Ultracold atoms

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A switchable atomic mirror

Rivka Bekenstein & Susanne F. Yelin

Controlling the response of a material to light at the single-atom level is a key factor for many quantum technologies. An experiment now shows how to control the optical properties of an atomic array by manipulating the state of a single atom.

Atomic arrays are one of the leading platforms in the fields of quantum simulation and computing. One approach to creating arrays of atoms involves two perpendicular light fields forming a so-called optical lattice, where the gradient of the interaction between light and atomic transitions serves as a force to keep atoms in place[1]. Reporting in *Nature Physics*, Kritsana Srakaew and colleagues have now shown experimentally how control of the quantum state of a single atom within an array allows to switch the direction of light scattered off of the array[2].

In atomic arrays setups, cooling the atoms to just slightly above absolute zero is necessary to achieve precise control over the atomic internal state. Such control is applicable down to single-atom precision using, for example, special combinations of microwave and tightly focused laser beams[3]. In a subwavelength array, where the distance between the atoms is smaller than their transition wavelength, any interaction with outside light leads to cooperative effects, that is, all the atoms are subject to pairwise dipole–dipole interaction. This creates a nonlinearity in the atoms that gives rise to a considerable change of the material response, such as the reflectivity of the array as a whole[4–7].

The theoretical concept of quantum metasurfaces has been recently proposed as a tool for quantum-level control of many-photon states by combining long-range interactions with cooperative atomic arrays[8]. The key idea is to utilize three atomic energy levels: the ground state, an intermediate excited state, and a Rydberg state, that is, a high-energy state. The cooperative effects responsible for the reflectivity are pronounced in the ground–excited transition while the Rydberg state offers long-range interaction for achieving quantum control by a single atom. Combining the transitions between these energy levels with long-range interactions between a single control atom and all nearby atoms allows to explore the interplay between two concepts: electromagnetically induced transparency and Rydberg blockade.

In the former scenario, the absence (presence) of a field coupling the intermediate excited state with the Rydberg state determines that another field can (cannot) couple to the ground-to-excited state transition. In the Rydberg blockade regime, the strong interaction between two atoms in the Rydberg state prevents more than one atom within a certain radius — which can be as big as the size of the array — to be resonantly excited into the Rydberg state. Thus, this could allow the translation of any single-atom state into a corresponding response of all the atoms.

By exciting a single control atom to a Rydberg level, Srakaew and colleagues have now demonstrated how to switch an atomic array between being reflective and transmissive, thus accomplishing a first step towards the realization of quantum metasurfaces[8]. The control, or

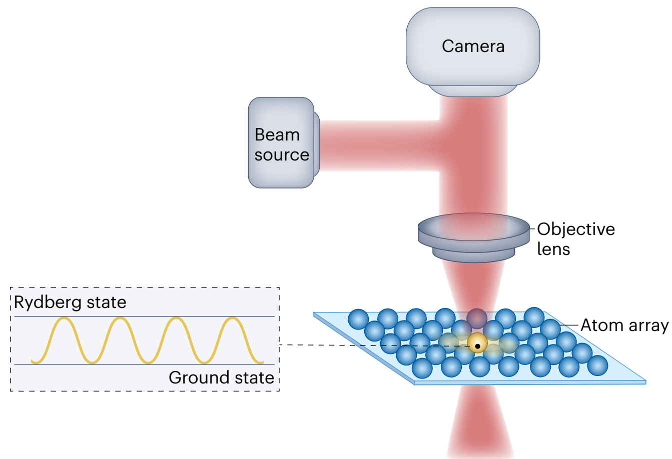

Fig. 1 | Experimental setup for the realization of a switchable atomic mirror. A laser beam (red) is focused to interact with a sub-wavelength atomic array, in which a single atom (yellow) can be excited to a Rydberg state. An objective lens collects the transmitted and reflected light, which then reaches an electron multiplying charge-coupled device camera. The state of the control atom (left) is coherently controlled by external fields and it can for example oscillate between the ground and the excited state. This oscillation causes the appearance and disappearance of a reflection peak in the array spectrum.

ancilla, atom, when excited into the Rydberg state, shifts the Rydberg state of the array atoms within the Rydberg blockade out of resonance (Fig. 1). Thus, in the presence of two light fields, one near resonance with the lower and one with the upper transition, the ancilla in the Rydberg state affects the array of atoms such that they act as two-level systems. The near-resonance light field thus saw the array as a subradiant surface with enhanced reflectivity, as discussed in refs. [4–7]. For the ancilla in any other state, the array atoms experienced electromagnetically induced transparency, and the lower transition was found to be transparent to the field coupling the lower transition.

Moreover, in order to distinguish the ancilla from other array atoms and to achieve longer interaction range, Srakaew and co-workers excited the ancilla atom to a higher Rydberg level using a single ultraviolet field, while the other atoms were pumped through the intermediate state to a lower Rydberg level. As a result, the team reported the probing of the spectrum of light scattered by the array in the presence of the pump laser field. They distinguished the two cases of the ancilla in a Rydberg state or in the ground state. In the ground state case, they observed splitting of the spectral line predicted by electromagnetically induced transparency. In the Rydberg case, an additional peak appeared, as a consequence of the reflection from the cooperative array.

This observation is evidence of the high degree of atomic control over the reflection of light from the atomic array. The reflectivity in the frequency spectrum of scattered light was pronounced only in arrays with spacing smaller than the resonant wavelength, that is, cooperative arrays. Srakaew et al. also demonstrated this effect dynamically.

By forcing oscillation of the ancilla's state, in the form of bouncing from the ground state to the excited state and back, they observed that the reflection or transmission of light was synchronized with the change of the ancilla state.

Finally, the authors observed an additional effect that limited the controlled reflectivity – dipolar exchange interaction. When exciting an atom to a Rydberg state, the excitation can be spontaneously transmitted to another atom within interaction range. Thus, although their control aimed at the reflectivity in a specific region within the array, it could be switched to another one by uncontrolled interaction. This might set a practical limit on the efficiency of quantum metasurfaces.

The achievement described in Srakaew and colleagues of single-atom control over the direction of scattered light is an exciting step towards the development of a new quantum light–matter interface. An example would be to prepare the ancilla in a quantum superposition state, which would in turn generate a superposition of the direction of the scattered light. This would enable the realization of many more proposals, such as entanglement schemes and nonlinear photonic interactions[9,10].

Rivka Bekenstein[1] ✉ & Susanne F. Yelin[2]
[1]Racah Institute of Physics, The Hebrew University of Jerusalem, Jerusalem, Israel. [2]Physics Department, Harvard University, Cambridge, MA, USA.
✉e-mail: rivka.bekenstein@mail.huji.ac.il

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Competing interests

The authors declare no competing interests.