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Jamie Gardner, Rodrigo Castillo-Garza, and Mark G. Raizen

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Note: Manipulation of supersonic atomic beams with static magnetic fields

Jamie Gardner,[a)] Rodrigo Castillo-Garza, and Mark G. Raizen
Center for Nonlinear Dynamics and Department of Physics, The University of Texas at Austin, Austin, Texas 78712, USA

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Neutral atom beams have broad applicability to atomic and molecular science, particularly in the study of nanofabrication,[1–4] cold chemistry,[5,6] and atom-surface interactions.[7–9] For beams of paramagnetic species, an inhomogeneous magnetic field can be used for redirection and spin separation.[10] This technique dates back to the Stern-Gerlach experiment and continues to be employed in several recent demonstrations of magnetic lenses and mirrors.[11–18] Because many experiments involve high velocity beams with a narrow energy distribution,[6,19–22] manipulation techniques for these particular cases merit further development. In this Note, we report the use of a planar Halbach array[23] to either deflect or to specularly reflect a high-velocity, nearly monoenergetic beam of neutral atoms in a spin-sensitive manner. We report our experimental results for metastable neon (Ne*) and helium (He*) atom beams generated with a pulsed supersonic nozzle.

The interaction energy between an atom and a magnetic field (B) is $m_F g_F \mu_B B$, where m_F is the atom's magnetic quantum number, g_F is the Landé g-factor, and μ_B is the Bohr magneton. In an inhomogeneous field, low-field seeking (LFS, $m_F g_F > 0$) atoms experience a force parallel to $\vec{\nabla}B$, away from a field maximum. The Halbach array consists of 100 commercial neodymium-iron-boron magnets (1 in. × 1/8 in. × 1/8 in., Grade N42, remanence ∼1.3 T, magnetized perpendicular to the long axis) assembled side-by-side such that each element's magnetization rotates counterclockwise by 90° with respect to its left-hand neighbor (Fig. 1). Constructive superposition yields a strong ($B_{max} \sim 1$ T), exponentially decaying ($\nabla B \sim 300$ T/m) magnetic field of rotating direction but constant magnitude along the top of the array.

We generate a fast beam of metastable atoms with a velocity dispersion of $\Delta v_{\parallel}/\langle v_{\parallel}\rangle \sim 0.01$ using an Even-Lavie pulsed supersonic nozzle in conjunction with an electron discharge source. When the nozzle is at room temperature, He* atoms exit with a velocity[24] of 1700–1800 m/s. Excited to the 2^3S_1 metastable state, He* has one LFS sublevel ($m_F = 1$). Ne* atoms are produced with a velocity of 800–900 m/s and, in the $3s[3/2]_2$ ($^3P_2$) state, have two LFS sublevels ($m_F = 1, 2$). After passing through a skimmer, the beam is collimated with a 300 μm circular aperture 0.88 m from the nozzle and propagates towards the array (Fig. 1). In the deflective case, the beam enters the field region from the side and travels along the array surface (Fig. 1(a)). Atoms in the beam deflect according to their magnetic moments. In reflection, the beam approaches the array at a grazing angle from above (Fig. 1(b)). Depending on their magnetic moments, atoms either bounce off the array field or collide with its surface and relax to the ground state. Once the beam has interacted with the array, we observe it using a microchannel plate detector in conjunction with a phosphor screen.

Figure 2 shows deflection for He* and Ne* beams passing parallel to the surface of the mirror (incident angle $\theta_{in} = 0°$) with a range of impact parameters h (Fig. 1). Spot locations are measured with respect to the undeflected $m_F = 0$ spot. As shown in Fig. 2, atoms in the beam deflect according to their magnetic moments and are spin separated, since different magnetic species deflect with different angles. These measurements agree well with numerical simulations of particle trajectories.

Figure 3(a) shows the outgoing angles of Ne* atoms for a range of θ_{in}. For shallow incidence, the edge effects of the array are important and cause deflective behavior (Fig. 1(a)). As θ_{in} increases, the atoms perceive the mirror as semi-infinite (Fig. 1(b)) and specular reflection takes place. In this regime, LFS atoms experience a repulsive

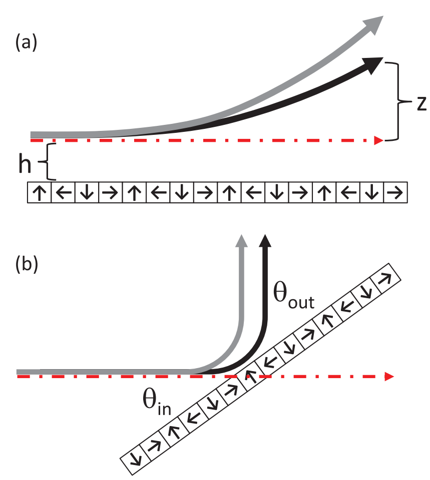

FIG. 1. Schematic of the array in the deflective (a) and reflective (b) configurations. In pure deflection, the atoms pass with impact parameter h parallel to the surface of the array. Different magnetic moments (represented by line shading) deflect by different distances z with respect to $m_F = 0$ atoms (red dotted line). In reflection, atoms arrive obliquely and depart with reversed velocity perpendicular to the array. Outgoing and incoming angles θ_{out} and θ_{in} are equal, though lower LFS magnetic moments penetrate closer to the array surface and eventually crash. These pure configurations can be mixed, as shown in Fig. 3 and described in the text. We have verified that atoms from the supersonic nozzle remain in the adiabatic regime while following this changing field direction. Hall probe measurements of the assembled array agree well with a finite-element model of the field.

a)Author to whom correspondence should be addressed. Electronic mail: jamie.gardner@gmail.com

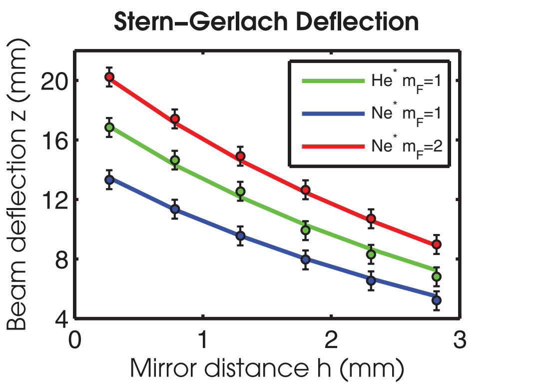

FIG. 2. Experimental and theoretical deflection of 3s[3/2]$_2$ ($^3P_2$) Ne* and 2^3S_1 He* for a range of impact parameters. Simulations use beam velocities of 800 m/s and 1700 m/s, respectively. The initial values of h and θ_{in} are fitting parameters. Systematic uncertainty is due to calibration of the imaging process.

force that reverses their perpendicular velocity ($v_\perp$) but leaves parallel velocity unchanged. In contrast to the deflective case, the outgoing angle (θ_{out}) in a reflection does not depend on magnetic moment. While a narrow, perfectly collimated beam

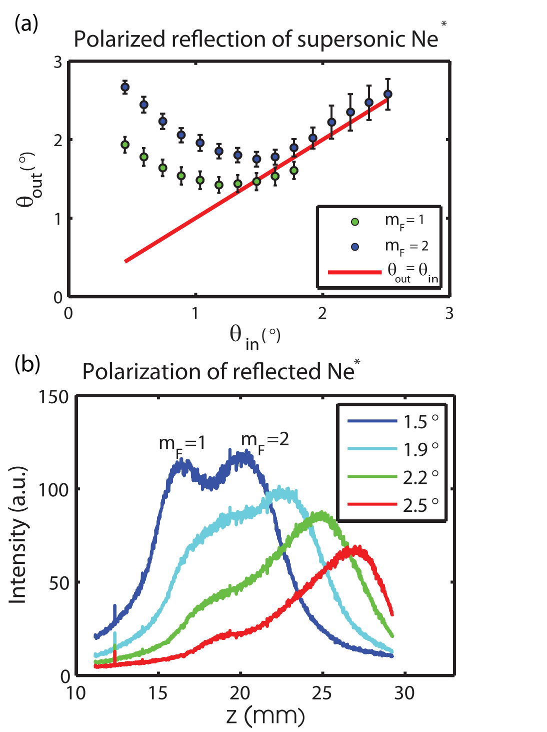

FIG. 3. (a) Outgoing angle as a function of incidence angle for Ne*. The red line represents ideal specular reflection ($\theta_{out} = \theta_{in}$). For low angles, atoms enter the field from the side and are partially deflected (see text), leading to m_F-dependent θ_{out}. For larger angles, the atoms perceive the mirror as semi-infinite and asymptotically approach specular reflection. Around 2°, the $m_F = 1$ atoms no longer interact strongly enough to reflect and crash into the array. The reflected beam above this critical angle is spin polarized. Angles are calculated by combining experimental deflection distances with geometrical information from simulations. Simulation parameters are consistent with those used in Fig. 2 and predicted deflections match well with observation. Uncertainty values reflect possible error in the calibration process and the disagreement between simulation and experiment. (b) Intensity profile for Ne* at a range of incidence angles, θ_{in}. At 1.5°, both LFS species are present and distinguishable. As the mirror angle increases towards 2.5°, the $m_F = 1$ atoms begin to collide with the array and drop out of the beam.

would be split into two parallel parts (Fig. 1(b)), the mirror does not efficiently spin-separate a divergent beam. Beam polarization occurs when only one magnetic species has a large enough magnetic moment to avoid colliding with the array.

Around $\theta_{in} = 2°$, the perpendicular kinetic energy $\frac{1}{2}mv_\perp{}^2$ approaches the maximum magnetic potential of the $m_F = 1$ Ne* atoms, which begin to crash into the array. The outgoing beam for $\theta_{in} \geq 2°$ is therefore predominantly spin polarized with $m_F = 2$. Intensity profiles in Fig. 1(b) show the progression from 1.5°, where there are two distinct spots, to 2.5°, where one spot has nearly vanished. Note that imperfect collimation and velocity dispersion broaden the cutoff of the $m_F = 1$ particles, reducing efficiency of polarization near the cutoff angle. Though it is outside the spatial range of our detector, we estimate the $m_F = 2$ beam to cut off around 3°.

In summary, we demonstrate the use of a Halbach array to either deflect or to specularly reflect a fast, nearly monochromatic beam of paramagnetic atoms. As a tool for beam manipulation and spin selection, this technique applies to any atom or molecule with an accessible magnetic state.

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