Rare Earth atoms see the light: Promising route for combined optical, solid state-based quantum information processing

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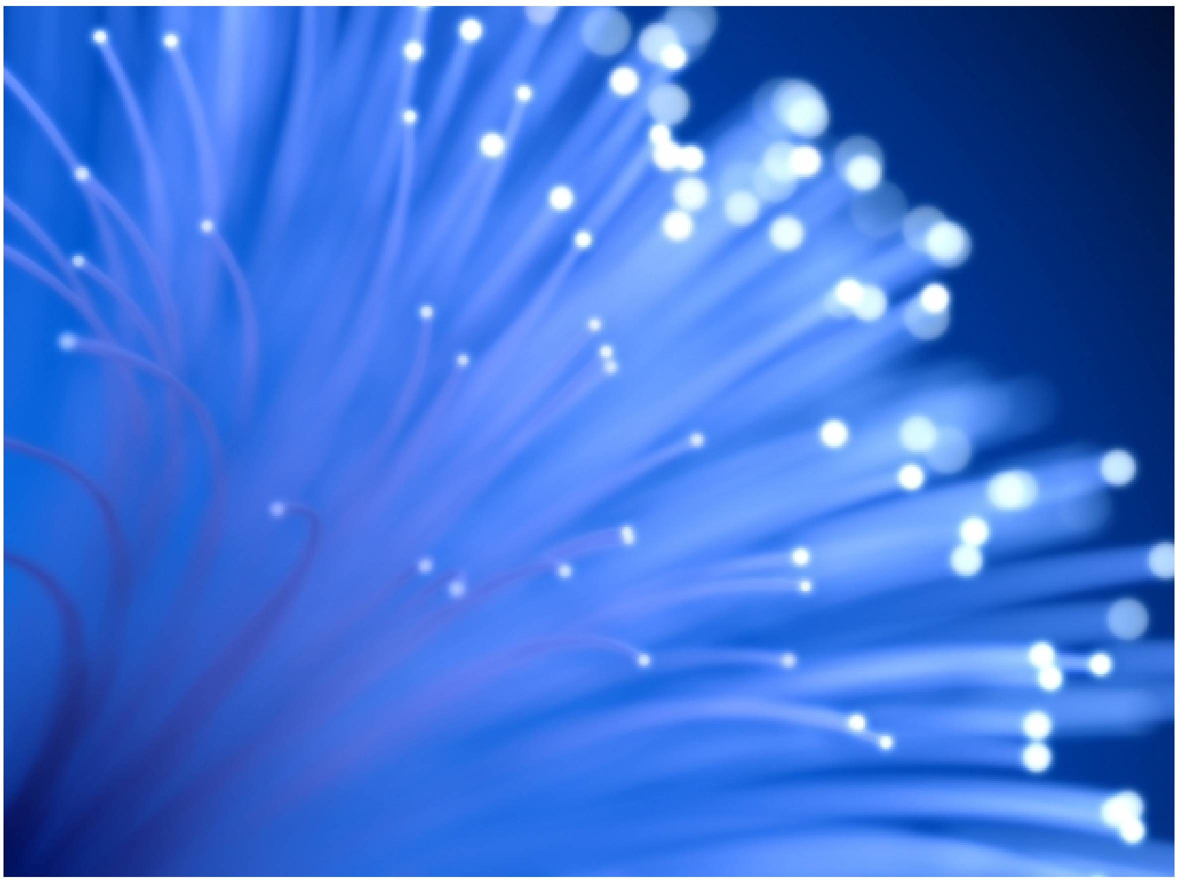

Credit: University of California - Santa Barbara

Tiny units of matter and chemistry that they are, atoms constitute the entire universe. Some rare atoms can store quantum information, an important phenomenon for scientists in their ongoing quest for a quantum Internet.

New research from UC Santa Barbara scientists and their Dutch colleagues exploits a system that has the potential to transfer optical quantum information to a locally stored solid-state quantum format, a requirement of quantum communication. The team's findings appear in the journal *Nature Photonics*.

"Our research aims at creating a quantum analog of current fiber optic technology in which light is used to transfer classical information—bits with values zero or one—between computers," said author Dirk Bouwmeester, a professor in UCSB's Department of Physics. "The rare earth atoms we're studying can store the superpositions of zero and one used in quantum computation. In addition, the light by which we communicate with these atoms can also store quantum information."

Atoms are each composed of a nucleus typically surrounded by inner shells full of electrons and often have a partially filled outer electron shell. The optical and chemical properties of the atoms are mainly determined by the electrons in the outer shell.

Rare earth atoms such as erbium and ytterbium have the opposite composition: a partially filled inner shell surrounded by filled outer shells. This special configuration is what enables these atoms to store quantum information.

However, the unique composition of rare earth atoms leads to electronic transitions so well shielded from the surrounding atoms that optical interactions are extremely weak. Even when implanted in a host material, these atoms maintain those shielded transitions, which in principle can be addressed optically in order to store and retrieve quantum information.

Bouwmeester collaborated with John Bowers, a professor in UCSB's Department of Electrical and Computer Engineering, and investigators at Leiden University in the Netherlands to strengthen these weak interactions by implanting ytterbium into ultra-high-quality optical storage rings on a silicon chip.

"The presence of the high-quality optical ring resonator—even if no light is injected—changes the fundamental optical properties of the embedded atoms, which leads to an order of magnitude increase in optical interaction strength with the ytterbium," Bouwmeester said. "This increase, known as the Purcell effect, has an intricate dependence on the geometry of the optical light confinement."

The team's findings indicate that new samples currently under development at UCSB can enable optical communication to a single ytterbium atom inside optical circuits on a silicon chip, a phenomenon of significant interest for quantum information storage. The experiments also explore the way in which the Purcell effect enhances optical interaction with an ensemble of a few hundred rare earth atoms. The grouping itself has interesting collective properties that can also be explored for the storage of quantum information.

Key is an effect called a photon echo, the result of two distinct light pulses, the first of which causes atoms in ytterbium to become partially excited.

"The first light pulse creates a set of atoms we 'talk' to in a specific state and we call that state 'in phase' because all the atoms are created at the same time by this optical pulse," Bouwmeester explained. "However, the individual atoms have slightly different frequencies because of residual coupling to neighboring atoms, which affects their time evolution and causes decoherence in the system." Decoherence is the inability to keep track of how the system evolves in all its details.

"The trick is that the second light pulse changes the state of the system so that it evolves backwards, causing the atoms to return to the initial phase," he continued. "This makes everything coherent and causes the atoms to collectively emit the light they absorbed from the first pulse."

The strength of the photon echo contains important information about the fundamental properties of the ytterbium in the host material. "By analyzing the strength of these photon echoes, we are learning about the fundamental interactions of ytterbium with its surroundings," Bouwmeester said. "Now we're working on strengthening the Purcell effect by making the storage rings we use smaller and smaller."

According to Bouwmeester, quantum computation needs to be compatible with optical communication for information to be shared and transmitted. "Our ultimate goal is to be able to communicate to a single ytterbium atom; then we can start transferring the quantum state of a single photon to a single ytterbium atom," he added. "Coupling the quantum state of a photon to a quantum solid state is essential for the existence of a quantum Internet."

More information: Multidimensional Purcell effect in an ytterbium-doped ring resonator, *Nature Photonics*, DOI: 10.1038/nphoton.2016.72

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