Measurement of the van der Waals Force in an Atomic Mirror

A. Landragin, J.-Y. Courtois, G. Labeyrie, N. Vansteenkiste, C. I. Westbrook, and A. Aspect
Institut d'Optique Théorique et Appliquée, URA 14 du CNRS, Université Paris Sud, B. P. 147 - F91403 Orsay, Cedex, France
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We have measured the attractive van der Waals force between a dielectric wall and an atom in its ground state. The method is a direct force measurement in which we use an evanescent wave atomic mirror to balance the van der Waals force and the inertia of the incident atom. [S0031-9007(96)00933-7]

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For many years, the van der Waals interaction between a ground state atom and a wall—dielectric or conductor—has attracted a lot of theoretical attention. Even the simple Lennard-Jones model [1] based on the electrostatic interaction between the atomic dipole and its image involves the quantum fluctuations of the atomic dipole. It was recognized by Casimir and Polder [2] that when the atom-wall distance z is not small compared to the wavelengths of the dominant atomic transitions, the z^{-3} law associated with the instantaneous electrostatic interaction is no longer valid. The full quantum treatment of the van der Waals attraction, leading to the famous long distance z^{-4} law, is a fundamental QED problem [3] involving the quantized electromagnetic field and retardation effects. The van der Waals energy shift can be considered a modification of the Lamb shift resulting from the modification of the density of modes of the electromagnetic field due to the presence of the wall. In the case of a dielectric wall, this density must take into account not only modes associated with traveling waves incident on, and reflected from, the vacuum-dielectric interface, but also evanescent waves [4,5].

In contrast to the theoretical work, few experimental results have been reported on the van der Waals interaction between an atom and a wall. The pioneering experiments of Ref. [6] studied the deflection of thermal atomic beam by a sharp metal or dielectric edge. The observed effect was extremely weak, because only a very small fraction of the atoms passed close enough to the interface to have an interaction energy comparable to their kinetic energy. Qualitative trends in agreement with the z^{-3} law were observed, but no precise quantitative comparison was possible. Recently, more precise data on the van der Waals interaction between an atom and a metal has been obtained by spectroscopic studies of Rydberg atoms in a micron-sized parallel-plate metallic cavity [7]. A study of the transmission of ground state atoms through a similar cavity also permitted the measurement of the Casimir Polder force on an atom in its ground state [8]. Another series of spectroscopic measurements on light reflected from the wall of a cell containing an atomic vapor has given information on the difference between the van der Waals shifts of various atomic levels, and interesting results have been obtained on the role of the frequency dependence of the dielectric constant of the wall [9].

In this paper, we report on new mechanical measurements for determining the van der Waals interaction between a ground state atom and a dielectric wall. The idea, first used in Ref. [10], is to release laser cooled atoms with a well-defined kinetic energy onto an evanescent wave atomic mirror. The atoms bounce if the reflecting potential barrier height is larger than their kinetic energy. The height of the reflecting potential, which is the sum of the repulsive dipole potential and of the attractive van der Waals potential (Fig. 1), can be calculated as a function of the evanescent wave parameters. Thus, with a measurement of the atomic kinetic energy and the intensity and detuning of the evanescent wave, we have a direct test of the theory of the van der Waals interaction. In our experiment we confirm the electrostatic model to within our uncertainty. In fact, the QED calculation is in slightly better agreement with our data, although the

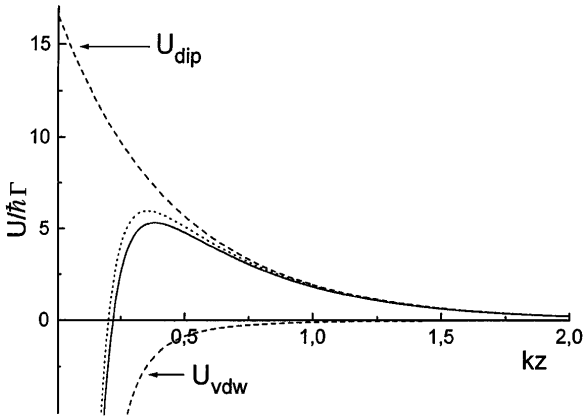

FIG. 1. Interaction potentials seen by a rubidium atom in an evanescent wave mirror, as a function of the distance in units of $\lambda/2\pi$. The solid line is the sum of the van der Waals potential in the electrostatic approximation (shown separately as the dashed line $U_{v\mathrm{dW}}$), and of the dipole potential U_{dip} due to the evanescent wave. The light shift due to the evanescent wave $\Lambda = 16.8\Gamma$ has been chosen so that the maximum value of the total potential equals the kinetic energy of the incident atoms in our experiment. The dotted line shows the total potential taking into account the full QED expression of the van der Waals potential, for the same value of the light shift.

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correction is on the order of our experimental uncertainty. To our knowledge, this is the first quantitative experimental test of the van der Waals interaction between a ground state atom and a dielectric wall.

In an evanescent wave mirror, atoms reflect on the potential barrier created by the quasiresonant interaction of the light electric field with the induced atomic dipole [11,12]. When the detuning $\Delta = \omega_L - \omega_{\rm at}$ between the evanescent wave and the atomic transition is large enough that the number of spontaneous emissions per bounce is negligible, the dipole potential is equal to the light shift of the ground state which, for a two level atom, is then approximated by

$$U_{\rm dip}(z) = \hbar\Lambda e^{-2\kappa z} = \frac{\hbar}{4}\frac{\Omega^2}{\Delta}e^{-2\kappa z}. \qquad (1)$$

We use Λ to denote the light shift of the ground state at the surface ($z = 0$) of the prism supporting the evanescent wave, and Ω is the corresponding Rabi frequency (we have assumed that the change in the atomic resonance frequency with z due to the van der Waals interaction is negligible compared with the detuning). For a positive ("blue") detuning, the dipole potential is positive, and thus repulsive for incident atoms.

In the short distance limit, the electrostatic model is valid, and the van der Waals potential arising from the dielectric wall supporting the evanescent wave assumes the simple form [13]

$$U_{v{\rm dW}}(z) = -\frac{\varepsilon_1 - 1}{\varepsilon_1 + 1}\frac{1}{48\pi\varepsilon_0}\frac{D^2}{z^3} = A\hbar\Gamma\left(\frac{1}{kz}\right)^3, \quad (2)$$

where ε_1 is the dielectric constant of the prism (taken to be frequency independent [14]), and D^2 only depends on the atomic state. For a state with a total electronic angular momentum $J \leq 1/2$, where the wave function has no quadrupolar component, D^2 is the variance of the atomic electric dipole in the atomic state. Even though $U_{v{\rm dW}}$ is the potential for the ground state of the atom, and involves a summation over all excited states, it is convenient to relate it to the radiative linewidth Γ and wave vector $k = 2\pi/\lambda$ of the dominant transition [3] ($\Gamma = 2\pi \times 5.9$ MHz and $\lambda = 780$ nm for the D_2 line of Rubidium used to reflect the atoms). For our prism of index $n_1 = 1.869$ at 780 nm, the dimensionless constant A in Eq. (2) is equal to 0.11 for rubidium in its ground state [13]. The solid line of Fig. 1 shows the total potential $V = U_{\rm dip} + U_{v{\rm dW}}$ as a function of the distance z to the interface, in units of k^{-1}, for a value of the light shift at the interface $\Lambda = 16.8\Gamma$. This corresponds to a barrier height $V_{\rm max}$ equal to the average kinetic energy of our falling atoms ($5.3\hbar\Gamma$). We see in Fig. 1 that in our situation the van der Waals term reduces the barrier height by a factor of 3, compared to the maximum value $U_{\rm dip}(z = 0)$ of the dipole potential alone.

If the intensity of the evanescent wave were uniform parallel to the interface, we would expect the number of reflected atoms to abruptly vanish when Λ goes below a threshold value Λ_T for which the barrier height is equal to the incident kinetic energy $E_{\rm in}$. In our experiment, the incident laser beam has a Gaussian profile, so that the surface where the reflecting potential is larger than $E_{\rm in}$ has an area

$$S = \pi\frac{w_x w_y}{2}\ln\left(\frac{\Lambda_0}{\Lambda_T}\right), \qquad (3)$$

where Λ_0 is the light shift at the center of the elliptical laser beam profile (w_x and w_y are the radii at e^{-2} of the intensity profile). If the cloud of incident atoms is uniform over the atomic mirror, the number N_r of reflected atoms is proportional to the area S. We then expect a logarithmic variation of N_r as a function of Λ_0, with a threshold Λ_T.

We use ^{85}Rb atoms, accumulated and cooled in a magneto-optical trap (MOT), as our source of cold atoms (see Ref. [15]). We trap approximately 10^8 atoms in a volume of about 0.5 mm^3, with a rms velocity of 5 to 7 times the recoil velocity ($v_{\rm recoil} = 6$ mm/s). We release the atoms onto the atomic mirror situated 15 mm below (Fig. 2). During the release we leave a repumping laser on to ensure that all atoms fall in the $F = 3$ ground state. The rms size of the atomic cloud is 5 mm when it reaches the mirror. The reflected atoms are detected by a horizontal retroreflected probe laser situated 10 mm above the prism, which is switched on 60 ms after the release of the atoms, i.e., after the bounce. The probe beam has a height 1 mm, a width 10 mm, and a power 5.5 μW. The probe is frequency modulated by an acousto-optic modulator such that the detuning is modulated between 5 and 9 MHz at 100 kHz. A lock-in amplifier detects this modulation, and the signal (see Fig. 2) is averaged about 30 times. The absorption peak at 81 ms after release, due

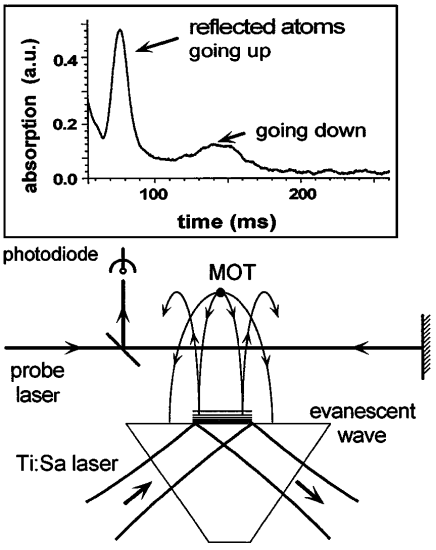

FIG. 2. Schematic of the experiment. The plot shows the absorption detected by the photodiode.

to the reflected atoms, appears on top of a reproducible slowly decaying background, which is present even when the atomic mirror is not switched on. We subtract this background and use the height of the resulting peak as a relative measure of the number N_r of reflected atoms (the width of the peak is observed to be constant).

The atomic mirror is an evanescent wave resulting from total internal reflection of a laser beam in a prism of index of refraction $n_1 = 1.869$ (at 780 nm) at an incidence angle $\theta_1 = 52°$. The corresponding decay constant of the evanescent wave is then $\kappa = \omega_L/c \times \sqrt{n_1^2 \sin^2\theta_1 - 1} = 1.08\omega_L/c$. The value of the electric field at the interface is deduced, using the Fresnel formulas [16], from the measured value of the power of the incident laser beam (varied between 1 and 4.4 W) and from its profile, determined with a charge coupled device camera ($w_x = 0.84$ mm, $w_y = 0.90$ mm). The laser detuning from resonance (varied between 0.5 and 6 GHz) is determined with a 50 MHz uncertainty using a rubidium reference line and a confocal Fabry-Perot interferometer. In the case of TE polarization, the polarization in the evanescent wave is linear, so for a detuning large compared to the hyperfine structure of the $6P_{3/2}$ state, the light shifts of all the Zeeman sublevels of the $F = 3$ ground state are equal. They assume the value corresponding to a $J = 1/2 \leftrightarrow J = 3/2$ transition with a linear polarization (Clebsch-Gordan coefficient $= \sqrt{2/3}$).

We show in Fig. 3(a) the result of a series of measurements with TE polarization. The number of reflected atoms is plotted as a function of the logarithm of the light shift at the center of the Gaussian profile Λ_0. For values of Λ_0 less than 50Γ, the points fall on a single line as expected. We attribute the deviations beyond 50Γ to clipping of the Gaussian wings of the laser profile, and to spontaneous emission. The linear fit to the data for Λ_0 less than 50Γ yields a measured threshold value $\Lambda_T = 14.9\Gamma$ with a 10% uncertainty, in marginal agreement with the value 16.8Γ predicted with the electrostatic model of the van der Waals potential of Eq. (2). The uncertainty in Λ_T is mostly due to the uncertainty in the value of the electric field at the interface, resulting from 5% in the laser beam power, 3% in the beam waist size, and 4% for the Fresnel coefficient (resulting from the 1° uncertainty in the angle of incidence).

A similar experiment was done with TM polarization, as shown in Fig. 3(b). The main difference is that the polarization in the evanescent wave is elliptical, so that, even in the large detuning limit, the seven Zeeman sublevels of the $F = 3$ level are subject to different light shifts, and therefore, have different thresholds for reflection. Our fit assuming equal populations for the seven Zeeman sublevels is shown in Fig. 3(b), and gives $\Lambda_T = 12.6\Gamma$. This value of Λ_T is less reliable because of our assumption of equal populations of the Zeeman sublevels, and we consider this result consistent with the TE value to within the uncertainty.

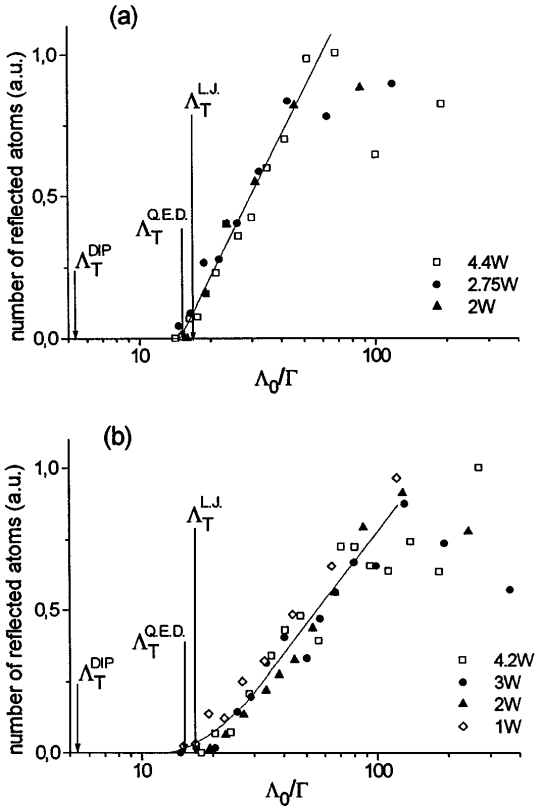

FIG. 3. Number of reflected atoms as a function of Λ_0, for various laser powers and detunings. (a) TE polarization; (b) TM polarization. The arrows show the predicted thresholds: ignoring the van der Waals interaction ($\Lambda_T^{\rm dip}$), using the electrostatic model ($\Lambda_T^{\rm LJ}$), and using the QED model ($\Lambda_T^{\rm QED}$).

As shown in Fig. 1, the position where our method probes the total reflecting potential corresponds, for our experimental parameters, to an atom-wall distance $z_m = 0.38k^{-1} = 47$ nm. At this distance, QED (Casimir-Polder) corrections to the electrostatic Lennard-Jones potential may play a role. We have, therefore, numerically evaluated this correction for our situation, in the range between 0 and $2k^{-1}$, using an expression derived in Ref. [4]. The ratio of the QED potential to the electrostatic potential varies between 1 and 0.3 in this range, and takes the value 0.70 at $z = 47$ nm. Its effect on the total potential is shown in Fig. 1, for $\Lambda = 16.8\Gamma$. We see that the predicted barrier height is increased by 10%. Accordingly, the threshold value predicted for $E_{\rm in} = 5.3\hbar\Gamma$ is decreased by 10%, i.e., $\Lambda_T^{\rm QED} = 15.3\Gamma$. The QED prediction for the threshold, therefore, appears to agree better with our data, although our 10% uncertainty does not fully discriminate between the electrostatic and the QED expressions.

An important consequence of this work is that the van der Waals interaction may have a big effect in atomic mirrors, and it should be taken into account

in the applications of evanescent wave atomic mirrors [17–19], or in other types of atomic mirrors, such as magnetic devices [20]. Note also that an atom with a given kinetic energy cannot reflect closer than a minimum distance (47 nm in our case).

Our experiment is a quantitative test of the van der Waals attraction of a ground state atom by a dielectric wall, at a well-defined distance. The uncertainty in the measurement of the van der Waals potential is approximately 30%. This is because our determination of Λ_T amounts to a 10% measurement of $U_{\rm dip} + U_{v{\rm dW}}$ at a point where $U_{v{\rm dW}} \cong U_{\rm dip}/3$. An increase in the accuracy should allow for a clear discrimination between the electrostatic and the QED models. The key point is an improved measurement of the incident laser intensity, to better determine the dipole potential. One could also directly measure the light shift in the evanescent wave by spectroscopic methods, taking advantage that the different Zeeman sublevels of the $5S_{1/2}$ ground have the same van der Waals shift but different light shifts. An interesting extension of this experiment is to repeat it at various incident atomic kinetic energies, allowing us to explore the van der Waals potential at various distances, in order to check the transition from the electrostatic to the QED regime. One can also test the van der Waals potential in the case of walls with several dielectric layers [21] that may exhibit resonances at atomic frequencies.

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