Optical Response of Gas-Phase Atoms at Less than $\lambda/80$ from a Dielectric Surface

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We present experimental observations of atom-light interactions within tens of nanometers (down to 11 nm) of a sapphire surface. Using photon counting we detect the fluorescence from of order one thousand Rb or Cs atoms, confined in a vapor with thickness much less than the optical excitation wavelength. The asymmetry in the spectral line shape provides a direct readout of the atom-surface potential. A numerical fit indicates a power law $-C_\alpha/r^\alpha$ with $\alpha = 3.02 \pm 0.06$ confirming that the van der Waals interaction dominates over other effects. The extreme sensitivity of our photon-counting technique may allow the search for atom-surface bound states.

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Atomic vapors are continuing to find new applications in quantum technologies such as chip-scale atomic clocks [1], magnetometry [2,3], magnetoencephalography [4], magnetocardiography [5], an atom-based optical isolator [6], quantum memories [7], frequency filtering [8,9], and in the field of nanoplasmonics (see Refs. [10,11] for reviews). As the miniaturization of these technologies progresses, many of these systems eventually reach the scale where the proximity of the atoms to a surface becomes significant. In this case a thorough understanding of the atom-surface interactions is essential. Many of the above applications use atoms in ground states or low-lying excited states, where the atom-surface (AS) interaction is relatively small as the induced dipole is only a few Debye. Even so, the AS interaction can still have a significant effect if the surface is in the near field of the atom, that is, within a fraction of the transition wavelength, λ, of the induced dipole. In this regime, the atom-surface potential is governed by an inverse power law $U_{\mathrm{vdW}} = -C_\alpha/r^\alpha$ where C_α is the coupling coefficient and r is the atom-surface distance. For an uncharged surface with $r < \lambda$ one expects a van der Waals interaction with $\alpha = 3$ [12]. However, if charges are present on the surface the Coulomb interaction may be larger than the van der Waals interaction, leading to a modification of α. The atom-surface potential is also strongly influenced by the presence of surface modes such as surface polaritons. However, for alkali atoms these couple more strongly to intermediate excited states where the energy level spacing is in the terahertz region [13–17]. Very close to the surface, bound states of the AS potential can be exploited, as recently demonstrated using He scattering from LiF surfaces [18]. The combination of bound states and surface resonances potentially allows guiding or trapping of atoms in close proximity to the surface [19]. This could lead to a new type of hybrid nanoscale atom-surface metamaterials, with atoms trapped in small channels that can be etched into any conceivable geometry, using focussed ion beam milling, for example [20].

The atom-surface interaction may be studied using a variety of methods. Scattering or deflection of an atom beam from a metallic surface [21–26], deflection of an ultracold atomic cloud from an atomic mirror [27,28] or diffraction of an atomic beam [29,30] have all been demonstrated. In these examples detection occurs after the interaction has taken place. For measurements of near-field effects at specific length scales such as atomic guiding, real-time *in situ* detection is preferable. Spectroscopic studies can be used, but come at the cost of probing a differential shift between two atomic states which both interact with the surface. The contribution from individual levels could be resolved using a multilevel excitation scheme, but that is not the focus of the present work. Considerable insight has been gained using frequency-modulated selective reflection spectroscopy in atomic vapors [31–34], which probes the vapor with a distance of order λ from the surface. Alternately, it is possible to investigate the AS interaction via atoms which are adsorbed on to a surface [35].

Although selective reflection spectroscopy is useful in determining the average shift from zero crossings, extracting detailed information from the line shape is complicated by the effects of dipole-dipole interactions between atoms, leading to self-broadening [36] and shifts [37], and for parallel surfaces the windows act as a low-finesse etalon which adds further complication to transmission and selective reflection signals [38,39].

In this work we detect fluorescence from an atomic vapor with nanoscale thickness, and use photon counting to probe