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# Spectroscopy of atoms confined to the single node of a standing wave in a parallel-plate cavity

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We have performed spectroscopy on sodium atoms that are optically channeled in the single node of a laser standing wave set up across a parallel-plate cavity. Using this technique we have extended our previous measurement of the Lennard-Jones van der Waals energy-level shift [Sandoghdar *et al.*, Phys. Rev. Lett. **68**, 3432 (1992)] down to a cavity width of ~500 nm. We discuss the applications of this technique to the precise measurement of atom-surface distances.

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In the past decade the field of atomic physics has witnessed impressive progress in the manipulation of neutral atoms using laser light. In particular, the optical dipole force has been used to trap or channel atoms in potentials created in one-, two-, or three-dimensional standing wave patterns [2]. Atoms in these potentials offer a simple realization of the quantum-mechanical particle in a box, and several recent experiments have studied the mechanical motion of such atoms [3–6]. From an applied point of view there has also been recent interest in optical channeling for its promise in atomic beam lithography with submicron resolution [7,8]. All these experiments however, involve thousands of channels or potential wells in typically millimeter-sized interaction regions. Here we study atoms in an isolated potential well.

In order to study atoms in the single node or antinode of a standing wave, one requires either a detector with subwavelength resolution or a system in which the atoms occupy only one such potential well. While the advent of near-field optical microscopes with nanometer resolution might bring us closer to the first option, a simple realization of the second possibility is a laser-light standing wave between two parallel mirrors, separated by only one wavelength. In the absence of the light a ground-state atom in such a cavity experiences cavity QED energy-level shifts due to the modification of the electromagnetic field by the mirrors [9,10]. Curve *a* in Fig. 1 is the potential calculated for the ground state of sodium between two plates separated by 0.5 $\mu$m. Once the laser light is turned on, the atom sees an additional optical dipole potential [11] approximated by

$$U_{\mathrm{opt}}(z)=\frac{\hbar\delta}{2}\ln[1+S(z)], \tag{1}$$

where $\delta$ is the detuning from resonance, $S$ is the saturation parameter, and $z$ is the displacement from the center of the cavity. Curve *b* in Fig. 1 shows the total potential for the ground-state atom in the presence of typical channeling light ($\delta=+52$ MHz, $S=0.01$ at the antinode). In particular, one sees that the optical dipole force makes a channel at the center that can hold the atom in place against the atom-cavity force. Anderson *et al.* [12] have already reported an increase in the number of atoms transmitted through the cavity as a result of confinement in such a potential. In this paper we report the first excitation spectra for channeled atoms.

We use a two-step resonant optical transition to excite the atoms to a low-lying $nS$ Rydberg state ($n=10,11,12$) for which there is a very strong atom-cavity van der Waals interaction. This is well approximated by an unretarded Lennard-Jones potential [13] because the coherence time of the electric dipole fluctuations is much longer than the propagation time for light crossing the cavity. The form of the potential is [14]

$$U_{\mathrm{LJ}}(z)=-\frac{\langle nS|d^2|nS\rangle}{6\pi\varepsilon_0 L^3}\sum_{\mathrm{odd}n}\left(\frac{1}{(n-2z/L)^3}+\frac{1}{(n+2z/L)^3}\right), \tag{2}$$

where $L$ is the separation between the two mirrors and $z$ is once again the position of the atom inside the cavity. This is plotted in curve *c* of Fig. 1 for the 12$S$ state of sodium. Whereas the ground-state shifts are in the kHz range, the Rydberg levels of interest here are shifted downards by several hundred MHz, causing a strong redshift of the excitation spectrum.

The experimental setup, shown in Fig. 2, is largely the same as our previous spectroscopy experiment in wider cavities where there was no optical manipulation of the atoms [1]. Ground-state sodium atoms from a thermal beam (~240°C) enter a cavity made from two plane gold-coated mirrors that are 8 mm long in the atomic beam direction and 3 cm high. They are arranged to form a wedge touching at the bottom and separated at the top by about 3 $\mu$m. The new feature of this experiment is the optical channeling light, which has a total power of about 3 mW and is detuned by +52 MHz from the transition $3S_{1/2,F=2}\rightarrow 3P_{3/2,F=3}$. This light is coupled into the cavity through the partially transmitting gold-coated mirrors and is cylindrically focused to a vertical waist of 600 $\mu$m and a horizontal waist of 9 mm along the atomic beam axis, with its maximum at the exit of the cavity. The height of this laser beam is adjusted to coincide with the second Fizeau fringe in the wedge so that it is

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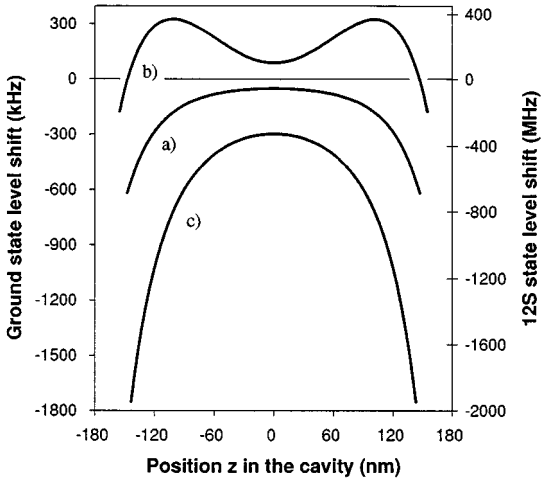


FIG. 1. Energy-level shifts of a sodium atom in a 504-nm-wide cavity. Curve $a$, ground state in an empty cavity. $b$, ground state in the presence of channeling light with $+52$ MHz detuning and saturation parameter 0.01 at the antinodes. Positive shift at the center is due to a small traveling-wave component of the light. $c$, much larger shift of the 12$S$ state; shift displayed on the right vertical axis.

resonant with the cavity. Because the reflectivity of the gold cavity wall at 589 nm is 65%, the optical field is predominantly a standing wave whose intensity gradient produces the optical dipole channel. The smaller traveling wave component gives rise to a weak radiation pressure force and induces a ground-state light shift of about 140 kHz (included in Fig. 1), neither of which is significant in this experiment. Although the wavelength of the light is 589 nm, the width of the cavity at this point is $\sim$504 nm because there is a phase shift associated with the imperfect reflectivity of the gold walls (see Ref. [1]).

Approximately 200 $\mu$m before leaving the cavity, the atoms encounter two superimposed laser beams, one yellow ($\lambda_1 = 589$ nm) and one blue ($\lambda_2 \approx 425$ nm), which excite them to a Rydberg state $nS$ ($n = 10$, 11, or 12) through the two-step resonant process $3S \rightarrow 3P \rightarrow nS$. These laser beams are focused to a waist of 300 $\mu$m and are adjusted to be at right angles to the atomic beam so as to eliminate the first-order Doppler effect. Most of the excited atoms are strongly attracted to the walls by the van der Waals force $-\nabla U_{\mathrm{LJ}}$ [see Eq. (2) and Fig. 1, curve $c$] and are lost from the beam. However, those located within $\sim$40 nm [15] of the center can emerge from the cavity and enter a detector where they

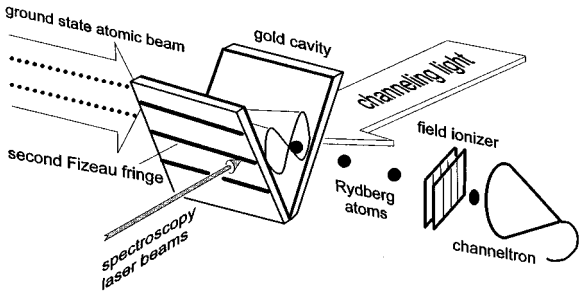


FIG. 2. Schematic view of the apparatus.

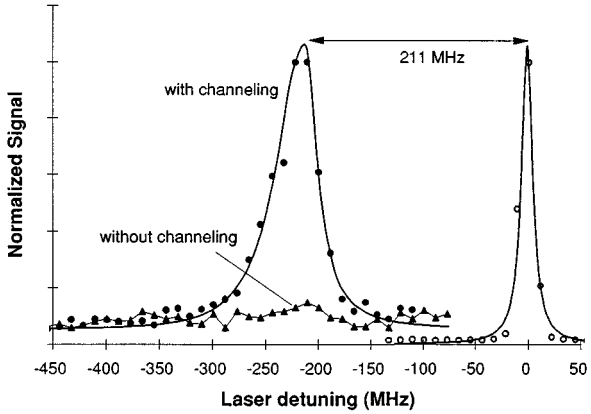


FIG. 3. Typical excitation spectra for the 11$S$ state. Left: atom in cavity, with and without channeling. Right: atom in free space.

are field ionized and counted using a channel electron multiplier. An auxiliary atomic beam is used to lock the yellow laser to the resonance line, while Rydberg excitation spectra from this same beam provide a reference line against which to measure the cavity shifts.

Figure 3 shows on the left a typical 11$S$ excitation spectrum for sodium atoms channeled at the center of the cavity, while on the right is the spectrum from unperturbed atoms in the reference atomic beam. The shift between the two is due primarily to the interaction between the cavity and the Rydberg atoms at its center. In the absence of the channeling light, no excitation signal could be detected because the ground-state atoms were lost to the cavity walls before they could reach the excitation region. The line from the atoms in the cavity is inhomogeneously broadened by a stray electric field due to the random patch potentials on the gold surfaces. The patch size is comparable with the 30-nm thickness of the gold coating and the patch potential is of order 100 mV [16]. Since the atoms at the center of the cavity "see" a region of roughly 100 patches on each side, the typical potential difference is of order 10 mV. The corresponding electric field is a few hundred V/cm, which varies randomly with a correlation length comparable to the 0.5 $\mu$m spacing of the mirrors. The Gaussian distribution of patch potentials leads to an exponential distribution of Stark shifts over the 300-$\mu$m region illuminated by the excitation light. The solid line in Fig. 3 is a convolution of Lorentzians with an exponential distribution of Stark shifts, chosen to fit our data. First, we find the homogeneous linewidth (typically 20 MHz due to power broadening) from the high-frequency edge of the excitation spectrum. Next, the mean Stark shift is chosen to reproduce the shape of the rest of the line, and corresponds typically to a patch field of 250 V/cm. Although the patch fields produce an appreciable tail on the red side of the line, there is very little shift of the peak because the most probable Stark shift is zero. Finally, the van der Waals shift is adjusted to obtain the correct position of the spectrum relative to the referencee line. We estimate that the uncertainty in the van der Waals shift determined by this procedure is about $\pm 10$ MHz.

In Fig. 4 we present the data from two sets of experimental runs, series $a$ and $b$. In both cases the cavity width $L$ was set close to 504 nm. The horizontal error bars are estimated at $\pm 30$ nm, mainly due to the uncertainty in positioning the

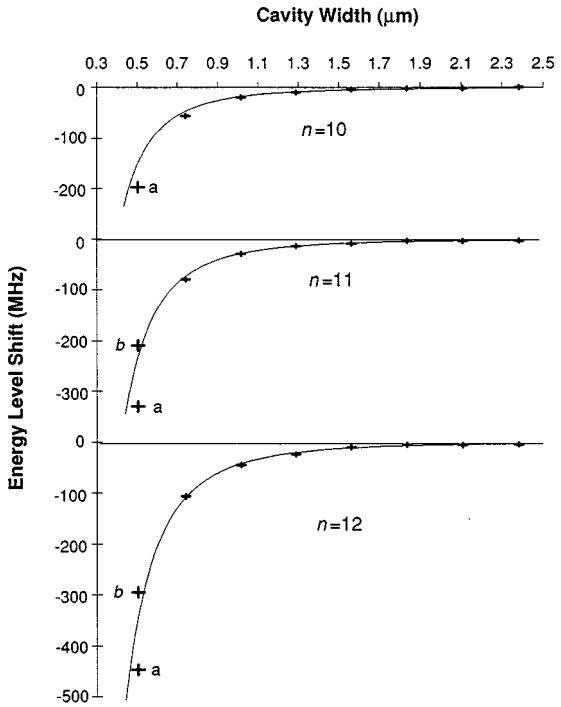


FIG. 4. Measured energy level shifts for 10$S$, 11$S$, and 12$S$ states as a function of cavity width. Labels $a$ and $b$ mark two different runs at 504-nm cavity width. Data for larger cavity widths are reproduced from our earlier publication [1]. Solid curves are theoretical predictons of the Lennard-Jones theory for an atom at the center of a parallel-plate cavity.

spectroscopy laser beams on the center of the Fizeau fringe. We have also included our earlier data points obtained in a variety of larger cavity widths without any channeling. There is moderately good agreement between these new measurements (labeled $a$ and $b$) and the Lennard-Jones potential (solid curves) for an atom at the center of the cavity given by

$$U_{\mathrm{LJ}}(z) = -\frac{7\zeta(3)\langle nS|d^2|nS\rangle}{24\pi\varepsilon_0 L^3}, \tag{3}$$

where $\zeta$ is the Riemann function. The new results can thus be regarded as an extension of our measurement of the Lennard-Jones van der Waals interaction to the smaller atom-surface distance of 252 nm.

An equally interesting point of view, however, is that we can reasonably assume the validity of the Lennard-Jones potential, then instead of testing it we can use it as a tool to measure the cavity width $L$. For example, in Fig. 4 the shifts

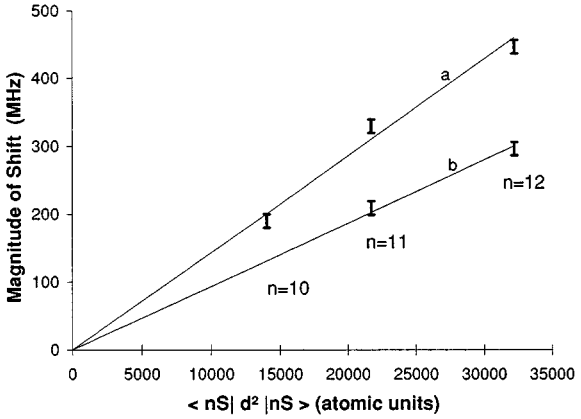


FIG. 5. Energy-level shifts measured in this work plotted as a function of mean square dipole moment $\langle nS|d^2|nS\rangle$. Straight-line fits to the data yield cavity widths of 456(7) nm for series $a$ and 527(7) nm for series $b$.

of series $a$ are systematically stronger than expected, while those of series $b$ are weaker. We attribute this to different cavity widths in the two sets of runs due to a small change in the vertical placement of the spectroscopy laser beams (see Fig. 2). This results in a discrepancy of tens of MHz in the measured shift because the gradient of the van der Waals potential is so steep. Figure 5 shows the shifts measured in this work as a function of the mean square electric dipole moment $\langle nS|d^2|nS\rangle$, together with least-squares straight-lines fits constrained to go through the origin. It is clear that the two series of runs belong to lines of different slope. Using Eq. (3), we determine from these slopes that the cavity widths were 456(7) and 527(7) nm in series $a$ and $b$, respectively.

It may be possible to extend this technique to study the distribution of atoms in the optical channel and their distance from the walls if, instead of detecting the production of Rydberg atoms, we measure the loss of ground-state atoms due to Rydberg excitation in the cavity. In that case the line will be inhomogeneously broadened by the van der Waals shift and the shape of the line will give direct information about the atomic wave function in the channel provided the patch fields are sufficiently small. Similarly, a standing wave with several nodes should then give rise to spectra with several features corresponding to atoms in different optical channels.

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