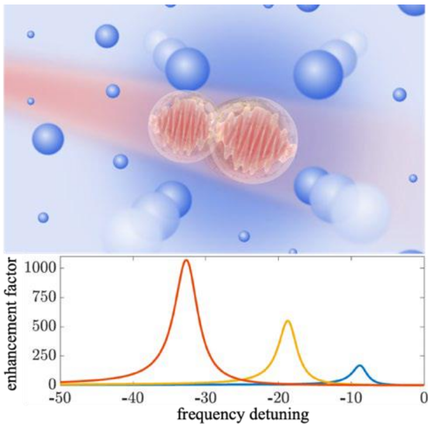
Scientific highlight

Several collaborations across three theory groups at CCQ and researchers at the Center for Hybrid Quantum Networks describe how collections of atoms can be used to generate and manipulate quantum states of light. The research suggests new ways to process optical quantum information.

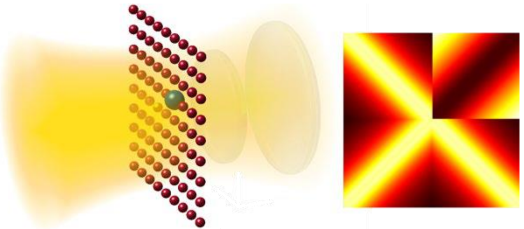
Photons – the elementary quanta of light – can cross each other unimpeded. This fundamental property of light is fundamental for the functioning of our modern communication networks, as it enables the transmission of optical information over long distances with low distortion. There are however many other applications that would become possible if photons could acquire strong interactions between them. Current approaches to generating such effective photon-photon interactions either aim to achieve strong coupling of light to a single quantum emitter or utilize large ensembles of particles with strong mutual interactions. Recent results from CCQ now point towards new routes to interacting photons based on different strategies.



Photons can undergo collisions during their propagating through an optical medium. Surprisingly, the strength of such collisional interactions can be greatly enhanced upon changing the frequency of the light field.

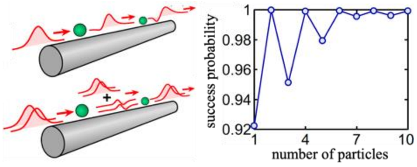
The optical nonlinearities of many materials, such as semiconductors, arise from interactions between their particles. Since those interactions are often weak it is intrinsically difficult to reach the regime of quantum nonlinear optics, in which individual photons can interact strongly with one another. A recent joint work from CCQ has now revised this paradigm and shown that strong photon-photon interactions can in fact be generated from weak interactions between the constituent particles of an optical medium. The discovered effect can be realized and exploited in different materials, which will be studied in CCQ in the coming years.

Strong coupling between light and an optical medium is often achieved by using large atomic ensembles, such that incident photons can simultaneously interact with as many particles as possible. Alternatively, ordered two-dimensional arrays of just a few atoms have recently been recognized as excellent light-matter interfaces. While being only as thin as a single atom, such mesoscopic lattices have remarkable optical properties and, for example, can act as a perfect mirror. Joint calculations by two theory groups at CCQ show that operating such lattices with highly excited atomic states creates an effective quantum filter that will perfectly transmit a single photon but reflects any other incident light. This mechanism makes novel types of mesoscale quantum-optical elements available to cold-atom experiments and could find exciting application that will be explored further in CCQ.



Shining light onto an array of atoms can generate strongly correlated quantum states of light. This is illustrated in the right panel, which shows a calculated density of two photons. The dark stripe in the upper right quadrant indicates that only one photon is transmitted at the time.

An important application is a so-called photon sorter, which can dissect a complex quantum state of light according to the different numbers of photons contained in it. While sorting elements according to their size maybe a simple task in our classical world, it can be exceedingly difficult quantum mechanically. Sending light onto a single particle in principle allows to sort photons, but only with a limited success probability that would give false results every now and then. Joint work between researchers from CCQ and the Hy-Q Center at the Niels Bohr Institute has discovered a remarkably simple solution to this problem and showed that proper coupling of two consecutive particles can increase the success probability to a strikingly high value of 99.97%. In fact, such nearly deterministic operations can be used for processing optical quantum information and quantum computing with light.



Few-particle systems can transfer light into distinct spatial modes, depending on the number of photons. Surprisingly, this process can become nearly perfect for more than a single particle.