultra-high vacuum environment.

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