Simulated quantum magnetism can control spin interactions at arbitrary distances

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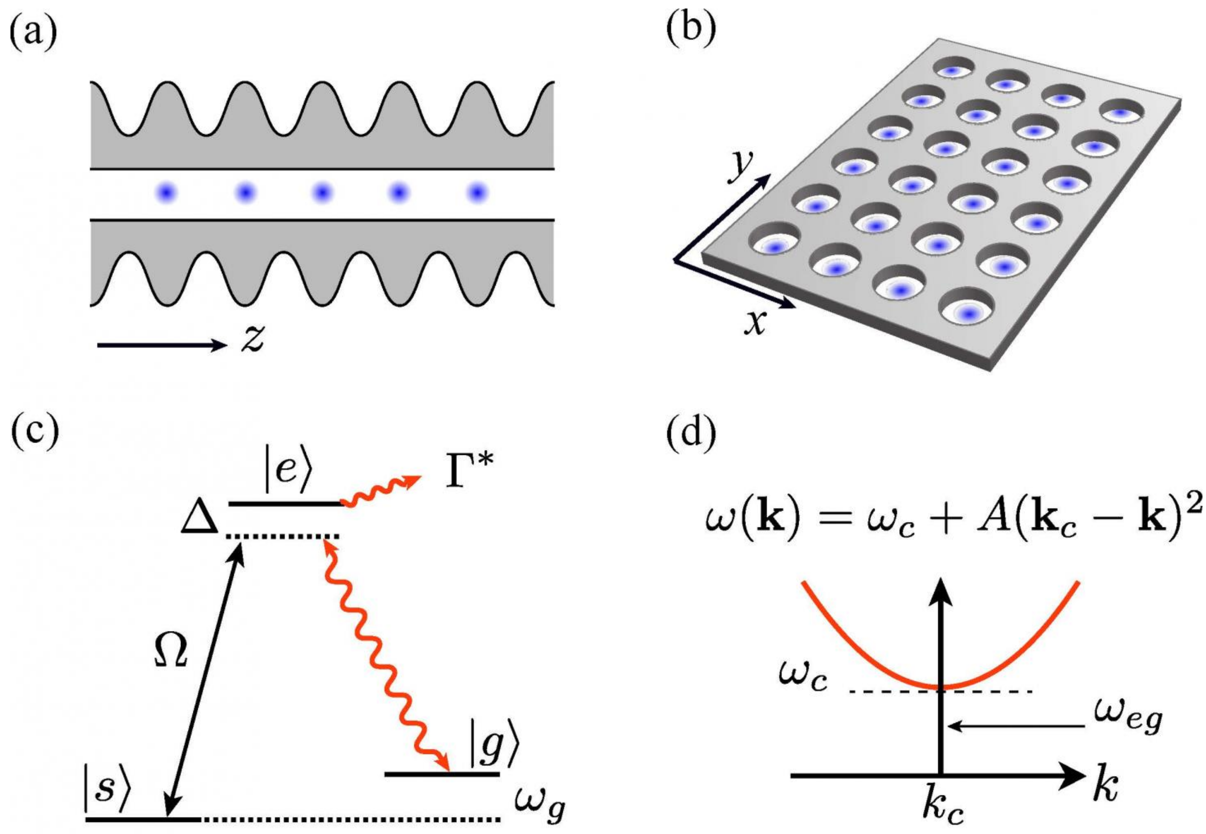

Photon-mediated atom–atom interactions in (*A*) 1D and (*B*) 2D PCWs. (*C*) Atomic-level scheme: atomic dipole |s> ↔|e> is coupled to an external pump, |g> ↔|e> coupled to a GM photon, and Γ*, the excited state decay rate to free space and leaky modes.[†] (*D*) Simplified band structure $\omega(\mathbf{k})$ near the band edge $\mathbf{k} = \mathbf{k}_c$ and $\omega(\mathbf{k}_c)=\omega_c$. Atomic transition frequency $\omega_{eg} = \omega_e - \omega_g$ lies within the band gap. {*To simplify the discussion, in this paper, we neglect decoherence effects caused by atomic emission into free space and leaky modes as well as photon loss due to imperfections in the PCW. These effects were both carefully discussed in refs. 36 and 37, suggesting the number of spin-exchange cycles in the presence of decoherence can realistically reach N ≈35∼100 using ultra-high Q PCWs.) Credit: Hung C-L, González-Tudela A, Cirac JI, Kimble HJ (2016) Quantum spin dynamics with pairwise-tunable, long-range interactions. *Proc Natl Acad Sci USA* 113:34 E4946-E4955.

(Phys.org)—Quantum magnetism, in which – unlike magnetism in macroscopic-scale materials, where electron spin orientation is random – atomic spins self-organize into one-dimensional rows that can be simulated using cold atoms trapped along a physical structure that guides optical spectrum electromagnetic waves known as a photonic crystal waveguide. Recently, scientists at Purdue University, Max-Planck-Institut für Quantenoptik, Germany, and California Institute of Technology, used this approach to devise a scheme for simulating quantum magnetism that provides full control of interactions between pairs of spins at arbitrary distances in 1D and 2D lattices, and moreover demonstrated the scheme's wide utility by generating several well-known spin models. The researchers state that their results allow the introduction of geometric phases into the spin system that could generate topological models with long-range spin–spin interactions.

Dr. Chen-Lung Hung, Dr. Alejandro González-Tudela and *Phys.org* discussed the study, its challenges and the resulting paper that they have published with their colleagues in *Proceedings of the National Academy of Sciences*. These challenges included using a two-photon Raman addressing scheme to devise their proposed atom-nanophotonic system – a system that can achieve arbitrary and dynamic control on the strength, phase, and length scale of spin interactions, as well as simulate quantum magnetism with full control of interactions between pairs of spins at arbitrary distances in 1D and 2D lattices. Moreover, the researchers showed that it is possible to introduce geometric phases into the spin system – and thereby realizing topological models with long-range spin–spin interactions – by carefully arranging the propagation phases of Raman beams.

"Cold atoms are an ideal system for studying quantum many-body problems due to their high degree of controllability and reproducibility," González-Tudela and Hung tell *Phys.org*. "To study various lattice spin models, state-of-the-art experiments load cold atoms into the so-called optical lattices, formed by interfering laser beams in free space. Despite past experimental successes in realizing, for example, superfluid-Mott insulator quantum phase transitions with cold atoms in optical lattices, there are, however, several limitations that preclude cold atoms from emulating a large class of many-body problems involving strong or long-range interactions." This is due to cold atoms being neutral systems that interact very weakly via contact potentials, González-Tudela explains, adding that this small interaction strength makes it difficult to study, for example, important quantum magnetism problems, since these require interactions between atoms in, at least, the adjacent lattice sites. "Decoherence sources can kick in before these very small interaction effects manifest – and on the other hand, short-range interactions also limit the amount of entanglement in the system."

To overcome this challenge and to increase interaction strength, González-Tudela continues, the scientists recently proposed[1] to interface cold atoms with structured dielectrics, which with suitable engineering allows increased interaction strengths and range by letting the atoms talk through guided photons in the structure. "However," he points out, "the spatial dependence of the interactions is fixed by the spatial profile of the photon modes and so does not allow for full control in the interactions. This is why, in this paper, we combine our current and previous ideas, employing external magnetic fields and external multi-frequency laser beams to achieve full controllability of spin-spin interactions." In short, these two extra ingredients allow the researchers to achieve not only full control of pair-wise interactions, but also to introduce space-dependent phases through sideband engineering in the control laser beams – and this improved control has important consequences:

- The ability to simulate long-range interactions with spatial dependence at will, not just fixed by the photon profile in the material. This has important consequences in the static properties of models that cannot be otherwise investigated, but also in the study of thermalization of closed systems with long-range interactions.
- The possibility of introducing space-dependent phases allows the engineering of models with non-trivial topology with long-range interactions, something that is very difficult to obtain in other platforms.
- The prospect of modifying boundary conditions at will allow exploration of non-trivial geometries that may give rise to exotic quantum states.

One of the key findings reported in the paper was the new avenues promised by the proposed platform for engineering a large class of spin Hamiltonians, including those exhibiting topological order or frustrated long-range magnetism (in which the atoms whose spin states are giving rise to quantum magnetism cannot settle into a state that minimizes each interaction). "Because the interactions can be engineered at will, many spin model that require long-range spin-exchange or direct spin-spin interactions can be engineered. Frustration phenomena due to competition between long-range spin-exchange and spin-spin interactions can be studied with great details. Moreover, by carefully controlling the optical phases of the external addressing laser beams, we can imprint a quantum mechanical phase on spins that hop along a closed contour. This gives us an opportunity to engineer the so-called geometrical phases in the spin model, which is responsible of inducing topological quantum phases such as quantum Hall states in 2D electron gases.

Another interesting result was showing that atom-nanophotonic systems present appealing platforms to engineer many-body quantum matter by using low-dimensional photons to mediate interaction between distant atom pairs. "Nanophotonic structures provide us a way to engineer the transport property of what we call *effectively low-dimensional photons* – that is, photons confined in a quasi-2D plane or a 1D wire. When used in nanophotonics, these low-dimensional photons are excellent force- or information-carrying mobile particles that can mediate interactions between distant atom pairs."

Relatedly, the study found that the proposed platform potentially allows for conducting detailed studies on quantum dynamics of long-range, strongly interacting spin systems that are driven out-of-equilibrium. "Dynamic control of interaction strengths is another important feature in our system," Hung points out. "In our Raman control scheme, long-range interaction can be dynamically adjusted via tuning either the amplitude or sidebands in the external control laser beam. Therefore, it will be very easy for the proposed platform to prepare a quantum system out-of-equilibrium and study the subsequent quantum spin dynamics."

On a more encompassing level, the paper states that the scientists expect that their platform may bring novel opportunities to the study of quantum thermalization in long-range many-body systems, or for further understanding of information propagation in a long-range quantum network. Specifically, not only could their platform allow the researchers to study dynamics of a quantum system driven out-of-equilibrium, as mentioned above, but also to investigate how quantum dynamics depends on the range of interactions. "This would provide information on how correlation or entanglement between atomic spins can propagate throughout the spin system, and whether the resulting spin state can still be analyzed as a pure state, or, rather, if it becomes indistinguishable from a statistical mixture," Hung says. This would therefore provide an opportunity to study quantum thermalization in long-range systems. "Moreover," he continues, "by arbitrary, pairwise engineering of spin-spin interactions, we could establish our model system as a 'miniature' long-range quantum network where atoms are viewed as quantum nodes interconnected via guided photons in the nanophotonic channels. Out-of-equilibrium studies in such systems could provide greater understanding of information propagation in a model quantum network."

Of significant importance to the future capabilities of quantum communications is the development of much more robust resistance to sudden decoherence than now exists. *Phys.org* therefore asked Hung if their scheme might be a factor in this effort. "Two conditions might lead to sudden decoherence between a pair of local quantum spins – namely, either through coupling to surrounding or distant spins via long-range interactions that we view as an environment, or through dissipative coupling to unwanted nanophotonic channels or to free space. There could be complex behaviors in the engineered spin system, so we may find new surprises."

The paper also discussed the possibility of engineering periodic boundary conditions, as explicitly shown in the 1D Haldane–Shastry model or in other global lattice topologies, by introducing long-range interactions between spins located at the boundaries of a finite system. "Long-range interaction allows us to connect distant spins located at the opposite end of the boundary in a finite system as well as to engineer the connectivity of a local spin to neighboring spins – thereby opening up ways to engineer the global topology of a lattice spin model."

A fascinating aspect of the study discussed in the paper was the possibility of creating previously-unavailable spin-lattice geometries, such as Möbius strip, torus, or lattice models with singular curvatures such as conic geometries that may lead to localized topological states with potential applications in quantum computations. "Boundary conditions and global lattice geometries can play an important role in lattice models exhibiting topological phases," Hung states. "In particular, topological properties manifest as spin transport at the boundaries or near special points with singular lattice curvatures – and these support topological excitations that are stable against local perturbations. Using the proposed platform, especially with arbitrary long-range interactions, we can engineer or even dynamically control the boundary conditions or lattice topologies that are unavailable in other experimental platforms such as cold atoms in optical lattices. This may open up new ways to engineer transport, localization, or even braiding operations of topological excitations," an abstract topological approach to determining quantum operations, "which may find significant applications in topological quantum computations."

In terms of their ongoing research, Hung tells *Phys.org* that the researchers had great initial successes in developing a prototype *alligator photonic crystal*[2]. "Our experimental groups at Caltech and Purdue University are currently developing new nanophotonic platforms with improved optical qualities and band structures that are capable of mediating stronger atom-photon interaction within a large array of trapped atoms to realize the proposed scheme. Another interesting avenue in atom-nanophotonic hybrid system," he continues, "is to use nanostructures and the resulting attractive vacuum forces to form nanoscale lattice potentials for cold atoms. The vacuum force-induced lattice potentials work just as optical lattices in free space for cold atoms, but the lattice spacing – as small as 50 nm – is much smaller than those of the optical lattices, which are limited by the wavelength of interfering lasers. Reduced lattice spacing leads to more than 100 times increased energy scale in the quantum lattice model, improving the low temperature limitation of cold atom experiments. In the long term," González-Tudela concludes, "the possibility of having a platform where long-range interactions can be controlled at will may also impact the simulation of quantum chemistry problems."

More information: Quantum spin dynamics with pairwise-tunable, long-range interactions, *Proceedings of the National Academy of Sciences* (2016) 113:34 E4946-E4955, doi:10.1073/pnas.1603777113

Related:

[1]Subwavelength vacuum lattices and atom–atom interactions in two-dimensional photonic crystals, *Nature Photonics* **9**, 320–325 (2015), doi:10.1038/nphoton.2015.54

[2]Atom–light interactions in photonic crystals, *Nature Communications* **5**, Article number: 3808 (2014), doi:10.1038/ncomms4808

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