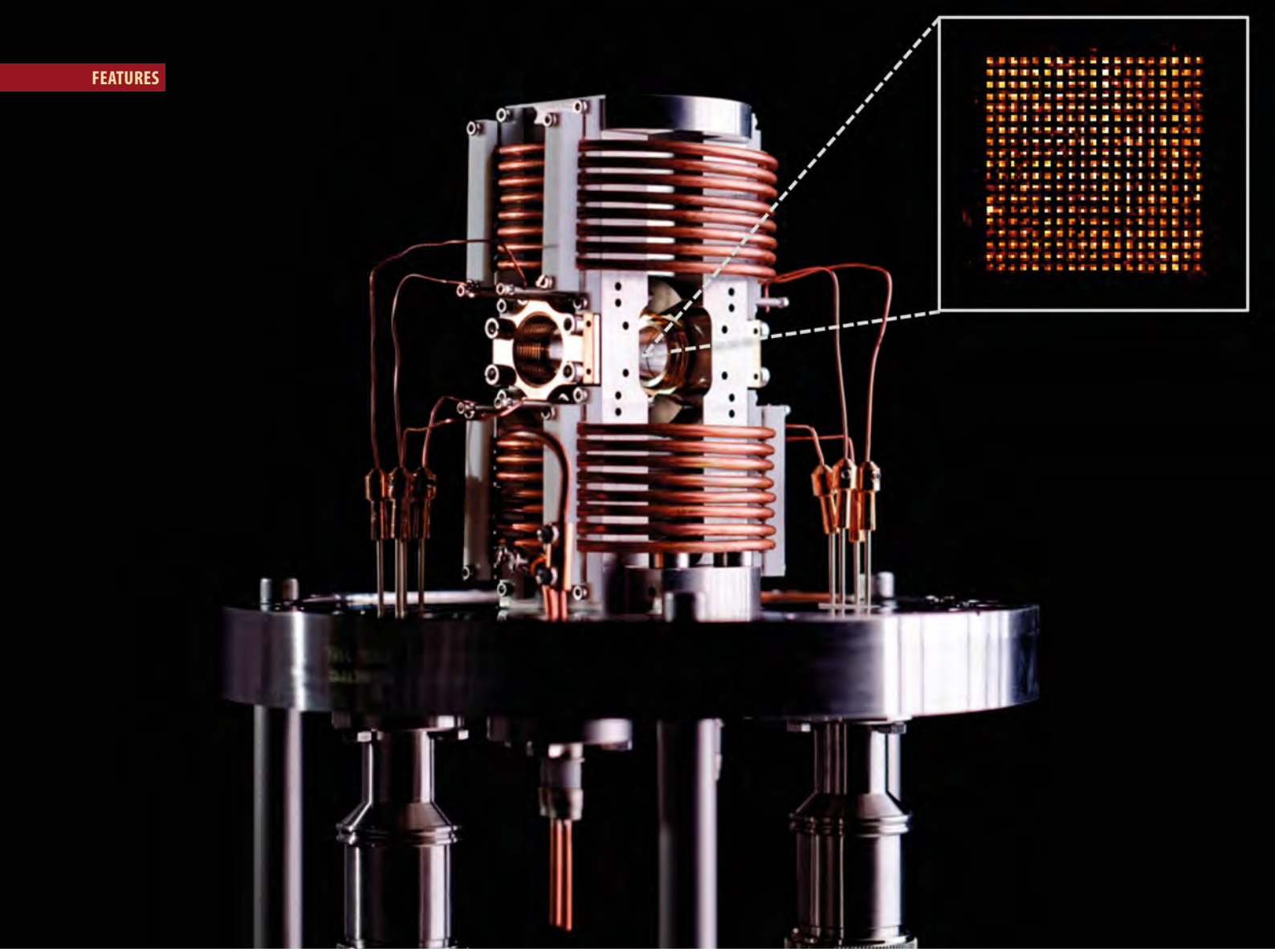


QUANTUM SIMULATION AND COMPUTING WITH ARRAYS OF SINGLE RYDBERG ATOMS

Thierry Lahaye[1] and Daniel Barredo[2] – DOI: https://doi.org/10.1051/epn/2022406

[1] Université Paris-Saclay, Institut d'Optique Graduate School, CNRS, Laboratoire Charles Fabry, 91127 Palaiseau, France

[2] Nanomaterials and Nanotechnology Research Center (CINN-CSIC), Universidad de Oviedo (UO), Principado de Asturias, 33940 El Entrego, Spain

Over the last years, a new platform for quantum technologies has emerged. It is based on arrays of single atoms arranged with almost arbitrary geometries, and made to interact by exciting them to Rydberg states. Compared with other platforms, such as trapped ions or superconducting qubits, atom arrays are quite competitive for applications such as quantum simulation of magnetism. We describe the experimental methods used in this field, and illustrate recent applications.

Since the 1980s, one can manipulate individual quantum objects (electrons, ions, photons…), and realize what was previously thought to remain *Gedankenexperimente*, for instance the demonstration of entanglement. Over this period, it has also been realized that harnessing the laws of quantum mechanics for practical applications, such as cryptography or computing, could lead to a second quantum revolution, with new and extremely efficient approaches to solving some problems. To do so however, one needs to exquisitely control large assemblies of quantum objects.

Even if the realization of a fully-fledged quantum computer remains a formidable task, tremendous progress has been made recently in manipulating larger and larger assemblies of quantum objects. One of the earliest applications of these systems will be *quantum simulation*: the realization of many-body systems governed by Hamiltonians usually studied in condensed-matter physics. Here, we describe one of the most appealing platforms for quantum simulation of spin Hamiltonians encountered in magnetism, namely arrays of single atoms with programmable geometries, and that interact strongly when excited to Rydberg states. We first describe the tools used to realize this platform, and then illustrate its use through recent experiments.

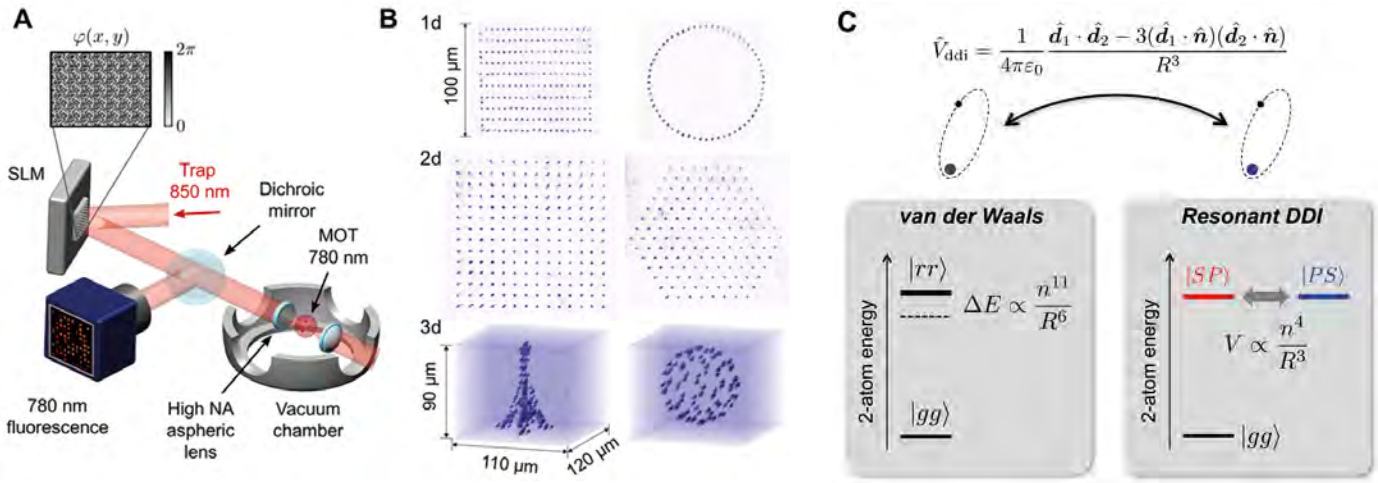
Experimental tools

Single atoms in optical tweezers were pioneered by the group of P. Grangier at Institut d'Optique in 2001 [1]. His team demonstrated that by tightly focusing a laser beam it is possible to create trapping volumes so small that, under certain conditions, only one atom fits inside. These optical tweezers are created with high-numerical-aperture optical systems, and a few milliwatts of light are enough to trap atoms from a magneto-optical trap (MOT). The atoms can be detected by fluorescence using the same optics that focuses the tweezers. During loading, when an atom enters the microtrap, it is further cooled down and stays trapped; whenever a second atom is loaded, a fast light-assisted collision takes place, leading to the loss of both atoms. This prevents the simultaneous presence of two atoms in the trap, but the loading is stochastic with an occupation probability of about 50%.

This can be extended to a larger number of traps with holographic methods (Fig. 1a). By imprinting an appropriate phase in the trapping beam with a spatial light modulator (SLM), a single trap can be replicated into hundreds of traps, each of them hosting at most one atom [2]. For a long time, the non-deterministic loading of the arrays hindered the use of this platform for quantum simulation. Since 2016, a simple approach has been broadly adopted to overcome this limitation. It consists in actively sorting the atoms in the arrays with dynamical optical tweezers. This assembling process obtains filling fractions near unity, and one can currently generate two- and three-dimensional [3] defect-free arrays containing more than 200 atoms with almost arbitrary geometries (Fig. 1b).

The spacing in these arrays is typically a few micrometers. At these distances, ground-state atoms hardly interact. To reach strong interactions, atoms are thus laser-excited to Rydberg levels, *i.e.* states with a principal quantum number $n >> 1$, where the size of the electronic orbit scales as n^2. These giant atoms thus exhibit very large electric dipole moment also scaling as n^2, responsible for strong dipole-dipole coupling between atoms (Fig. 1C). This coupling can give rise to either a van der Waals shift (for identical Rydberg levels, the interaction then scales as n^{11}/R^6, where R is the distance between the two atoms), either to a resonant dipolar interaction where atoms coherently exchange their internal states (for opposite parity Rydberg levels, the exchange frequency scaling as n^4/R^3). These tunable interactions reach tens of megahertz at distances of a few micrometers, thus setting sub-microsecond timescales for the dynamics, much shorter than the lifetimes of Rydberg states.

◂ **P. 28:** The heart of the experiment: high-NA aspheric lenses, magnetic coils, and control electrodes are held together inside an ultra-high vacuum chamber. Inset: fluorescence emitted by an array of 361 rubidium atoms. The lattice spacing is 5 µm.



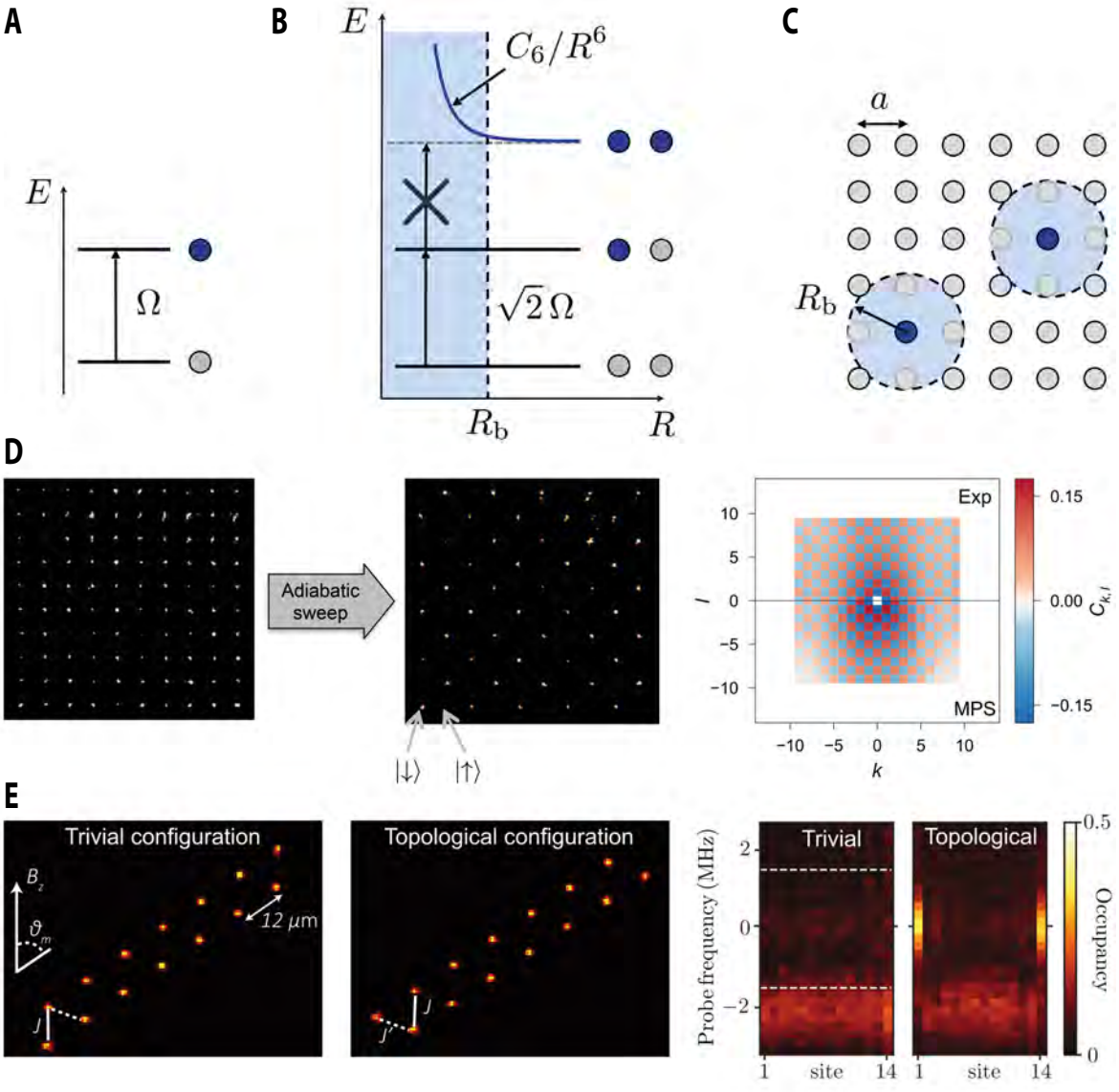
▾ **FIG. 1:** Experimental tools. a) Sketch of the experimental setup. b) Examples of arrays of single atoms. c) The electric dipole-dipole interaction (DDI) between Rydberg atoms can give rise to different types of interactions (see text).

Quantum simulation of spin models

These interactions can be harnessed to realize strongly correlated quantum states. A basic concept at play for this is *Rydberg blockade*. Consider first a resonant laser, driving an atom with a Rabi frequency Ω, and making it oscillate between the ground and Rydberg states (Fig. 2a). For two atoms separated by a distance smaller than the *blockade radius* R_b, only one of the two atoms can be excited, as the doubly excited state is shifted out of resonance by van der Waals interactions (Fig. 2b). This mechanism is central for creating entanglement and realizing two-atom quantum gates.

In a large array where the lattice spacing a is comparable to R_b, many atoms can be Rydberg-excited, but those excitations are strongly correlated (Fig. 2c). One can show that, if we encode spin states in the ground and Rydberg states, the Hamiltonian describing the combined effect of laser driving and of van der Waals interactions is equivalent to the quantum Ising model used in quantum magnetism, that describes arrays of spins interacting with $J_{ij}\sigma_i^z\sigma_j^z$ interaction terms between spins i and j (σ^z denotes the Pauli matrix). The laser plays the role of an external magnetic field. One can adiabatically prepare the many-body ground state of this system (Fig. 2d). Starting with all atoms in $|\downarrow\rangle$ (left) and slowly varying the amplitude and frequency of the laser, one excites only every second atom due to the Rydberg blockade, resulting in a checkerboard pattern (middle), which is nothing but an antiferromagnet. The right panel in Figure 2D shows the spin-spin correlation function $C_{k,l}$ for a 10 × 10 array, measured on the system (top) and calculated using state-of-the-art numerical techniques such as Matrix Product States (MPS), showing excellent agreement and validating the quantum simulator. For our system sizes of ~200 spins, even approximate numerical simulations of the dynamics become intractable [4].

The platform can also be used to implement 2D XY spin models, where the spins rotate in a plane and now interact via an interaction $J_{ij}(\sigma_i^x\sigma_j^x + \sigma_i^y\sigma_j^y)$. To do so, one encodes the spin states in opposite-parity Rydberg levels, and the dipolar interaction gives couplings $J_{ij} \propto 1/R^3_{ij}$. The role of magnetic fields is mimicked here by microwaves. Interestingly, XY magnets are equivalent to systems of hard-core bosons, where bosons can hop around a lattice,



▸ **FIG. 2:** Quantum simulation of spin Hamiltonians. A, B, C: Principle of the Rydberg blockade: the van der Waals interaction C_6/R^6 prevents the simultaneous Rydberg excitation of two nearby atoms. D: Adiabatic preparation of an Ising antiferromagnet using van der Waals interactions. E: Observation of edge states in a Su-Schrieffer-Heeger chain. The topological and trivial chains differ only by the position of one atom, making the chain start either with a strong coupling J or with a weak one J′. This translates in a drastic change in the eigenstates of the system, with zero-energy edge states appearing only for the topological configuration.

but with an occupancy that cannot exceed one on a given site. We have used such an approach to study interacting topological matter [5] in a Su-Schrieffer-Heeger chain (Fig 2e). Topological matter can also be explored using the Ising Hamiltonian: recently, a $\mathbb{Z}_2$ spin liquid, an intriguing state of matter with exotic properties, has been realized [6].

Future developments

Rydberg arrays based on alkali atoms such as rubidium (Rb) or caesium (Cs) have become an almost ideal platform for quantum simulation of spin models. They already allow investigating non-trivial phases of matter. More recently, the use of tweezers arrays has been extended to other species such as strontium [7] or ytterbium, with promising applications also in metrology. The platform is obviously very appealing for quantum computing; gates based on the Rydberg blockade have seen their fidelities improve steadily.

The current interest in quantum technologies has led to the emergence of several companies in the US and in Europe that aim at developing Quantum Processing Units based on Rydberg arrays and making them available on the cloud to scientists and industrial users. There is no doubt that widespread access to such machines will lead to exciting developments. ■

About the authors

Thierry Lahaye is a CNRS scientist at Institut d'Optique. He is an experimentalist and has worked for twenty years in atomic physics. Since 2012, in the group led by Antoine Browaeys, he has applied the Rydberg array platform to quantum simulation of spin models. He is also a co-founder of the company Pasqal.

Daniel Barredo is a Ramón y Cajal Research Fellow at CSIC, where he continues his research on Rydberg atom arrays, after having worked for more than eight years with Thierry Lahaye and Antoine Browaeys at the Institut d'Optique on these topics.

References

[1] N. Schlosser *et al.*, *Nature* **411**, 1024 (2001)
[2] A. Browaeys and T. Lahaye, *Nature Phys.* **16**, 132 (2020)
[3] D. Barredo *et al.*, *Nature* **561**, 79 (2018)
[4] P. Scholl *et al.*, *Nature* **595**, 233 (2021)
[5] S. de Léséleuc *et al.*, *Science* **365**, 775 (2019)
[6] G. Semeghini *et al.*, *Science* **374**, 1242 (2021)
[7] I. Madjarov *et al.*, *Nature Phys.* **16**, 857 (2020)