Interfacing Light and a Single Atom with a Lens

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We investigate both experimentally and theoretically the interaction of a single atom with a coherent focused light beam. The strength of this interaction will determine the viability of implementing several quantum information protocols, e.g. photonic phase gate. In our experiment, a single ^{87}Rb atom is localized in a far-off resonance optical dipole trap (FORT) formed by strongly focused light at 980 nm. The scattering probability of a weak coherent light beam (probe), resonant to a two-level cycling transition of the trapped atom, is obtained from a transmission measurement of the probe through the FORT region (Fig. 1). This measurement directly quantifies the scattering probability of the probe by a single atom.

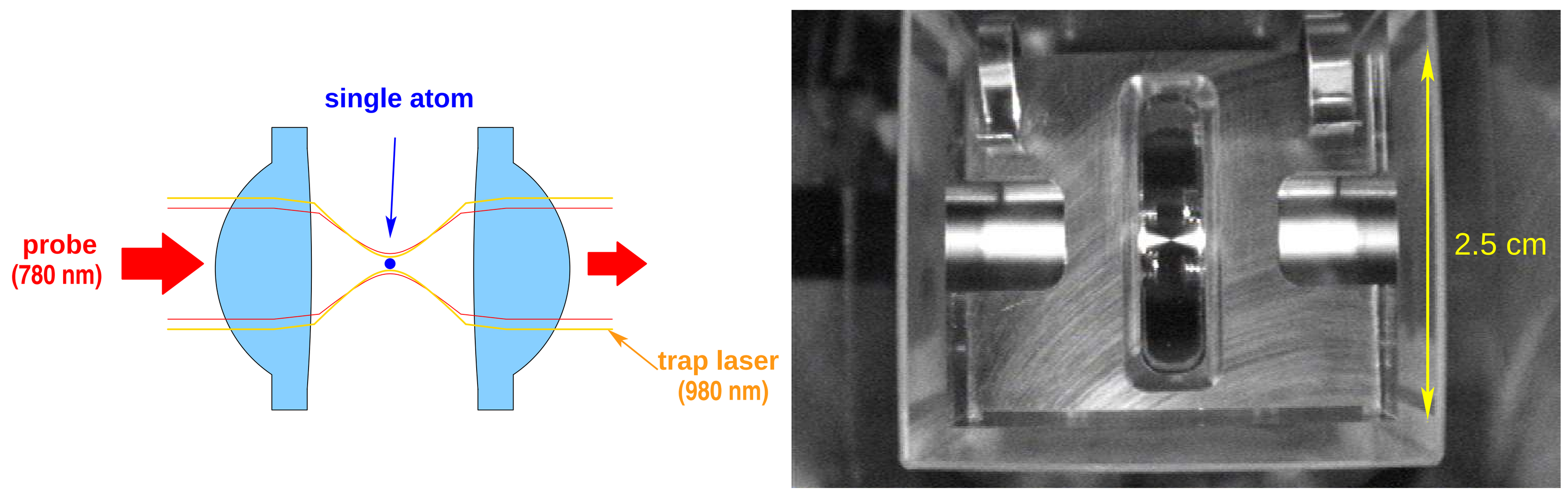

FIGURE 1: (Left) A probe focused onto a single atom localized by an optical dipole trap. Part of the probe is scattered by the atom, resulting in a drop in transmission. (Right) Photograph of the probe beam passing through the lens system. The bright white beam is due to fluoroscence of Rubidium atoms.

Experimental Setup

The heart of our setup consists of two identical aspheric lenses mounted in a confocal arrangement inside an ultra high vacuum chamber. The Gaussian probe beam is delivered from a single mode fiber, focused by the first lens, fully collected by the second lens, and finally coupled again into a single mode fiber connected to a Si-avalanche photodiode. Cold atoms are loaded into the FORT from a magneto optical trap (MOT). The FORT beam has a waist of 1.4 μm at the focus. Due to the small size of the FORT, a collisional blockade mechanism allows no more than one atom in the trap at any time[1,2,3]. The transmission value is defined as the ratio of count rates of detector D1 with to without an atom in the trap.

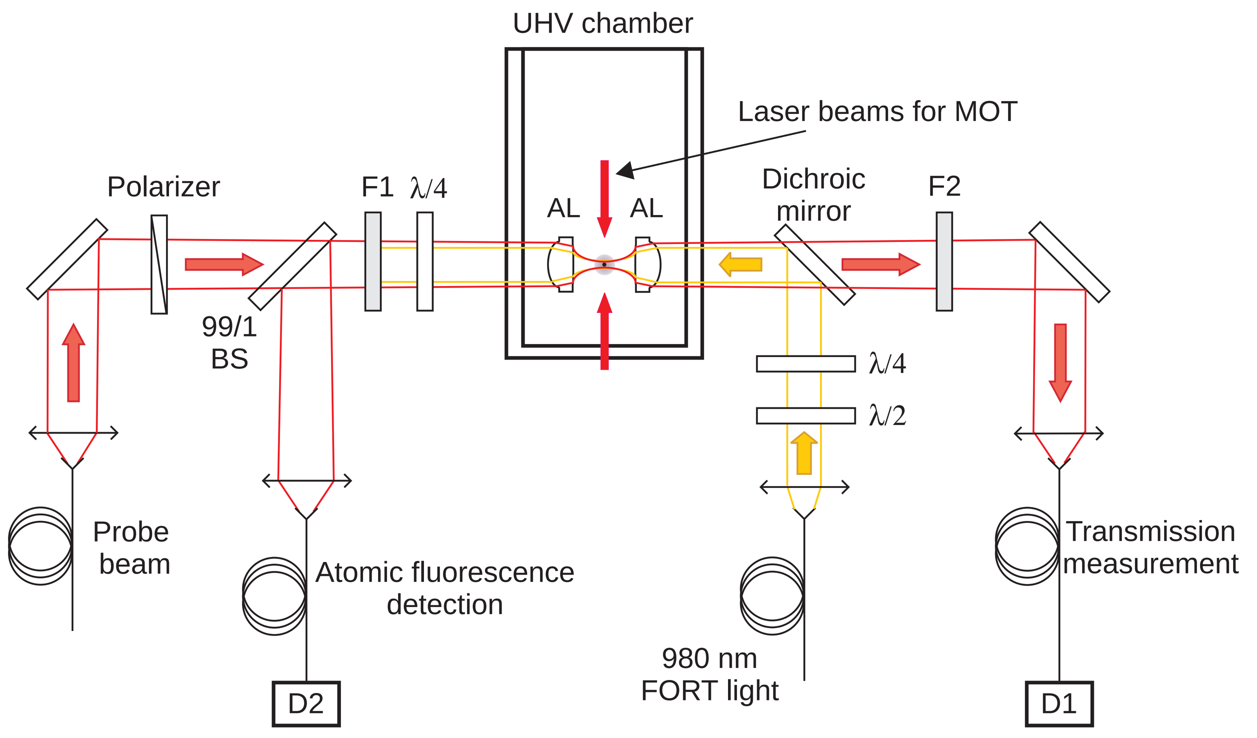

FIGURE 2: Experimental setup for measuring the extinction of a light beam by a single atom. AL — aspheric lenses (f = 4.5 mm, NA = 0.55), F1 — filter to block 980 nm light, F2 — 780 nm line filter to block 795 nm repump light, D1 and D2 — Si-avalanche photodiodes.

In order to achieve maximum extinction, the ^{87}Rb atom is optically pumped into the $|5S_{\frac{1}{2}}$, F=2, $|m_F|$=2⟩ to $|5P_{\frac{3}{2}}$, F′=3, $|m_{F'}|$=3⟩ transition, using a circularly polarized probe. The 980 nm FORT light is also circularly polarized. The atom in the FORT experiences an AC Stark shift as shown in figure 3.

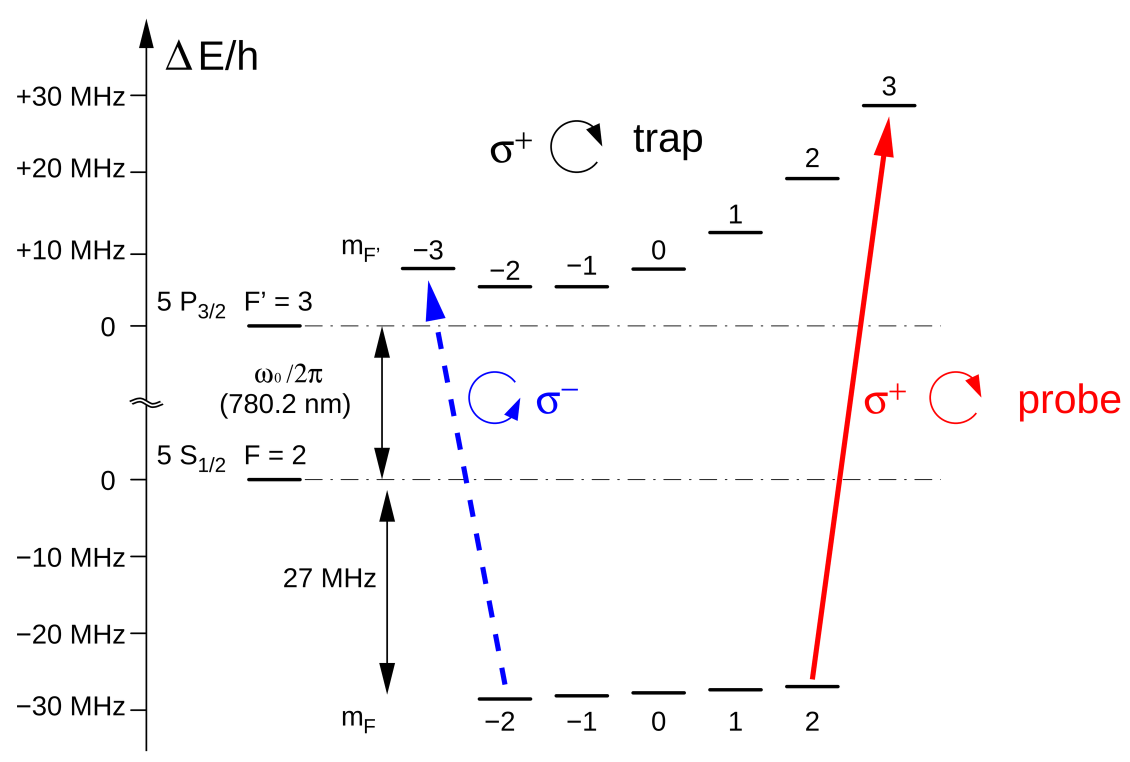

FIGURE 3: AC Stark shift of ^{87}Rb atom in the 980 nm circularly polarized FORT, calculated for our experimental parameters.

Transmission Spectra of a Single Atom

Figure 4 shows the transmission spectra a single ^{87}Rb atom obtained for left-hand and right-hand circularly polarized probes. The horizontal axis shows the probe detuning from the natural resonant frequency of the aforementioned transition (without AC Stark shift). A maximum extinction of 10.4 ± 0.1% is measured for this particular setup in which the probe has a focal waist of $\simeq$ 0.8 μm. The σ^- probe gives a bigger extinction because optical pumping is more efficient for this polarization[3].

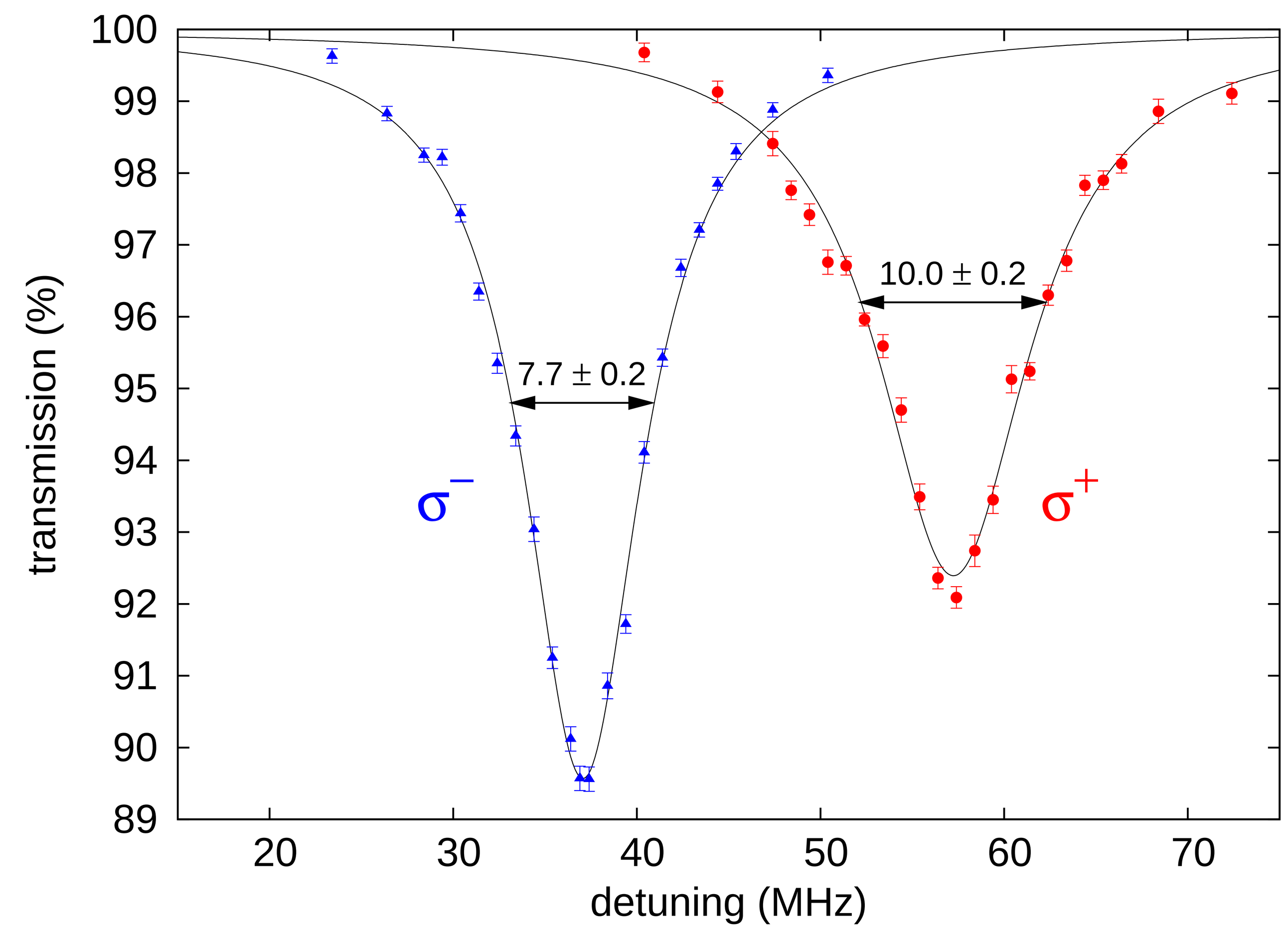

FIGURE 4: Transmission spectra of a single ^{87}Rb atom. The full-width-half-maximum of the transmission spectra are comparable to the natural linewidth of the D2 transition in ^{87}Rb atom (6 MHz).

Theoretical Model

We define the scattering probability of a probe by an atom as the ratio of the total power scattered by the atom to the total incident power. Power scattered by the atom is solely determined by the field properties at the location of the atom under the semi-classical approximation, in which the optical field is assumed to be unaffected by the presence of the atom in the field. A typical way of calculating the field at the focus is by using the *paraxial* approximation. However, this approximation greatly overestimates the scattering probability for strong focusing. To obtain more realistic results, van Enk and Kimble[4] approached the problem by

1) choosing an arbitrary focusing field that is physical,

2) deconstructing this field into a complete set of modes that satisfies Maxwell's equations,

3) propagating these modes to the focus, thus obtaining the field at the focus exactly without approximation.

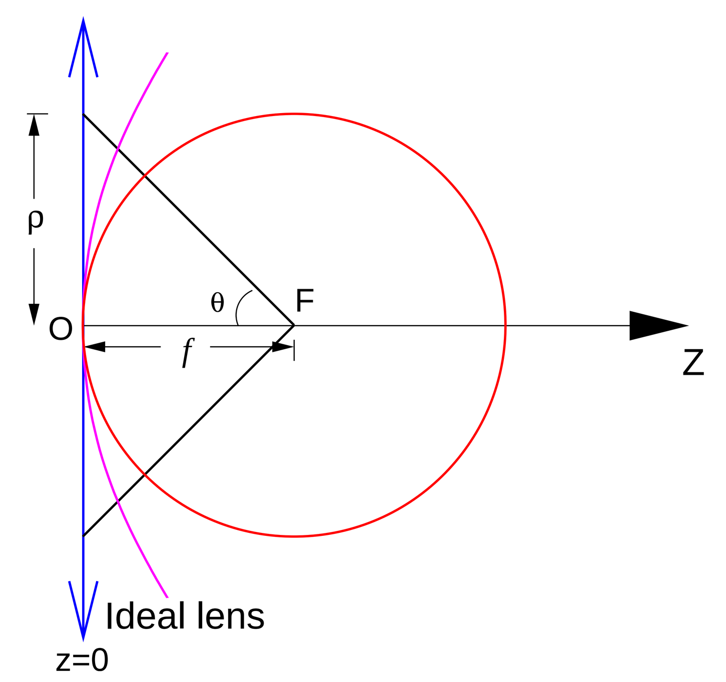

FIGURE 5: Wavefront of a parabolic (purple) and spherical (red) focusing field after the ideal lens with a focal length f.

To obtain an analytical expression for step 2, van Enk and Kimble adopted a focusing field with a *parabolic* wavefront. Their model gives a very dim prediction for the scattering probability of a light beam by a single atom in free space[4]. Extension of their model by adopting a focusing field with a *spherical* wavefront[5] predicts that high scattering probability can be achieved using lenses with realistic numerical apertures.

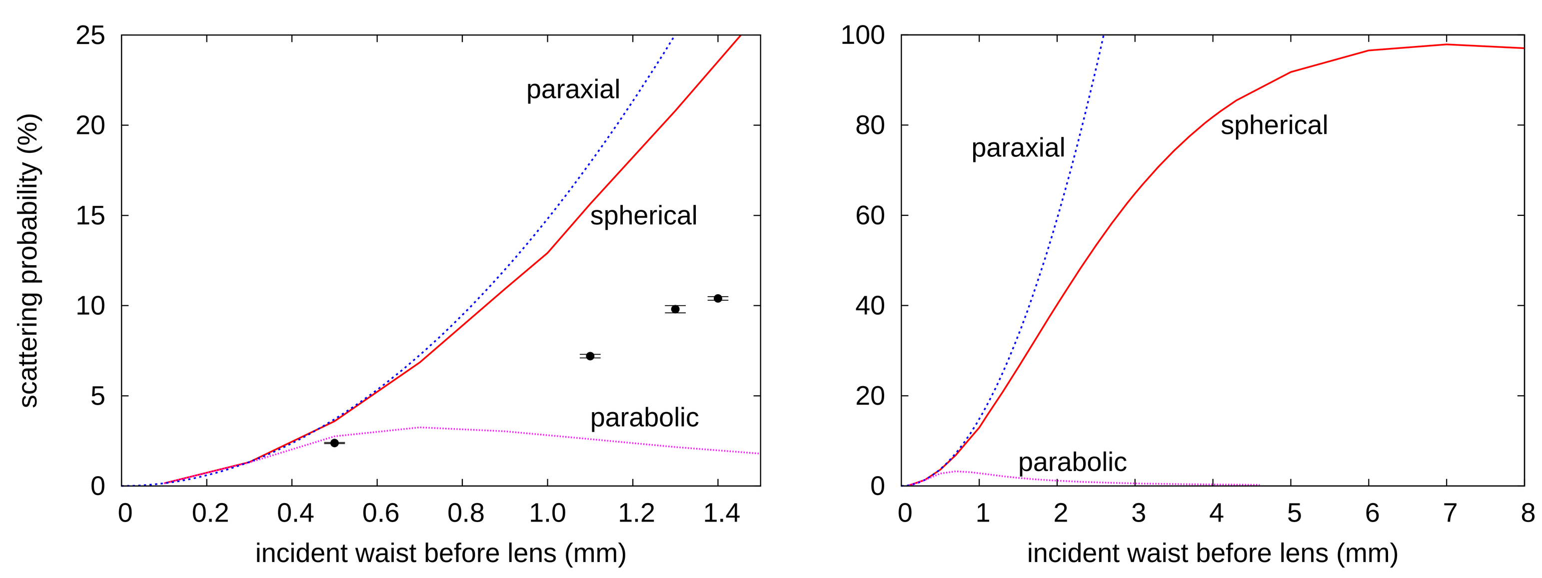

FIGURE 6: Dependence of scattering probability on the incident waist of the Gaussian probe. The curves are calculated for a lens with a focal length of 4.5 mm. (Top) Comparison with experimental data. (Bottom) Extending the models to strong focusing regime.

References

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