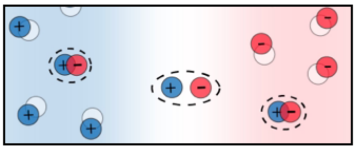
## Scientific highlights

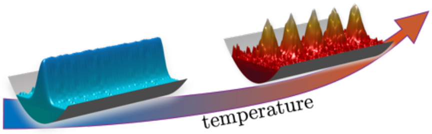
**Theoretical work at CCQ reveals a rich spectrum of collective phenomena in complex systems with dipole-dipole interactions. The findings could revise previous paradigms about the behaviour of matter and point towards new ways to manipulate quantum states of light.**


Dipolar excitons in a semiconductor.

Interactions between dipoles are essential to understand a vast range of elementary processes in nature, from biology to chemistry and physics. At CCQ we recently investigated a more exotic hybrid system that is composed of light and matter – and, yet, also features strong dipole-dipole interactions[1]. When light is absorbed by a material it can liberate electrons from their parent atoms that make up the material. Such free electrons can bind together with the positive charge they left behind and thereby form so-called excitons, which can be seen as solid-state counterparts of atoms. A strong inhomogeneous electric field can trap and, at the same time, polarize the artificial atoms, giving rise to a new type of excitons with extraordinarily strong dipole-dipole interactions. One can now ask what effect this has for the light that generated these exotic excitons. If the light-matter coupling is sufficiently strong, photons coalesce with excitons and form a hybrid quantum particle, termed polariton. Since two excitons interact via their dipole moments, one would anticipate that the polaritons inherit some of this interaction. Surprisingly, it turns out that the resulting interaction can even surpass the original particle interaction, and it does so by a substantial amount. This counter-intuitive finding has profound consequences for the optical properties of the material and lays the foundation for engineering strong optical nonlinearities that can act at the ultimate quantum level of individual photons. In fact, these insights come at an exciting time, where dipolar polaritons are discovered in a range of settings from new classes of two-dimensional quantum materials to Rydberg-excitons, as shown in recent work by CCQ members and international collaborators[2].


Light can be confined between two lattices of atoms

We can nowadays construct quantum materials particle by particle, e.g., using optical traps that confine individual atoms in regular structures. Such synthetic matter is often used for quantum-simulation technologies, but it can serve as a light-matter interface with extraordinary properties. For example, atoms in two-dimensional lattices may not merely scatter incident light but can efficiently exchange photons even across a single layer. This in turn generates effective dipole-dipole interactions between the particles and causes atoms to act in unison, giving rise to a wealth of fascinating collective effects. At CCQ we have considered two such layers[3] and found that these can be used as a photon trap to confine light over virtually arbitrary long times. Under this confinement, photons can acquire particle properties and feature strong effective interactions. This offers exciting avenues towards observing exotic photon matter, such as fluids or solids of light, or realizing atomic-scale optical elements to control light quantum by quantum.



A dipolar quantum fluid is found to crystallize upon raising its temperature.

The elementary magnetic dipoles of atoms can also lead to strong interactions between particles that are of broad scientific and technological significance. Ultracold gases of magnetic atoms have recently moved into the spotlight, since they made it possible to observe a long-sought phase of matter, the so-called supersolid. In a supersolid, atoms freeze into a rigid solid and, at the same time, can freely flow through the crystal without resistance. At CCQ we have investigated this contradictory quantum state at finite temperatures and discovered a surprise[4]. It is common knowledge that the cooling of a liquid leads to its crystallization, while heating tends to vaporize the fluid into a gas. Studying a dipolar quantum fluid, we stunningly found the exact opposite behavior, namely the formation of a supersolid upon raising the temperature. The results explain observations by our experimental collaborators at the University of Innsbruck and open the door for exploring the unusual thermodynamics of dipolar quantum fluids in the coming years.

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[1] E.R. Christensen et al., *Microscopic theory of cavity-enhanced interactions of dipolaritons*, arXiv: 2212.02597 (2022).

[2] K. Orfanakis *et al.*, *Rydberg-exciton polaritons in a $Cu_2O$ semiconductor microcavity*, Nature Materials **21**, 767 (2022).

[3] S.P. Pedersen *et al.*, *Quantum nonlinear metasurfaces from dual arrays of ultracold atoms*, Phys. Rev. Res. **5**, L012047 (2023).

[4] J. Sanchez-Baena et al., Heating a dipolar quantum fluid into a solid, arXiv: 2209.00335, accepted in Nature Comm. (2022).