QUANTUM OPTICS

Crystals of atoms and light

Cold atoms and photons confined together in high-quality optical resonators self-organize into complicated crystalline structures that have an optical-wavelength scale. Complex solid-state phenomena can be studied in real time on directly observable scales.

Helmut Ritsch

Just as matter is used to control the propagation of light waves, light can be used to manipulate matter waves. In typical situations, such as when light is guided by lenses or mirrors or when particles are trapped by optical tweezers and laser cooling, only one of the two effects is significant.

However, confining a cold gas in a high-finesse optical resonator creates an unusual situation in which particles and photons dynamically influence each other's motion by momentum exchange on an equal footing. The particles create a dynamic refractive index that diffracts the light waves. These interfere and form structured optical potentials that guide the particles' motion. In the simple generic case of high-field-seeking atoms in between two plane mirrors, one finds a well-defined threshold illumination intensity above which the particles order in a regular crystalline structure. They form ordered patterns with Bragg planes, which optimally couple the pump laser into the resonator[1]. This maximizes the resonator field and thus minimizes the potential energy of particles trapped around local field maxima. The scaling of this phase-stable super-radiant scattering with the square of the particle number has been observed experimentally, and is a clear signature of such self-ordering[2].

Sarang Gopalakrishnan and colleagues, reporting on page 845 of this issue[3], generalize the description of these complex coupled nonlinear dynamics by considering ultracold quantum gases in a multimode optical resonator. Here, photons and atoms can dynamically occupy a large number of modes. Using a functional-integral formalism adapted from quantum field theory, Gopalakrishnan *et al.* are able to derive an effective atom-only action from which they uncover a wealth of new phenomena in this generalized configuration. One important result is that the phase transition to a crystal arrangement is first order and persists down to zero temperature. This represents a genuine quantum phase transition that involves translational-symmetry breaking. It is analogous to Brazovskii's transition — where a uniform spatial distribution abruptly transforms into a stripe pattern[4]. This phase transition at zero temperature is solely driven by quantum fluctuations of the particle fields, which are dynamically amplified and develop into macroscopic spatial-density variations. (This resembles the way that large-scale structures are supposed to have appeared from quantum noise in the early Universe.) The spatial correlations and the form of the emerging structures are determined by the wavevectors supported by the optical-resonator geometry. With the help of extra confinement potentials for the particles that are introduced by light sheets, the dimensions of the emerging patterns can be externally controlled. Models with several interacting layered planes can be implemented.

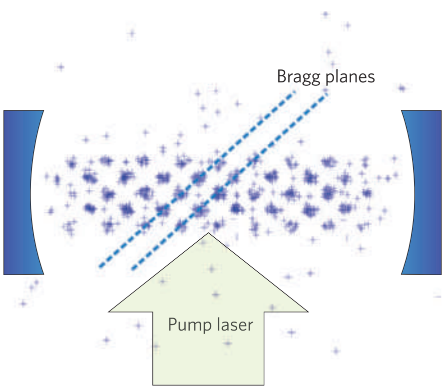

Figure 1 | Simulated stationary distribution of 1,000 high-field-seeking atoms in an optical resonator transversely illuminated by laser light. The atoms self-order in a crystalline structure with Bragg planes (dashed diagonal lines as a guide to the eye) maximizing the coherent scattering into the resonator mode as predicted and observed in refs 1 and 2.

As an extra bonus, the set-up includes a built-in non-destructive monitoring system by virtue of analysis of the scattered light fields. In particular, at near-zero temperature the scattered light contains clear signatures of the nucleation of new atomic quantum phases[5]. Thus, real-time non-destructive monitoring of the dynamics of a quantum phase transition can be foreseen.

As cavity quantum electrodynamics (QED) set-ups with single particles coupled to super-mirror resonators pose severe experimental challenges, theoretical considerations invoking degenerate quantum gases were long considered to be thought experiments only. However, using the recent exciting developments in the optical manipulation of ultracold gases, several teams have now implemented cavity-QED systems involving Bose–Einstein condensates and super mirrors. Up to a million atoms at close to $T = 0$ can be trapped in the field of a few photons (or even a single one)[6,7]. These experiments enter the strong-coupling regime where coherent quantum coupling dominates dissipation by more than three orders of magnitude. Here, the optical potentials and thus the light forces have genuine quantum properties so that the light and the particles become dynamically entangled. As a consequence, the dynamics can lead to superpositions of light-field states associated with different atomic quantum phases as an exotic form of a Schrödinger-cat state. The strong coherent coupling of atoms and photons can also be used as a controllable prototype interface of photonic- and atom-based quantum computing.

Whereas ultracold atoms interact directly only at close distances, the modification of the light field induced by a single particle influences the optical potential for virtually all other particles in the system[8]. This long-range interaction can be tailored through the mirror geometry, and acts in a similar way to acoustic phonons in solid crystals. This adds an extra dimension to optical-lattice physics with ultracold quantum gases, which is already one of the most fruitful areas at the boundary of atomic and solid-state physics[9], including the physics of phonons, polarons or momentum-space pairing of particles.

The tremendous recent progress has now surpassed the limits in readily available theoretical models. In complex field structures, such as those in degenerate multimode resonators, which involve both long-range interactions and short-range collisions in three dimensions, even powerful numerical solid-state methods such as the density matrix renormalization group are hardly applicable. The quantum field theoretical-path-integral-based methods presented by Gopalakrishnan *et al.* open a new route to theoretical analysis and even quantitative understanding of the underlying physical mechanisms. As an example, the authors study the formation of dislocations and domain boundaries in two-dimensional layered configurations that originate only from quantum noise in the zero-temperature limit. Ultimately, the corresponding experimental studies will, nevertheless, go beyond any theoretical predictability and allow us to simulate and study new solid-state and field-theoretical phenomena in a precisely controllable and directly observable fashion. ❒

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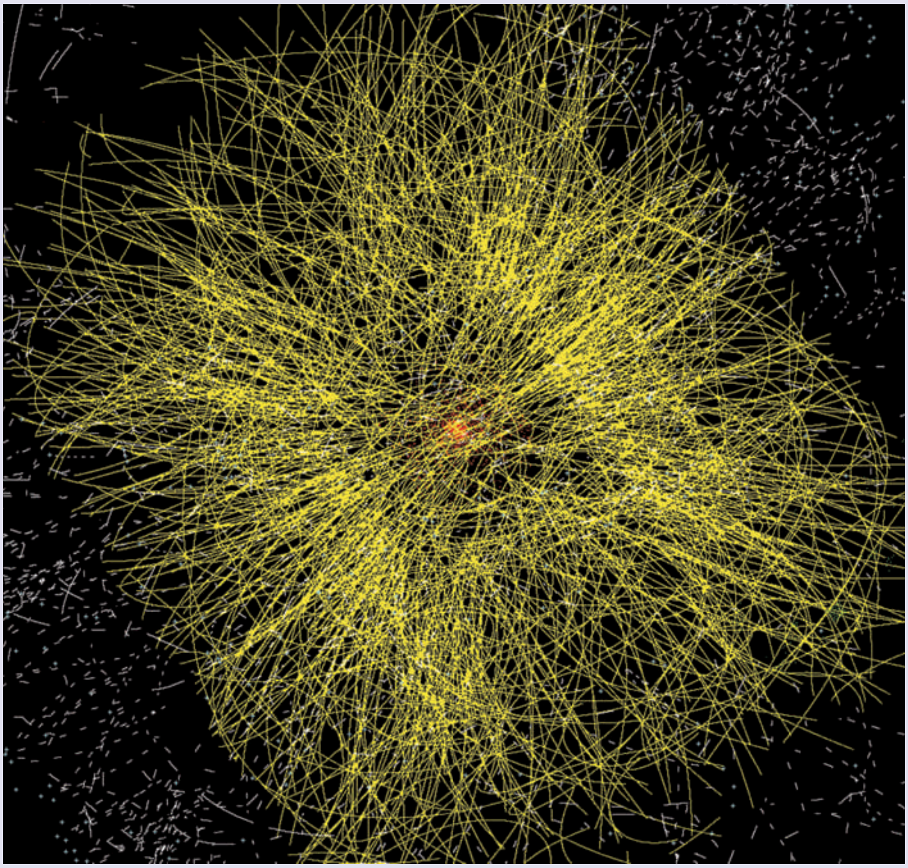
PARTICLE PHYSICS

Environmental concerns



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CERN's Large Hadron Collider (LHC) will fire up again this month, with its three detectors, ATLAS, CMS and LHCb, poised to begin close monitoring of the proton–proton collisions in pursuit of such novelties as supersymmetry and the Higgs boson. Also part of the programme are 'heavy ion' collisions — using the LHC to collide lead ions instead of protons, in the hope of creating quark–gluon plasma — for which a dedicated detector called ALICE has been built.

Heavy-ion physics poses particular challenges, owing to the terrific density of quarks and gluons involved in each collision. ALICE will have to cope with a multitude of tracks from the particles produced, as pictured in this simulation. For theorists, modelling the process is also tricky, but Korinna Zapp and colleagues have a proposal that may help (*Phys. Rev. Lett.* **103,** 152302; 2009).

Quarks and gluons (known collectively as partons) emerging from any type of collision may radiate a gluon. This can happen repeatedly, to create what is known as a parton shower; eventually the partons will group together (or 'hadronize') to form the composite particles that are observed in detectors. The process can be quite effectively modelled when the colliding particles are electrons or protons, but in the heavy-ion case the parton shower develops in a 'dense QCD-matter' environment, packed with other quarks and gluons that may also be radiating.

Zapp *et al.* have devised an algorithm to take account of the non-Abelian Landau–Pomeranchuk–Migdal effect — or rather, the quantum interference between spatially separated incidences of gluon radiation — which occurs in such an environment. They define a 'gluon formation time', based on the gluon energy and the transverse momentum of the gluon radiated previously. The Landau–Pomeranchuk–Migdal effect is then accounted for by requiring that, for a gluon radiated within the formation time, the momentum transfer is coherent; and for a gluon radiated later than the formation time, it is incoherent.

The algorithm can be incorporated straightforwardly in so-called Monte Carlo simulations of heavy-ion collisions, ahead of the first heavy-ion run at the LHC, scheduled for late 2010.

ALISON WRIGHT