Measurement of the Casimir-Polder Force

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We have studied the deflection of ground-state sodium atoms passing through a micron-sized parallel-plate cavity by measuring the intensity of a sodium atomic beam transmitted through the cavity as a function of cavity plate separation. This experiment provides clear evidence for the existence of the Casimir-Polder force, which is due to modification of the ground-state Lamb shift in the confined space of a cavity. Our results confirm the magnitude of the force and the distance dependence predicted by quantum electrodynamics.

Physicists have long been intrigued by the idea that the electromagnetic vacuum interacts with charged particles to produce observable effects. The first experimental verification of this idea was the discovery [1] that the $2S_{1/2}$ and $2P_{1/2}$ states of hydrogen are not degenerate. Crudely speaking, the degeneracy is split by the ac Stark effect due to the interaction with the vacuum. Energy shifts of this type are now well established and are generally known as Lamb shifts. The vacuum field in the vicinity of a conducting plate is different from that of free space. In particular, at a distance L from the plate, the spatial distribution, polarization, and spectral density of the vacuum field are substantially altered for frequencies below $\sim c/L$ because of the boundary conditions imposed by the plate. The first discussion of a physical effect due to this modification of the vacuum dates back to 1948 and the seminal work of Casimir [2]. Casimir and Polder [3] discussed the interaction of a neutral atom with a plane conducting plate and showed that the modified vacuum gives rise to a spatially varying Lamb shift whose gradient corresponds to an attractive long-range force. Similar long-range forces are found between any pair of neutral objects, the most famous example being perhaps the Casimir force between two conducting plates. We refer to any such force on an isolated atom as a Casimir-Polder force.

Although some quantitative measurements exist on the long-range forces between macroscopic dielectrics [4], the Casimir force has been studied only qualitatively [5], and the Casimir-Polder interaction has eluded detection altogether [6]. Recent experiments on the Rydberg states of helium [7] have yielded precise measurements of the long-range interaction between the Rydberg electron and the He$^+$ core, but have not yet reached the point of testing the Casimir-Polder interaction [8], known in that system as V''_{ret}. In the experiment reported here we have probed the vacuum field in a parallel-plate cavity using a beam of ground-state sodium atoms. Since the vacuum field varies with position, the atoms experience a Casimir-Polder force which pushes them towards the cavity walls. We have used the deflection of the beam to demonstrate the existence of this force and to confirm quantitatively the strength predicted by quantum electro-

dynamics.

For a spherical ground-state atom ($3s$ sodium) between parallel ideal mirrors, the position-dependent atom-cavity interaction potential can be written in the following form [9]:

$$U(z) = -\sum_e \frac{\pi|d_{eg}|^2}{6\varepsilon_0 L^3} \int_0^\infty d\rho \, \frac{\rho^2 \cosh(2\pi\rho z/L)}{\sinh(\pi\rho)} \times \tan^{-1}\left[\frac{\rho\lambda_{eg}}{2L}\right], \qquad (1)$$

where z is the distance of the atom from the center of cavity. The sum is over excited states, L is the plate separation, d_{eg} is the matrix element of the electric dipole operator between states e and g, λ_{eg} is the wavelength of the e-g transition, and ρ is a dummy variable. For sodium, the $3s$-$3p$ dipole matrix element is so strong that it accounts for over 98% of the interaction energy in Eq. (1). Position-independent terms have been omitted since they do not give rise to a force on the atom.

We can distinguish two extreme cases of this interaction. In the first, the cavity width L is much less than the wavelength of the resonance transition $\lambda_{3s,3p}$. This is the van der Waals limit, where Eq. (1) can be rewritten as

$$U_{\text{vdW}}(z) = -\frac{1}{4\pi\varepsilon_0} \frac{2\langle g|d^2|g\rangle}{3L^3} \times \sum_{\text{odd } n} \left[\frac{1}{(n-2z/L)^3} + \frac{1}{(n+2z/L)^3}\right], \qquad (2)$$

which is precisely the spherically averaged interaction energy of a static electric dipole coupled with its multiple electric images in the cavity walls. This "instantaneous" van der Waals interaction between an atom and a cavity was recently investigated with high precision [10] by means of laser spectroscopy of Rydberg atoms in a micron-sized cavity.

Since the atom is in its ground state, the field that is emitted and reabsorbed can only be a virtual one, existing for a time of order $\lambda_{3s,3p}/2\pi c$ or less in accordance with the uncertainty principle. This places a distance limit of order $\lambda_{3s,3p}/2\pi$ on the ground-state van der Waals interaction. Outside that range, when $L \gg \lambda_{3s,3p}/2\pi$ and

the atom is not close to one of the cavity walls, Eq. (1) is well approximated by the Casimir-Polder potential

$$U_{CP} = -\frac{1}{4\pi\varepsilon_0}\frac{\pi^3\hbar c\alpha_{stat}}{L^4}\left[\frac{3-2\cos^2(\pi z/L)}{8\cos^4(\pi z/L)}\right]. \quad (3)$$

The appearance here of the static electric polarizability α_{stat} emphasizes that this interaction can be viewed as a modification of the Stark shift induced by the low-frequency part of the vacuum spectrum. Thus, the exact potential of Eq. (1) evolves from an instantaneous L^{-3} van der Waals potential when the cavity is narrow into a L^{-4} retarded Casimir-Polder potential when the cavity is wide. The gradient of this potential gives rise at long range to an attractive Casimir-Polder force between the atom and the cavity walls which is the force we have measured in this experiment.

We remark that the situation is quite different if the atom is in an excited state, for example, a Rydberg state, with electric dipole transitions to lower-lying levels. In that case it can emit real photons whose range is unlimited. After being reflected by the cavity walls, these resonant photons perturb the atom in a way that is analogous to the classical interaction between an antenna and its reflected field [11], and this cavity-pulling effect in excited states is so large that it obscures the modification of the Lamb shift [9]. This is the reason that our experiment was conducted on a ground state.

Figure 1 shows the ground-state energy level shifts calculated for sodium in a cavity 1 μm wide. Also shown are the asymptotic van der Waals and Casimir-Polder potentials. Evidently, the physical potential is much more closely approximated by the Casimir-Polder potential, which is to be expected since the propagation time from the center to one mirror and back is approximately 10 times the natural scale $\lambda_{3s,3p}/2\pi c$.

The main components of our apparatus are shown in Fig. 2. Sodium atoms at 180 °C effuse from a vertical oven slit, 50 μm wide and 1 cm high, into a vacuum of approximately 10^{-7} torr. After traveling a distance of

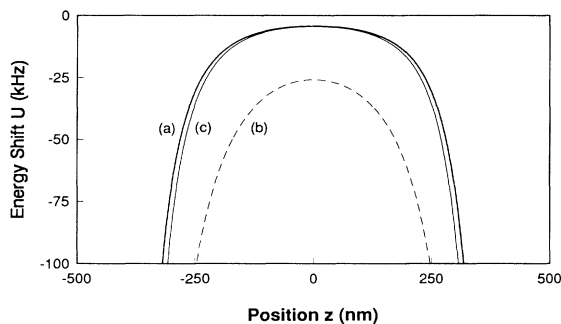18 cm, they enter a gold cavity 3 cm high, 8 mm long, and adjustable in width from 0.5 to 8 μm. Here they are deflected by a cavity-QED potential of the type shown in Fig. 1, and any atoms that hit the walls stick there with high probability. Some of those that exit from the cavity are then resonantly excited to the 12s state by two superimposed laser beams of wavelengths 589 and 425 nm so that they can be field ionized and detected using a channel electron multiplier. The laser beams are both focused so that detection occurs over a small height (~ 200 μm), corresponding to a very well defined cavity width. The essence of the experiment is to observe the transmitted intensity of the ground-state atomic beam as a function of the cavity width. The measured transmission function is then compared with theoretical curves based on various atom-cavity interaction potentials to see which one is correct.

Now we give some practical details. The cavity walls are made by thermal evaporation of chromium (~ 0.7 nm) followed by gold (42 ± 3 nm) onto two flat fused silica substrates [12]. These are assembled face to face, touching each other at the bottom to form a wedge. One of the substrates is held fixed while the other is able to move so that the cavity width can be adjusted, and a thin nickel foil (1.2 μm) is inserted at the top to ensure that there is always an opening. In order to set the mirror separation, we illuminate the cavity with mercury-green ($\lambda = 546$ nm) or sodium-yellow ($\lambda = 589$ nm) light to produce interference fringes. These are viewed in a telescope and adjusted by varying the cavity width until a maximum or minimum of the interference pattern coincides precisely with the height of the detection lasers. The absolute order number at this point, n, is found by counting fringes from the bottom where the mirrors are in contact, and the width L of the cavity is then given by the formula $L = n\lambda/2 - l_\lambda$. Based on the measured optical properties of our mirrors, we calculate that the phase-shift correction l_λ is 72 nm for mercury-green and 85 nm for sodium-yellow with a systematic uncertainty of ± 5 nm.

We measure the intensity of the transmitted beam $I(L)$ at various cavity widths L and normalize each one

FIG. 1. Ground-state energy level shifts for a sodium atom in a parallel-plate cavity 1 μm wide. Curve a, energy according to QED potential in Eq. (1). Curve b, instantaneous van der Waals potential [Eq. (2)]. Curve c, asymptotic Casimir-Polder potential [Eq. (3)].
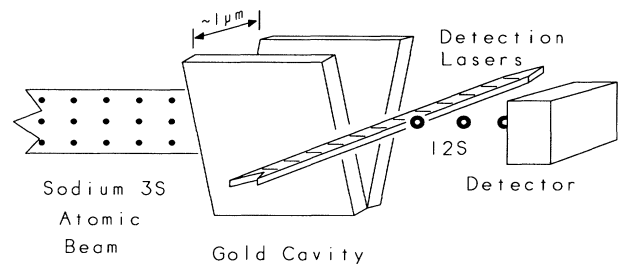

FIG. 2. Sodium ground-state beam enters the micron-sized gold cavity. Atoms which emerge at a particular height in the wedge, corresponding to a chosen mirror separation, are excited by detection lasers to the 12s state and detected by field ionization.
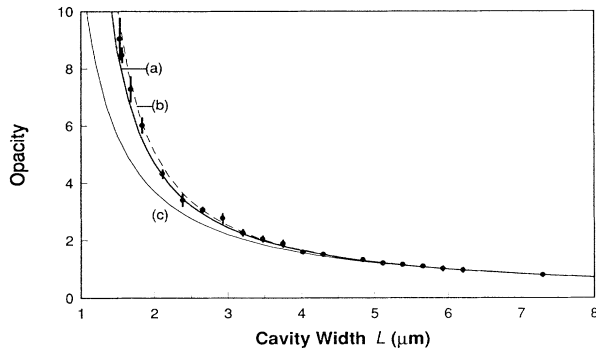
FIG. 3. Measured cavity opacity (see text) vs cavity width. Curves show theoretical opacities for various assumed atom-cavity interaction potentials. Curve a, QED interaction [Eq. (1)]; curve b, van der Waals interaction [Eq. (2)]; and curve c, no interaction.
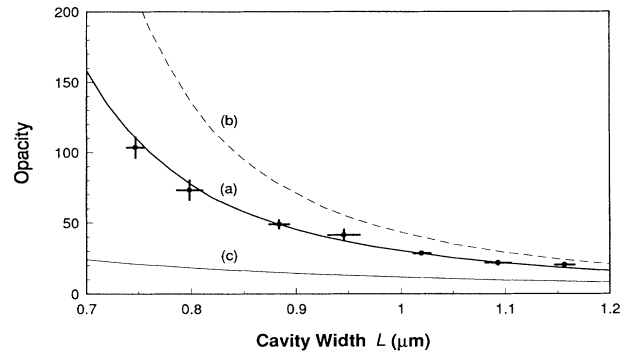

FIG. 4. Measured cavity opacity (see text) vs cavity width. Curves show theoretical opacities for various assumed atom-cavity interaction potentials. Curve a, QED interaction [Eq. (1)]; curve b, van der Waals interaction [Eq. (2)]; and curve c, no interaction.

to $I(6 \ \mu m)$ to determine the relative transmission $T(L)$ $=I(L)/I(6 \ \mu m)$. Since the interesting region of the experiment is at small transmission, we find it useful to display our results in terms of $1/T(L)$, which we call the opacity. The opacities measured for cavity widths greater than 1.2 μm are plotted in Fig. 3 with uncertainties due partly to random counting statistics and partly to systematic drifts of the atomic beam intensity and detection efficiency. The uncertainty in cavity width, which is also a combination of random and systematic errors, is comparable with the line thickness. In addition, there are three calculated curves: curve a which assumes the QED potential of Eq. (1), curve b based on the unretarded van der Waals potential of Eq. (2), and curve c which supposes there is no atom-cavity interaction at all. These are the result of a Monte Carlo calculation in which atoms having a Maxwell-Boltzmann velocity distribution within the oven fly randomly into the cavity and propagate under the influence of whichever potential is assumed. Those that hit the wall stick, while those that emerge are counted. There are no fitting parameters. Our measurements do not differentiate between the theoretical curves when the cavity is larger than about 3 μm because the forces are too weak to produce appreciable deflection of the atomic beam over the 8 mm interaction length. In smaller cavities, however, it is evident that an interaction exists, since the experimental points are completely inconsistent with curve c, although it is difficult using these results to distinguish between curves a and b.

In order to demonstrate the Casimir-Polder force definitively, we extended our measurements to even smaller cavity widths where the forces are stronger and the opacity discriminates more effectively between the different hypotheses. Figure 4 is the extension of Fig. 3 down to $L = 0.7 \ \mu m$, showing the same three theoretical hypotheses. Before arriving at a conclusion, we consider a number of systematic effects.

First, as the cavity width decreases and the transmitted beam intensity approaches zero, it becomes increasingly

important to eliminate any backgrounds in the detected intensity. One part of the background rate, about 100 counts per second due to scattered light interacting with the sodium vapor in the chamber, is easily measured by translating the sodium oven to the side so that there is no direct path from the source to the detector. For comparison, the beam intensity at $L = 1 \ \mu m$ is typically 6000 counts per second. More troublesome is the possibility that some atoms in the beam bounce at grazing incidence on the cavity walls and are subsequently detected. Such a background is eliminated together with the direct atomic beam when we move the oven to the side, and must be accounted for separately. For this purpose we reduce the cavity width to 0.474 μm where the intensity of atoms transmitted through the cavity is typically only 100 counts per second. Although we do not know the fraction due to bouncing, it must be between zero and unity and therefore this figure allows us to add to the measurements made using wider cavities a small systematic uncertainty that is included in the error bars of Figs. 3 and 4.

Second, we consider the possibility that gradients of a stray electric field inside the cavity are deflecting the atomic beam. In order to check this, we measure the electric field at the center of the cavity by laser exciting the highly polarizable $10D_{5/2}$ state of sodium inside the cavity and measuring the shift of the spectrum relative to free-space excitation, as described more fully in a previous publication [10]. The field depends strongly on the width of the cavity but much less on the position of the laser beam exciting the atoms, indicating that the surface is reasonably homogeneous when viewed from distances of order 1 μm and averaged over the ~200 μm diam laser beam. The measured field in the worst of the four cavities used for this experiment is well characterized by the formula

$$E^2 = \left[\frac{39}{L}\right]^2 + \left[\frac{58}{L^2}\right]^2, \tag{4}$$

where E is the rms value in V/cm and L is the cavity width in micrometers. We interpret the first term as being due to a contact potential difference of 4 mV between the two gold surfaces, while the second is consistent with a patch-effect field due to surface patches of $\sim$40 nm size (the gold layer thickness) and $\sim$150 mV rms potential. The corresponding Stark shift of the $3s$ ground state is less than 3% of the Casimir-Polder shift over the whole range of cavity widths in Fig. 4. Since the field gradient cannot be much greater than E/L, any electric deflection of the atomic beam is negligible in comparison with the Casimir-Polder deflection [13].

Another possible source of Stark shift is the blackbody field in the cavity. However, our cavity is somewhat colder than room temperature, at which we calculate that the rms thermal field is only $17L^{-1/2}$ V/cm (with L in μm) and the Fourier components of the field are all far below the atomic resonance frequency. The blackbody shift is therefore less than 1% of the Casimir shift over the range of Fig. 4. Furthermore, this field is almost all in the spatially uniform $n=0$ modes which produce no deflecting force.

A third consideration is the imperfect reflectivity of the gold cavity walls, as opposed to the perfect conductor assumed in the theory. The Casimir-Polder force is associated with the long-wavelength end of the vacuum spectrum $(\lambda > L)$, where the cavity modes are significantly different from free space. Over most of this range the reflection loss of the gold surfaces is negligible, being less than 4% for wavelengths longer than 0.7 μm; however, it rises rapidly at shorter wavelengths, reaching 60% at $\lambda = 0.5$ μm. Consequently, the force should become weaker and the experimental points should start to fall below the theoretical line as L approaches 0.5 μm. There is a hint of this effect in the two points taken between 0.7 and 0.8 μm which are both low and suggest that it would be interesting in the future to extend this work to narrower cavities.

Since no significant systematic corrections are required, we conclude that the experimental results shown in Fig. 4 are in excellent agreement with the full QED interaction potential (a) and are inconsistent with the instantaneous van der Waals interaction (b). If the strength of the interaction is treated as a variable parameter, a least-squares fit gives

$$U(\text{expt})/U(\text{theory}) = 1.02 \pm 0.13 . \tag{5}$$

This experiment therefore provides the first measurement of the Casimir-Polder force, verifying the L^{-4} dependence of the retarded QED potential at long range and excluding the L^{-3} unretarded potential. We have shown that the boundary around an atom affects not only its semiclassical properties, as several previous experiments have shown [14], but also the Lamb shift, which is a purely quantum-electrodynamic effect.

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