

Direct Observation of *s*-Wave Atomic Collisions

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We observe the angular distribution of *s*-wave scattering of Cs atoms in an atomic fountain by selecting and probing atomic velocities. At an average temperature of $T = 0.89 \mu\text{K}$ the scattering is predominantly *s*-wave and we have a sensitivity to *p*-wave cross sections as small as 0.1% of the *s*-wave. The cross section is $4 \times 10^{-11} \text{ cm}^2$ for atoms in the $F = 3, m_F = 0$ state colliding with atoms distributed among the $F = 4, m_F$ states. We also demonstrate a multiply loaded magneto-optic trap and a temperature of $1.53(7) \mu\text{K}$.

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At μK temperatures, quantum effects lead to novel phenomena in atom-atom interactions. These include quantum collective behaviors such as Bose-Einstein condensation, other indistinguishable particle effects, and cross sections as large as 10^6 \AA^2 . The potentially large cross sections occur because the de Broglie wavelength of the atom is much larger than the range of the interatomic potential. For Cs, $\lambda_{\text{de Broglie}} = 3000 \text{ \AA}$ at $1 \mu\text{K}$. Therefore only *s*-wave scattering is expected and cross sections may be as large as $\lambda_{\text{de Broglie}}^2/\pi$ [1]. These ultracold collisions play an important role in recent attempts to achieve Bose condensation by evaporative cooling in a trap [2] and also produce large frequency shifts imposing limitations on precision measurements using cold atoms [3–5].

Ultracold atom-atom collisions have previously been observed using four techniques: thermalization of atoms in a trap [2], cryogenic He beams [6], cryogenic H masers and their precursors [7], and frequency shifts in a laser-cooled Cs fountain clock [5]. All of these techniques are primarily sensitive to the total collision cross section and not to the angular distribution of the scattering. Here we observe the angular distribution of *s*-wave atomic scattering for the first time. We also demonstrate a multiply loaded magneto-optic trap (MOT) and low temperatures in a Cs fountain.

We begin with a sample of atoms at $1.5 \mu\text{K}$. We then select a narrow velocity class by transferring atoms from one ground state sublevel to another using the Doppler shift on a two-photon (Raman) transition [8]. The selected atoms collide, which redistributes their velocities. By probing the resulting distribution, we observe the effects of collisions.

The measured velocity distribution is sensitive to the angular distribution of the scattering. This is most clearly illustrated when the selected velocity v'_\parallel is much greater than the most probable thermal speed $v = (2kT/m)^{1/2}$. Here the velocity change after a single collision is $\frac{1}{2} v'_\parallel [\cos(\theta) - 1]$, where θ is the center-of-mass scattering angle. When $v'_\parallel \gg v$, the expression for the velocity change is not so simple because the Doppler shift only selects and probes one component of the atom's velocity. Therefore we must integrate over the initial and final

transverse velocities of the detected atom and over all the velocity components of the atoms with which it collides. This velocity redistribution is characterized by the velocity-changing collision kernel $W(v'_\parallel \rightarrow v_\parallel)$ [9].

A schematic of the vacuum chamber for our multiply loaded magneto-optic trap (MOT) is shown in Fig. 1. In the "vapor cell MOT," slow atoms in the room temperature Cs gas are slowed and trapped [10]. These atoms are then launched upwards by cooling into a moving frame [8]. The atoms are captured by the "UHV MOT" in Fig. 1. To multiply load [11], the vapor cell MOT is loaded again and more atoms are launched into the UHV MOT. The vapor cell MOT has a trap lifetime of 100 to 200 ms and, in this experiment, cold atoms are loaded for 46 ms and launched into the UHV MOT every 50 ms. During the launch the detuning of the downward propagating laser beams is -16 MHz and the atoms are accelerated to 10 m/s before leaving the laser beams. By multiply loading a trap in ultrahigh vacuum, we have a high loading rate and a long lifetime. We have

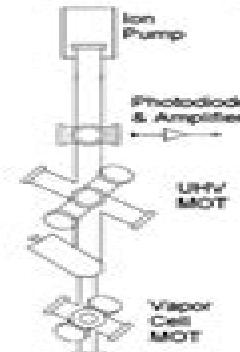


FIG. 1. Schematic of double magneto-optic trap (MOT) and fountain. Atoms are captured from Cs vapor in the "vapor cell MOT" and launched into the "UHV MOT." For scale, the window diameter is 5.1 cm [17]. The bias magnetic field and the Raman, "clearing," and "detection" laser beams are perpendicular to the plane of the figure.

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