RYDBERG ATOMS

There can be only one

In an ensemble of atoms with long-range dipolar interactions between them, only one atom can be excited at a time. This 'dipole blockade' has now been observed for two single atoms positioned at macroscopic distances.

Matthias Weidemüller

Imagine a gas of atoms irradiated by a laser at resonance with an electronic transition. Naively, one would expect that each atom undergoes oscillations between the ground state and the excited state, driven by the coherent light field. This simple picture, however, breaks down when the excited atoms interact with each other. The excitation of one atom then shifts other atoms out of resonance — this is because the interaction energy has to be added to, or subtracted from, the excitation energy for attractive and repulsive interactions, respectively (Fig. 1a). As a consequence, excitation of multiple atoms in the gas is suppressed. This interaction-induced blockade effect is reminiscent of the Coulomb blockade in solid-state tunnel junctions, where the charging energy of a quantum dot impedes its population by more than one electron. In the case of atomic excitation, the strongest forces are exerted by the electric dipole interaction, and therefore the atomic blockade effect has become known as 'dipole blockade'. Two independent teams, reporting on pages 110 (ref. 1) and 115 (ref. 2) of this issue, have now observed the dipole-blockade effect in its simplest and purest form, with two atoms separated by macroscopic distances of several micrometres.

In order to ensure sufficiently strong interactions over large distances, the two groups use laser excitation into states with high principal quantum numbers: so-called Rydberg states. Because of the weak electric binding forces of the outer electron to the nucleus, Rydberg atoms[3] — atoms in Rydberg states — react sensitively to external electric fields. The polarizability of a Rydberg atom (which determines the strength of the dipole moment induced by a given electrical field) scales with the seventh power of the principal quantum number, and the van der Waals interaction between atoms, therefore, with the eleventh power. If two atoms in the electronic ground state are separated by a few micrometres, van der Waals interactions have a negligible influence on their dynamics. Owing to the extreme scaling, however, two Rydberg atoms may interact over these macroscopic scales — leading, for instance, to measurable mechanical forces[4]. (As an example, the frequency shift for atoms in a state with principal quantum number 80 at a distance of 5 μm is of the order of a few hundred MHz.) The Rydberg excitation blockade was first observed in ultracold gases[5,6], and has been recently demonstrated most spectacularly in a dense gas near quantum degeneracy, where thousands of atoms were blocked from excitation in the vicinity of a single Rydberg excitation[7].

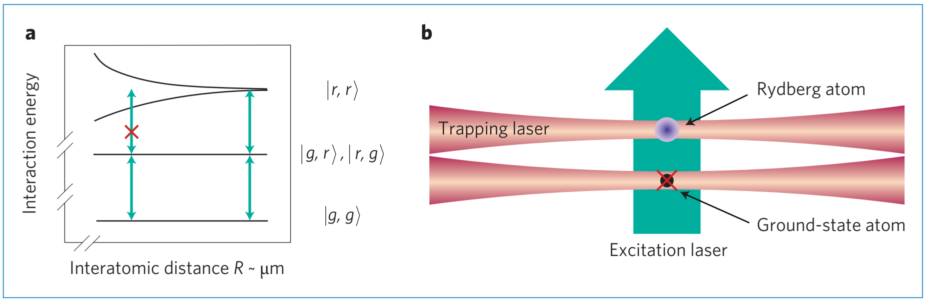

Figure 1 | Rydberg dipole blockade. **a,** Two atoms in a Rydberg state ($|r\rangle$) interact via dipolar forces over distances of several micrometres, whereas the interaction involving atoms in the ground state ($|g\rangle$) is negligible. Either atom can be excited by a resonant laser field, but not both atoms simultaneously, if the interaction-induced energy shift is larger than the width of the resonance line. **b,** In the experiments of Urban *et al.*[1] and Gaëtan *et al.*[2], two single atoms are held in independent optical dipole traps formed by the foci of two far-detuned laser beams. The distance between the atoms can be adjusted down to a few microns. The atoms are illuminated by a resonant laser field exciting them to Rydberg states.

A peculiar effect directly linked to the dipole blockade is the formation of a highly entangled state. As the excitation process does not distinguish between the atoms, each atom can in principle be excited with equal probability, but only one single excitation is allowed in the entire ensemble. The single Rydberg excitation is thus shared equally among the atoms, giving rise to a highly entangled many-body quantum state. The state is a superposition of quantum states characterized by one specific atom being excited into a Rydberg state and the others remaining in the ground state. The collectiveness of this many-body excited state becomes manifest in a deviation of the Rabi frequency — that is, the frequency of the oscillation between ground and excited state — from the single-atom Rabi frequency. The collective Rabi frequency is given by $\sqrt{N}$ times the single-atom Rabi frequency, where N indicates the number of entangled atoms. It has been theoretically predicted for some years that the deterministic quantum entanglement induced by dipolar interactions provides an excellent resource to implement gates for quantum-information processing with neutral atoms[8,9].

It is these applications, involving precise control over single quantum systems, that Erich Urban *et al.*[1] and Alpha Gaëtan *et al.*[2] are interested in. In their experiments (Fig. 1b), single atoms are trapped in two optical tweezers formed by the foci of far-detuned laser beams at controllable distance. The atoms are excited to principal quantum numbers between 60 and 80, which means that the extension of each atom's outer-electron wave packet is on the order of 100 nm. The distance between the excited atoms is several micrometres, two orders of magnitude larger. And whereas the details of the two experiments are quite different, both groups find clear evidence for the suppression of double Rydberg excitation resulting from the dipole blockade. Also, the results of Gaëtan *et al.*[2] clearly show the $\sqrt{2}$ increase in the Rabi frequency for the collective excitation of two atoms in the dipole blockade regime.

Rydberg atoms have been the subject of intense investigation since the early days of atomic physics, with ever new twists and surprises. The field started with the spectroscopical observations of Rydberg atoms in the laboratory and in outer space during the first half of the twentieth century, and continued with the study of electron dynamics in Rydberg states prepared by tunable laser fields in the second half. We are currently witnessing the emergence of a third era of Rydberg physics; that is, the investigation of few- and many-body effects owing to the long-range interactions of these atoms. Investigations include exotic molecules with extreme binding lengths, coherent many-body energy and charge-transport phenomena, and strongly correlated dipolar gases. The results regarding the dipole blockade between two single atoms[1,2] represent a further exquisite example for the wealth of physics offered by correlated Rydberg atoms. Although the quantum-state and motional manipulation of single neutral atoms has undergone tremendous progress in the past ten years[10], efficient methods for entangling two or more neutral atoms in a deterministic way have still been lacking. With the advances by Urban *et al.*[1] and Gaëtan *et al.*[2], the door is now wide-open for the application of Rydberg atoms for neutral-atom quantum gates and for fundamental investigations on the nature of quantum entanglement. ❐

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References

1. Urban, E. *et al. Nature Phys.* **5,** 110–114 (2009).
2. Gaëtan, A. *et al. Nature Phys.* **5,** 115–118 (2009).
3. Gallagher, T. F. *Rydberg Atoms* (Cambridge Univ. Press, 1994).
4. Amthor, T., Reetz-Lamour, M., Westermann, S., Denskat, J. & Weidemüller, M. *Phys. Rev. Lett.* **98,** 023004 (2007).
5. Tong, D. *et al. Phys. Rev. Lett.* **93,** 063001 (2004).
6. Singer, K., Reetz-Lamour, M., Amthor, T., Marcassa, L.G. & Weidemüller. M. *Phys. Rev. Lett.* **93,** 163001 (2004).
7. Heidemann, R. *et al. Phys. Rev. Lett.* **99,** 163601 (2007).
8. Jaksch, D. *et al. Phys. Rev. Lett.* **85,** 2208–2211 (2000).
9. Lukin, M. D. *et al. Phys. Rev. Lett.* **87,** 037901 (2001).
10. Meschede, D. & Rauschenbeutel, A. *Adv. At. Mol. Opt. Phys.* **53,** 75–104 (2006).

PLASMA PHYSICS

A new spin on quantum plasmas

A model for dense degenerate plasmas that incorporates electron spin indicates that quantum effects can be seen even under conditions previously considered to be in the classical regime.

Padma Kant Shukla

In a classical plasma, the particle number density is low and the temperature high. In contrast, the electron number density in a quantum plasma is much higher and the temperature correspondingly lower. Reporting in *Physical Review Letters*, Gert Brodin and co-workers[1] have increased our understanding of quantum plasmas by developing an improved model that includes the influence of electron spin.

Quantum plasmas are common not only in astrophysical environments[2], such as the interiors of superdense white dwarfs and Jupiter, neutron stars and magnetars, but they are also producible in the laboratory[3], in nanostructured materials and quantum wells. Importantly, Fermi-degenerate plasmas — plasmas at such a high density that the Pauli exclusion principle comes into play — may also arise when a pellet of hydrogen is compressed to many times its solid density, which is important for inertial confinement fusion.

In a dense Fermi-degenerate plasma, electron–electron and ion–electron collision frequencies are smaller than the classical predictions, whereas insignificant ion–ion collisions follow the classical limit. Owing to the high electron number density, the electron plasma frequency is extremely high and it far exceeds the electron collision frequency. Such properties lead to many novel effects[4–6]. Some of the important ones are: a Fermi-degenerate electron/positron equation of state that is significantly different from that of the Maxwell–Boltzmann laws; quantum electron/positron tunnelling effects due to the finite width of the electron wave function; and the electron/positron-1/2-spin effect due to random orientation of the plasma particles in a non-uniform magnetic field.

Brodin and colleagues[1,6] have investigated novel collective electromagnetic wave phenomena involving the electron-1/2-spin effect. In thermodynamic equilibrium, some of the electron spins tend to align with an external magnetic field. Subsequently, there emerges a plasma magnetization in the direction of this field. When the variation of the magnetic field occurs on a timescale shorter than the characteristic spin-relaxation time, the degree of spin alignment can be approximated as constant. Spontaneous spin changes do not occur for single electrons (owing to angular momentum conservation) and so this spin-relaxation time[7] is also larger than the inverse electron-collision frequency. The electron spin modifies the plasma current density and introduces a magnetic moment force on the electrons. Accounting for this anomalous magnetic moment, characterized by the electron-spin g-factor ($g \approx 2.002319$), Brodin *et al.*[1] have developed a spin-force-modified kinetic theory for a magnetized plasma with immobile ions. A new high-frequency ordinary mode, which is polarized parallel to the external magnetic field direction, appears. Furthermore, the model also identifies new types of wave–particle interactions involving the electron spin state.

There have been several previous approaches to treat collective interactions[5,6] in dense quantum plasmas. The quantum hydrodynamical model is one such example. This model considers a number of forces acting on the electrons: the Fermi pressure that arises because of the high density, the quantum force[4,5] due to collective electron tunnelling through the so-called Bohm potential and the electrostatic force. The net effect of these forces is that the electrons oscillate around the heavy ions — so-called electron plasma oscillations. The model of Brodin *et al.* extends these ideas by introducing the effect of the anomalous electron spin, but ignores quantum mechanical and quantum tunnelling effects. Brodin *et al.* stress that their model is only valid in the weak quantum regime where the characteristic length-scale is larger than the thermal de Broglie wavelength, and the Zeeman energy density is much