Nonlinear photon-atom coupling in free space

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Strongly interacting photons constitute a novel platform to study many-body physics and enable building blocks for quantum technologies. As photon-photon interaction is negligible in free space, a medium is needed to mediate interactions. A single atom can absorb only one photon at a time and is therefore, in principle, well suited to couple simultaneously impinging photons. However, interactions between atoms and photons strong enough to enter the nonlinear regime at the single-photon level have been implemented only in the context of cavity quantum electrodynamics and Rydberg quantum optics. We follow a conceptually simpler approach by using tightly focused free-space modes to achieve a high interaction probability. So far focusing the photons onto the atom with a lens has yielded only moderate interaction strengths. We show that nonlinear interactions at the single-photon level can be realized in free space, i.e., in the absence of waveguides and resonators, by using a different focusing geometry.

To realize strong interactions between a propagating photon and a single atom in free space, the photon needs to be tightly focused to a small volume. From imaging it is well-known that high spatial resolution requires optical elements which cover a large fraction of the solid angle. In standard confocal optical microscopy the excitation light is focused through a lens that can cover only up to half of the solid angle. By using two opposing lenses with coinciding focal points, known as 4Pi arrangement, this limitation can been overcome: the path of the incident beam is split, and the object is simultaneously illuminated by two counterpropagating fields. In this way the input mode covers almost the entire solid angle, limited only by the numerical aperture of the focusing lenses. The symmetry between imaging and excitation of quantum emitter suggests that a 4Pi arrangement can also be used to efficiently couple light to an atom.

I will present our experimental results on light scattering by an atom in the 4Pi-arrangement [1]. In our experiment, we hold a single ^{87}Rb atom between two lenses with a far off-resonant optical dipole trap operating at a wavelength 851 nm [2]. We compare 4Pi and one-sided illumination by performing a transmission experiment with a weak coherent field driving the closed transition near 780 nm. Simultaneously illuminated by two counter-propagating parts of the probe field, we find a strong increase in the light-atom interaction and observe that the atom scatters approximately 36% of the incident light. We also observe that the photon statistics of the transmitted field are modified – indicating nonlinear photon-atom interaction.

Our work establishes the 4Pi arrangement as an effective technique to couple a propagating field to an atom and as an experimental alternative to cavity QED and Rydberg quantum optics to implement effective interactions between photons.

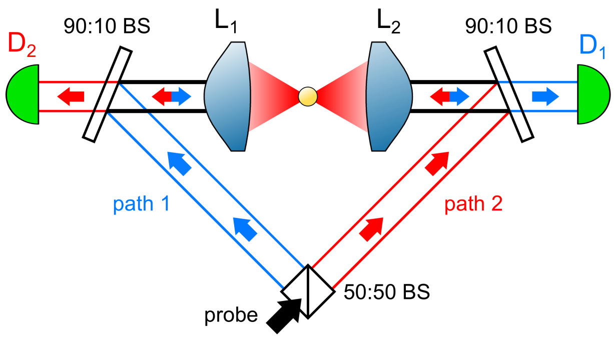

Figure 1: Concept of 4Pi illumination. The probe beam (black arrow) is split into path 1 (blue arrows) and path 2 (red arrows). The two beams then illuminate the atom from counter-propagating directions. The mode overlap of the incident light and the atomic dipole doubles compared to one-sided illumination when the counter-propagating excitation fields interfere constructively at the position of the atom.

[1] Y.S. Chin, M. Steiner, C. Kurtsiefer, Nature Comm **8**, 1200 (2017)

[2] Y.S. Chin, M. Steiner, C. Kurtsiefer, Phys. Rev. A **95**, 043809 (2017)