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Rydberg atoms, topological order and quantum magnets

1. **Observation of a symmetry-protected topological phase of interacting bosons with Rydberg atoms**
   Authors: Sylvain de Lésĺeuc, Vincent Lienhard, Pascal Scholl, Daniel Barredo, Sebastian Weber, Nicolai Lang, Hans Peter Büchler, Thierry Lahaye, Antoine Browaeys
   Science **365**, 775–780 (2019); arXiv:1810.13286
2. **Synthetic three-dimensional atomic structures assembled atom by atom**
   Authors: Daniel Barredo, Vincent Lienhard, Sylvain de Léséleuc, Thierry Lahaye, and Antoine Browaeys
   Nature **561** 79-82 (2018); arXiv:1712.02727

*Recommended with a Commentary by Thierry Giamarchi,
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Cold atoms have provided a remarkable route to realize quantum simulators (QS), namely experimental realizations that are as close as possible to model systems (such as e.g. the Hubbard model) and that can serve as direct experimental "solution" of the properties of such paradigmatic models.

Many progress have been made along this line (some of which commented upon by the present author in previous Journal clubs as well as in [1], a recent Journal club by S. Girvin on quantum simulation). The traditional platforms for such quantum simulation are trapped ions, or cold atoms in optical lattices, with also recently QS made of polaritons [2].

Another important and recent platform for quantum simulations has been provided by Rydberg atoms, which will be the object of the present commentary, and the two mentioned papers. Without entering into details Rydberg atoms are atoms excited in a very high excited state. The resulting state has two very interesting properties for realizing a quantum simulator. The first one is that the atoms can be manipulated by tweezers and thus arranged at will in 1D, 2D and 3D structures as shown by the Harvard (see e.g. [3, 4]) and Institut d'Optique (see commented paper 2) groups. The particularly impressive Eiffel tower made of Rydberg atoms shown in Fig. 2 of commented paper 2 is quite representative in this respect of the degree of control that one can achieve with such systems. It is thus possible with such a platform, by programming the tweezers to essentially realize any lattice desired.

The second interest is the fact that the Rydberg atoms thus interact with a long range interaction, which is the van der Waals one. It can be controlled by the position of the atoms on the lattice. This allows to modelize such systems by the z component of Ising spins

$$H = \sum_{i,j} J_{i,j}(S_i^z + \frac{1}{2})(S_j^z + \frac{1}{2}) \tag{1}$$

where $J_{i,j} \sim 1/R_{i,j}^6$, where $R_{i,j}$ is the distance between the two atoms, is a long range coupling which exists when the atom is in the Rydberg state. This allows formal mapping of $|g\rangle \to |\downarrow\rangle$ and $|r\rangle \to |\uparrow\rangle$ (since then more sophisticated schemes have been developed). Using these properties it is possible to tackle the quantum simulations of the statics and dynamics of phases with long range Ising interactions as was done in [4] (reported in the comment [1]) or in [5].

Another interesting route, that was followed in particular by the Insitut d'Optique group is to use these Rydberg atoms, not between a low excited state and a Rydberg state but between two different Rydberg states, for example the $60P_{1/2}$ and the $60S_{1/2}$ states as depicted in the Fig. 1 of commented paper 1. These two states are now interacting via a dipolar interaction. This can thus induce a transition between the two states leading to an Hamiltonian of the form

$$H = \sum_{i,j} \frac{J_{i,j}^{xy}}{2}(S_i^+ S_j^- + \text{h.c.}) \tag{2}$$

where now $J_{i,j}^{xy} \sim (3\cos(\theta_{i,j})^2 - 1)/R_{i,j}^3$, where $\theta_{i,j}$ is the angle between the two sites, and the mapping is $|S\rangle \to |\downarrow\rangle$ and $|P\rangle \to |\downarrow\rangle$. The constraint of having only two states being realized automatically, this is faithful description of a spin-1/2 system. The precise control of the interaction provided by the positioning of the atoms, the absence of thermal effects, as well as the possibility to image the whole system in a single shot, comparable to what is possible in optical lattices by quantum microscope systems, make thus this platform ideal to observe physics for which non-local observable are crucial.

This was spectacularly demonstrated in the commented paper 1, in which a Su-Schrieffer-Heeger (SSH) model [6], namely an alternate of strong an weak bonds was realized and its topological properties studied (see Fig. 1 of commented paper 1). Indeed for such a model, a singlet dimer occurs on each strong bond. Thus if, for a system of finite size, the system starts and ends with strong bonds, the phase is trivial, dimers covering each strong bond. On the contrary if weak bonds occur at the edge zero energy states excitations (free spin 1/2) that have a topological character are left dangling, separated by a bulk of dimers (and thus gapped) excitations (see Fig. 1 and Fig. 2D of commented paper 1 for the description of the system and of the two phases).

The Rydberg platform allowing for a direct, and spatially resolved imaging of the system, shows very clearly (see Fig. 2B of commented paper 1) the differences between the topologically trivial and non-trivial phases by imaging the zero energy states trapped at the edge. An interesting advantage of the degree of control provided by the precise positioning of the atoms on the lattice is that it is possible to test the robustness of the topological phase to symmetry breaking perturbations. For example, by choosing the position of the atoms it is possible to perfectly cancel the exchange between the second neighbors (by putting them at the nodes of the dipolar interaction (see Fig. 1A of the commented paper 1)) or not. Fig. 5

of the commented paper 1 shows the consequences of such a perturbation on the topological order.

The Rydberg platform has thus spectacularly demonstrated, in these recent works, its capability to tackle non trivial simulations either for Ising like arrangements of spins, or as was more the focuss of the present comment for the dynamics and non-trivial phases of spin 1/2 coupled by an XY exchange. It has thus demonstrated its complementarity to the platform made of hard core bosons in optical lattices (see e.g. [7]) or the ones based on fermionic systems in optical lattices and quantum microscopes. It shares the with the latter the ability to measure in a single shot the whole system, thus giving access to topological or string order parameters, but suffers less (at least for the moment) of temperature limitations (the fermionic systems are still plagued by a temperature of the order of the magnetic exchange, even if the situation improved markedly recently).

At the moment only the separate simulation of either mostly Ising systems or pure XY systems has been demonstrated but the platform has clearly the capability to put both the zz coupling term and the xy ones provided a workable sweet spot between the dipolar and van der Waals terms can be found. If this is the case this will be a very strong contender for simulation of quantum magnetic systems given the other advantages of this platform, offering also a strong complementarity to the more conventional probes (neutrons, NMR) that we are used to in the condensed matter context.

References

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