

Recent Progress in Dielectric Cavity QED and Long-Range Atom–Surface Interactions

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Abstract—We explore experimentally various situations when the van der Waals long-range atom–surface interaction is resonantly enhanced, and eventually turned into repulsion, as due to a resonant coupling between a virtual emission of the excited atom, and a virtual absorption of the dielectric into a surface polariton mode.

1. INTRODUCTION

The optical properties of atoms are strongly modified when they are confined near dielectric surfaces, or inside dielectric media. They are submitted to highly inhomogeneous surface potentials, their energy levels are shifted, their transition probabilities are altered, and forbidden transitions can get surface-allowed. Some of the recent developments in this field concern the influence of dielectric dispersion [1] (e.g., related to absorption bands), or dielectric cavity resonances (like Mie resonances of dielectric microspheres), which can lead to *resonantly-enhanced* atom–dielectric *attraction* or *repulsion*, with the prediction of possible atom orbiting [2]. All these phenomena have implications in dielectric cavity QED.

2. PRINCIPLE

The van der Waals (vW) interaction between an atom and a surface originates in the quantum fluctuations of the atomic dipole: the fluctuating dipole polarizes the surface, and induces a dipole image instantaneously correlated with the atomic dipole. This near-field image is responsible for the *attractive* character of the vW interaction, which scales in z^{-3} (z , atom–surface distance). For a dielectric surface of permittivity ϵ , this attraction is weighted by an *electrostatic image* coefficient, $(\epsilon - 1)/(\epsilon + 1)$.

Turning the vW attraction into *repulsion* may occur in the presence of a resonant virtual coupling between the atom and the dielectric surface. This coupling appears when a de-excitation channel of the excited atom couples with a surface resonance (“*surface polariton*”). Surface guided modes are characterized by an exponentially decaying e.m. field on both sides of the vacuum–dielectric interface, and exist for *dispersive* media of permittivity $\epsilon(\omega)$, when $(\epsilon + 1) < 0$. Their dispersion relation satisfies to $k_s^2 = k_0^2 \epsilon/(\epsilon + 1)$, where k_s is the mode wavevector along the surface, and $k_0 = \omega/c$. On the vacuum side, their spatial extension range

is governed by $\Lambda = (-\epsilon - 1)^{1/2}/k_0$. Surface *polaritons* correspond more specifically to the poles of $1/(\epsilon + 1)$, for which k_s gets infinite and $\Lambda \approx 0$, i.e., the mode volume decreases and the corresponding vacuum field diverges, implying a maximum coupling between the e.m. guided wave and the material excitation.

The coupling between the atomic oscillator and the polariton resonance is thus reflected in the poles of the surface response $S(\omega) = [\epsilon(\omega) - 1]/[\epsilon(\omega) + 1]$. For an atom with a de-excitation channel at ω_a close to a surface resonance, the surface response can be magnified, according to the *dielectric image coefficient* $2\text{Re}(S(\omega_a))$ [1]. This coefficient turns to be negative if the image dipole is out-of-phase (*phase-reversed*), hence leading to vW repulsion.

3. SELECTIVE REFLECTION EXPERIMENTS

We have predicted such a repulsion for a Cs* ($6D_{3/2}$) atom in the vicinity of a sapphire interface. Indeed, the $6D_{3/2} - 7P_{1/2}$ decay channel at 12.15 μm (very weak radiative transition, probability $\sim 10^5 \text{ s}^{-1}$) falls in the range of the sapphire surface resonance around 12 μm [1].

The experimental evidence [3] for the predicted repulsive potential has been based upon a careful analysis of high resolution selective reflection (SR) spectra, as recorded at a Cs vapor/sapphire interface. In the SR technique, one monitors the frequency dependence of light reflectivity near an atomic resonance at the interface. It allows for exploring the response of short-lived excited states, contrary to atomic beam deflection studies [4]. Here, as described in [3], we have extended the technique to a two-step process $6S_{1/2} - 6P_{1/2} - 6D_{3/2}$, with a 894 nm laser populating Cs* ($6P_{1/2}$) via a broadband excitation process, and a 876 nm laser probing the refractive index of the Cs* vapor (within a depth $\lambda/2\pi \sim 140 \text{ nm}$).

Figure 1 compares (FM) SR spectra, as obtained from the two different windows of a single Cs cell. Striking differences (lineshift, lineshape distortion,

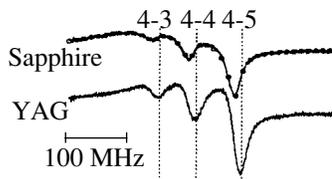


Fig. 1. Comparison between SR spectra on sapphire and YAG windows. The dotted curve (for sapphire) is a fit centered on the Cs transitions in free space (dashed lines).

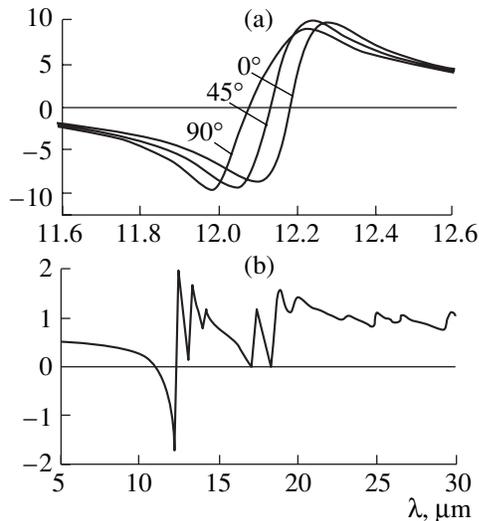


Fig. 2. (a) Predicted sapphire surface response, $\text{Re}[S(\omega)]$, for various c -axis orientations (angle given between c -axis and surface normal). (b) Predicted YAG surface response, $\text{Re}[S(\omega)]$.

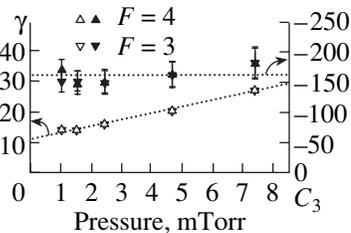


Fig. 3. C_3 ($\text{kHz } \mu\text{m}^3$) as obtained by a fitting of experimental curves in a pressure range in which the width γ (MHz) varies appreciably.

amplitude, ...) are observed between the sapphire window, and the YAG one (for which only a very weak resonant interaction is expected see the YAG surface dielectric response given in Fig. 2b). These spectra have been interpreted using a theoretical model of (FM) selective reflection taking into account the atom-surface interaction, according to a well-established method [5]. As shown in Fig. 3, consistent fits for the sapphire interface are obtained, independently of the experimental conditions (Cs density), with a blue-

shifted resonance, corresponding to a repulsive surface potential: $\omega(z) = \omega_\infty - C_3 z^{-3}$, with $C_3 < 0$ ($\omega(z)$ is the vW shifted atomic resonance, normally centered at ω_∞ in free space).

Sapphire is birefringent and this repulsive potential is observed for a c -axis normal to the interface. It has been experimentally checked that a change in the direction of the c -axis leads to a loss of the resonant coupling [3]. This loss reflects the shift of the polariton resonance with the c -axis orientation (Fig. 2a), as predicted from a theoretical analysis of the vW interaction between an excited atom and an arbitrary birefringent surface, based on linear response theory and generalized susceptibilities for both atom and e.m. field [6].

Analogous experiments at Rb*/sapphire interface have been performed [3], showing a Rb($6D$)/sapphire resonant coupling, due to de-excitation channels also located within the sapphire surface polariton resonance ($6D_{3/2} \rightarrow 6P_{1/2}$, $6P_{3/2}$: 12.21 and 11.74 μm , $6D_{5/2} \rightarrow 6P_{3/2}$: 12.24 μm). This might provide a new tool, of an unprecedented accuracy, to probe a polariton resonance. Note that due to the relatively broad wings of dielectric surface resonances, it is not uncommon to predict a vW enhanced repulsion/attraction for a given excited state. For instance, we also observed a resonant coupling of the Cs ($9S_{1/2}$) state (de-excitation channels at 8.3 and 8.9 μm) with a fused silica surface.

4. PROPERTIES

The mechanical repulsion, predicted to be nearly infinite (in $1/z^3$) at small distances, is appealing for various applications ("atom repellers"), in spite of the finite lifetime of excited atoms. Similar resonant effects on the excited-state lifetime (related to $\text{Im}[S(\omega)]$) are also predicted (surface-induced change in the de-excitation branching ratio) and are now under experimental study. More generally these effects are associated with the coupling with a *real* cavity (metallic or dielectric) in cavity QED. In a further step, one could consider the influence of a *real* excitation of the cavity associated with non-zero temperatures in cavity QED. One may expect the reverse coupling, involving virtual *absorption* of the atom (hence, possibly in the ground state), along with a virtual *de-excitation* of a polariton mode, leading to long-range surface repulsion of ground-state atoms or molecules. Finally note that engineering of the atom-surface interaction also appears feasible through a structuring of the surface (waveguide, etc.)

On the other hand, the quadrupolar anisotropy of the atom-surface vW interaction (because of cylindrical symmetry around surface normal) may induce atom symmetry break. It results in a degeneracy lifting of the Zeeman multiplet, along with the appearance of *free-space forbidden* transitions [7]. Off-diagonal vW interactions and surface-induced level mixing produce a population transfer between metastable states ($^3P_0 - ^3P_2$) of rare gases (Ar, Kr), which has been recently

observed in a beam–surface diffraction experiment [8]. Because of energy and linear momentum conservation, this inelastic process also results in an effective repulsion of the metastable atom by the surface.

Finally vW interactions can be modified *via* alterations in the surface near-field symmetry (surface form factor). An adequate change of the surface geometry (e.g., from planar interface, to spherical or cylindrical geometries) alters the symmetry break, and then selectively enhances forbidden lines (like quadrupole transitions) with respect to electric dipole transitions [9]. It may become particularly important for microbodies like dielectric microsphere or fibers.

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