Bichromatic force on helium

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We have observed the bichromatic force on metastable He using fiber amplifiers to produce the high power of light needed at $\lambda = 1.083\ \mu$m. We have done deflection experiments to confirm that the very large magnitude of the force scales to He, and preliminary deceleration experiments for eventual trap loading. Our measurements support earlier experiments in Rb. Helium is ideally suited for this kind of beam slowing because its slowing length with the usual radiative force is more than a factor of 100 larger than with the bichromatic force. Thus, loading a MOT will be much more effective because of the much larger angular capture range associated with the shorter distance.

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The bichromatic force [1] has been carefully measured in Rb and shown to be extremely strong and also to have a very large velocity range [2,3]. We report here the observation and measurement of the bichromatic force on metastable $2\,^3S$ helium (He*) using a cryogenic atomic beam source and optical fiber amplifiers to produce the required high-power light [4]. These measurements demonstrate the scaling of the bichromatic force, and are a prelude to exploitation of this technique for the slowing and trapping of He* in a high-density magneto-optical trap (MOT) [4].

He* is an attractive choice for exploitation of the bichromatic force for several reasons. To begin, the slowing length L for the radiative force whose maximum value is $F_{rad} = \hbar k \gamma/2$ is $L = (4/3) k_B T/F_{rad} = (4/3) T/kT_D$, where the optical wavelength $\lambda \equiv 2\pi/k = 1.083\ \mu$m, k_B is Boltzmann's constant, $\gamma \equiv 1/\tau$ is the decay rate of the excited state, and T_D is the Doppler temperature given by $k_B T_D = \hbar\gamma/2$. For He*, T_D is about 40 μK, and for a discharge source of typical kinetic temperature $T = 600$ K, L is over 3.5 m [5]. Even for a liquid-nitrogen (LN_2)-cooled source whose characteristic kinetic temperature is $T = 150$ K, L is nearly 1 m. But the bichromatic force can slow such 1000 m/s atoms in a distance less than 1 cm, and thus there can be a much smaller loss of atoms from angular dispersion and diffusive heating.

Our atomic beam source is modeled after the reverse flow design of Shimizu [6] with modifications originated by Mastwijk *et al.* [7]. It consists of a 1-cm-diam quartz tube with a 1-mm-diam tungsten needle along its axis and a 3-cm-diam LN_2-cooled stainless-steel coaxial jacket (see Fig. 1). He gas enters the region between the jacket and the quartz tube from the back, is cooled as it flows toward the front, and the cold gas enters the tube. The negative high voltage on the needle feeds a 1–10-mA discharge to a grounded plate with a 500-μm aperture that serves as both an anode and a beam skimmer, and the He gas supports the discharge. Among the discharge products that flow through the aperture into the high vacuum side of the apparatus, we have measured $\sim 10^{14}$ He* atoms/s/sr with a velocity distribution typical of ~ 150 K.

We have characterized the velocity distribution of atoms in the beam using a time-of-flight (TOF) method with a tuning-fork beam chopper. The ~ 200 Hz chopper was mounted just inside the beam chamber, immediately downstream from the skimmer aperture (see Fig. 1). A 250-μm slit in a piece of brass shim stock was mounted on one of the vanes and served to make the opening time as small as 100 μs. The detector was a multichannel plate (MCP) mounted $z_0 = 90$ cm downstream of the chopper (see left side of Fig. 1). Both atoms and uv light from the discharge eject electrons from the front of the MCP (He* atoms carry high internal energy ~ 20 eV), and these electrons were amplified and accelerated towards a stainless-steel plate. The time dependence of the current was recorded with a digital scope.

The electrons ejected by the uv light marked the chopper's opening time, and the TOF signal from the atoms was recorded and converted to a velocity distribution as shown in Fig. 2. From such TOF signals, we determined the mean atomic velocity at low discharge current (~ 2 mA) to be $\overline{v} \sim 950$ m/s, and the full width at half maximum to be ~ 350 m/s.

We implemented the bichromatic force on He* by driving the $2\,^3S_1 \rightarrow 2\,^3P_2$ transition at $\lambda = 1083$ nm using the amplified light that originates from an external cavity-stabilized

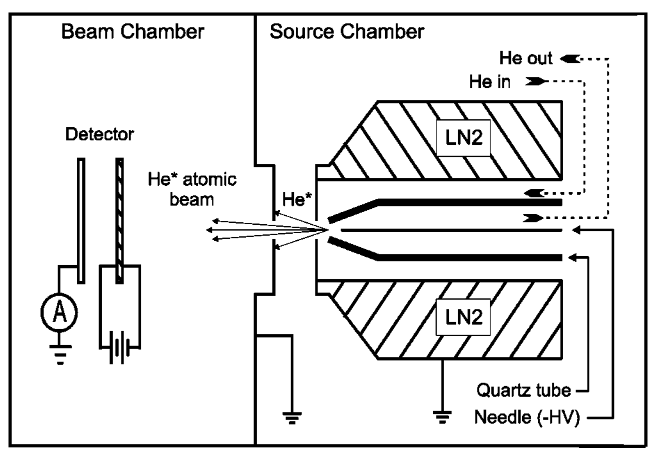

FIG. 1. This source is only about 30 cm long and produces about 10^{14} He* atoms/s. The LN_2 reservoir holds for a few hours. For TOF measurements, the chopper is placed just inside the beam chamber, adjacent to the aperture. For deflection experiments, the simple detector is replaced by a He* imaging system. The drawing is not to scale.

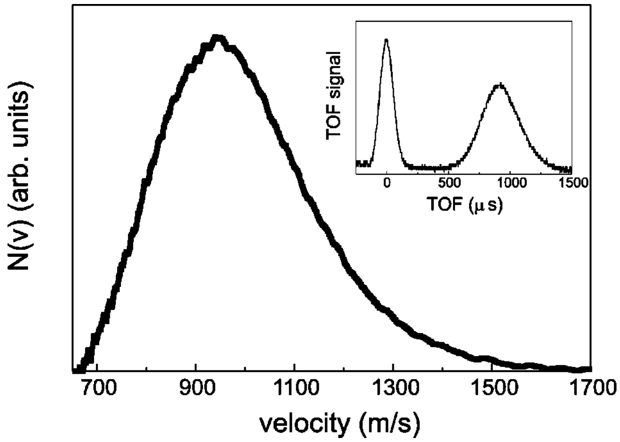

FIG. 2. A typical velocity distribution $N(v)dv$ derived from TOF signal $N(t)dt$ using $dv=(z_0/v^2)dt$, where Z_0 is the flight length. The initial short pulse of uv light shows the opening time and resolution of the system to be ~ 100 μs, whereas the flight time is ~ 1 ms. The velocity distribution is somewhat supersonic. The inset shows the raw TOF signal.

SDL-6702-H1 diode laser. The diode laser frequency was locked to atomic resonance by saturated absorption spectroscopy in a static cell with a weak rf discharge. The light double-passed a 75-MHz acoustic-optic modulator (AOM) that was operated at 50% efficiency to make four frequencies [2,3]. One of the two emerging beams had frequency components shifted by $\pm\delta\sim\pm 75$ MHz$\sim\pm 45\gamma$, where $\gamma^{-1}\equiv\tau\sim 100$ ns is the $2\,^3P$ lifetime. This beam was injected into a diode-pumped fiber amplifier (Optocomm Innovation) to produce several hundred milliwatts of bichromatic light.

The output beam size was focused to $d\sim 5$ mm horizontally and 1.5 mm vertically, and its peak intensity was ~ 3.3 W/cm^2 total, so about half that in each frequency component. This is $\sim 2\times 10^4 I_{sat}$ of 160 μW/cm^2. The peak Rabi frequency $\overline{\Omega}_R$ was $\sim 70\gamma$, and numerical calculations show that the bichromatic force maintains its strength over the range of $\Omega_R\sim(50-70)\gamma$. Thus, the effective interaction length was $d\sim 3.5$ mm, corresponding to a time of $\sim 35\tau$. This beam was retroreflected by a mirror at an adjustable distance to control the relative phase of the beat frequency in the optical field [2,3]. The conterpropagating laser beams crossed the atomic beam perpendicularly.

For these deflection experiments, the stainless-steel TOF detector was replaced by a phosphor screen to provide spatial instead of temporal information. The screen was viewed through a window by a video camera connected to a PC via a frame grabber card. The atomic beam chopper was replaced by a 500-μm-wide slit to define and collimate the beam and thereby enable one-dimensional transverse measurements of atomic deflection. To characterize the apparatus, we did several ordinary Doppler deflection experiments with a single laser beam using a wide range of laser parameters, and compared the measurements with straightforward calculations [5]. The agreement was excellent in every detail.

A typical single-frame image from bichromatic deflection is shown in Fig. 3 (no averaging). The atomic beam appears as a vertical stripe in the absence of laser light, and its ends

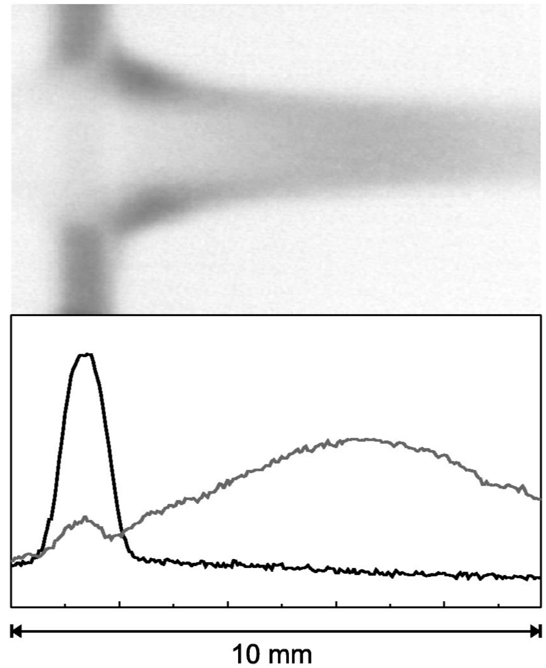

FIG. 3. The upper part is a direct image of a single frame (1/30 s) of the MCP using the video frame grabber. The lower trace is a plot of the middle section of the upper image, and shows that the atoms are deflected by ~ 5.5 mm over their 30-cm flight path, corresponding to a transverse velocity change of 18 m/s during the 3.5-μs interaction time. This corresponds to a force of $11\times F_{rad}=11\hbar k\gamma/2$.

show no deflection from the optical force, since the atoms at the top and bottom of the beam do not pass through the laser light. The maximum deflection occurs at the center, and can be reversed by moving the retroreflection mirror by an appropriate amount.

In most cases, the images from bichromatic deflection showed some of the atoms spread in the direction opposite to the force. We attribute this to the long lifetime of the $2\,^3P$ states resulting in a small number N of spontaneous emissions during the interaction time. The directionality of the bichromatic force derives from correction of the phase errors by spontaneous emission events, and if their number is small, there is a high probability that this correction will fail to varying degrees [3]. In the limit of zero correction (corresponding to infinite lifetime), the bichromatic force produces an atomic beam splitter [8].

A simple numerical simulation was made to illustrate the importance of the small value of $N=d/\overline{v}\tau\sim 17$. We allowed an atom starting from $v=0$ to change the direction of the force on it with a probability that depends on both the direction and the relative phase of the beat envelopes from the bichromatic beams. The results averaged over a large number of atoms are indeed consistent with our measurements. We found that for a few hundred nanosecond interaction time, a large number of atoms end up at the edges of the profiles: these atoms are not undergoing any spontaneous emission.

We used the measured deflections to extract a force value of ~ 11 times larger than $F_{rad}=\hbar k\gamma/2$, the maximum ob-

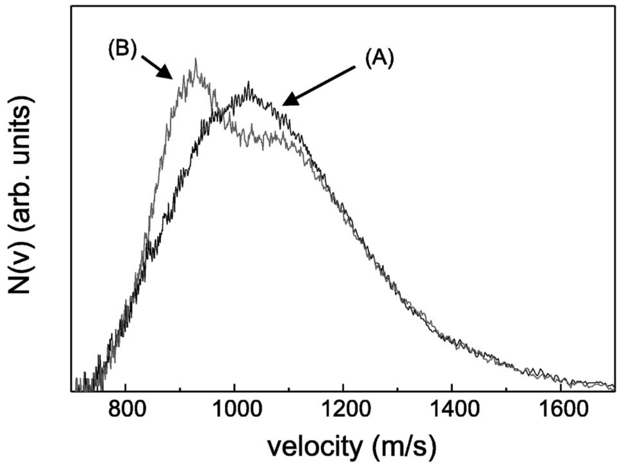

FIG. 4. The velocity distribution derived from the TOF signal for decelerated atoms. Trace (A) shows the source velocity distribution (at a somewhat higher current than in Fig. 2), and trace (B) shows the small deceleration. The atoms are slowed by the expected $\sim$100 m/s. Changing the relative phase of the counterpropagating beams results in acceleration by about the same amount.

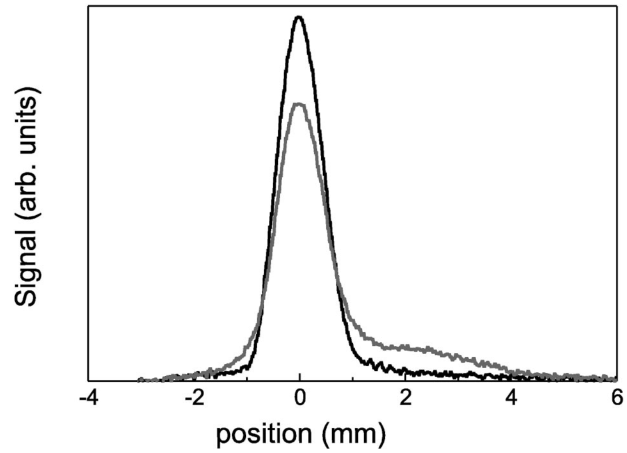

FIG. 5. The decelerated atoms are deflected and appear at the right of the main peak of undecelerated atoms (those with velocities outside the window defined by δ; see Fig. 4. Their centroid is at $\sim$2.5 mm corresponding to a longitudinal velocity change of $\sim$100 m/s.

tainable radiative force, in good agreement with our numerical calculations and about half of that estimated from a simple model [2]. Apart from the huge magnitude of the force, we did many other tests to demonstrate that this was not simply a Doppler deflection:

(i) If either of the two bichromatic frequencies were blocked, the atoms were no longer deflected.

(ii) If the retroreflected beam was blocked, the atoms were no longer deflected.

(iii) We reversed the relative phase and observed the deflection in the opposite direction.

(iv) The bichromatic deflection was much larger than the Doppler deflection for an interaction distance of a few mm.

(v) The force was maximum when the carrier laser frequency was just on resonance.

(vi) The maximum deflection was observed in a σ^+-σ^+ configuration, but it was considerably less in a lin-lin configuration, which compromised the virtual two-level atom configuration achieved by optical pumping

We have also performed preliminary deceleration experiments using the bichromatic force at a small angle to the atomic velocities. Under our experimental conditions, we can expect only a small deceleration limited by our beam geometry and AOM bandwidth. We used two diode-laser–AOM combinations to make a total of four frequencies in the laboratory frame that became two frequencies detuned from resonance by $\pm\delta=\pm75$ MHz when Doppler shifted into the atomic rest frame at $v\sim950$ m/s [2,3]. The velocity range that can be covered by this value of δ is $\Delta v=4\delta/3k$ ~110 m/s. These beams were injected into two fiber amplifiers whose output beams were aligned to produce a force at a small angle (3°) to the velocities of the He* atoms. Since the atoms pass through the laser beam at such a small angle, it was not expanded because the interaction length in the 1.5-mm beam waist focus was 20 mm, consistent with achieving $\Delta v\sim100$ m/s with $F\approx11F_{rad}$.

We have used the TOF detector apparatus to observe such decelerations of up to $\sim$100 m/s as shown in Fig. 4. The slowed atoms appear on the velocity distribution derived from the TOF signal as a shoulder delayed by $\sim$100 m/s. They are not clearly resolved because their difference of arrival time is only a bit larger than the temporal resolution of $\sim$100 μs, as shown by the raw TOF data in the inset of Fig. 2. As a check on this, we also changed the relative phase of the bichromatic fields and observed the acceleration of the atoms by the same amount.

Because the deceleration is at an angle to the atomic beam axis, we expect the slowed atoms to also be deflected out of the beam. With the imaging detector, we were able to observe deflected atoms as shown in Fig. 5 corresponding to the slower atoms' signal detected by TOF. The 2.5-mm deflection of atoms originally at velocity $\sim$950 m/s corresponds to a transverse velocity of $\sim$5 m/s over the 50-cm flight path from the laser interaction region to the detector. Since the sine of (3°) is 0.052, this corresponds to a longitudinal velocity change of $\sim$100 m/s.

With the 1 W of laser power available to us from the fiber amplifiers, the fully implemented bichromatic force has the capability to stop our He* beam in a distance of *less than 1 cm*. This is much shorter than the $\sim$1 m required to stop He* with the radiative force, and so we expect a much smaller loss from small acceptance angles and diffusion of the beam along an extended path. We are building a MOT, and hence expect much higher loading rates and densities in it. The deflection of the slowed atoms will allow the MOT to be located outside of the atomic and laser beams, in a region ideally suited for a high capture rate and long lifetime.

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