QUANTUM PHYSICS

Atoms in chequerboard order

Cheng Chin and Nathan Gemelke

Bose–Einstein condensates are ideal tools with which exotic phenomena can be investigated. The hitherto-unrealized Dicke quantum phase transition has now been observed with one such system in an optical cavity.

In 1954, Robert H. Dicke at Princeton University, inspired by his work on coherent microwave radiation from ammonia molecules, conceived a fascinating phenomenon[1]. He predicted that a dense, extremely elongated cloud of atoms, once excited by light, could decay radiatively by spontaneously emitting photons along the cloud's long axis, much like a firecracker or sparkler ignited at both ends. Dicke named this effect superradiance — 'super' because the collectively emitted photons would form electromagnetic waves that are coherent (the waves' peaks and troughs line up), in contrast to photons emitted by independently decaying atoms, which generally form incoherent waves.

One of the cleanest demonstrations of superradiance was based on a Bose–Einstein condensate (an ultracold sample of atoms all in the lowest-energy quantum state) placed in a cigar-shaped magnetic trap[2]. On page 1301 of this issue, Baumann and colleagues[3] show that when a condensate is sandwiched between two highly reflective mirrors (an optical cavity) and is appropriately illuminated with incident laser light, superradiance also occurs and is accompanied by a spontaneously broken spatial symmetry. What's more, the symmetry breaking is immediately followed by a quantum phase transition of the atoms from a superfluid state, in which the atoms flow en masse without friction, to a supersolid state — a superfluid with non-trivial long-range atomic density order.

This amazing streak of quantum wonders comes from the mere addition of an optical cavity. The cavity greatly enhances the superradiance because the emitted photons are bounced back and forth between the cavity's mirrors, repeatedly traversing the condensate. Just as a person in a lift with two parallel mirrors sees infinite self-images, in the optical cavity many mirror images of the condensate are formed. Together, these images make the condensate look like an extremely elongated sample, providing an excellent condition for superradiance.

Baumann *et al.*[3] show that an optical potential, formed by adding the incident and superradiated light, can easily redistribute atoms in a condensate. Interestingly, depending on the relative optical phase of the superradiated light (0 if the waves' peaks line up exactly with those of the incident light, and π if the peaks lie in the incident light's troughs), the atoms self-organize into one of two distinct chequerboard patterns of a two-dimensional square lattice (Fig. 1). Even more amazingly, when the atoms do so, they further enhance the superradiance of the type that supports the chequerboard. Small quantum fluctuations in the condensate's density that favour one optical phase over the other can grow exponentially and lead to a runaway dominance of

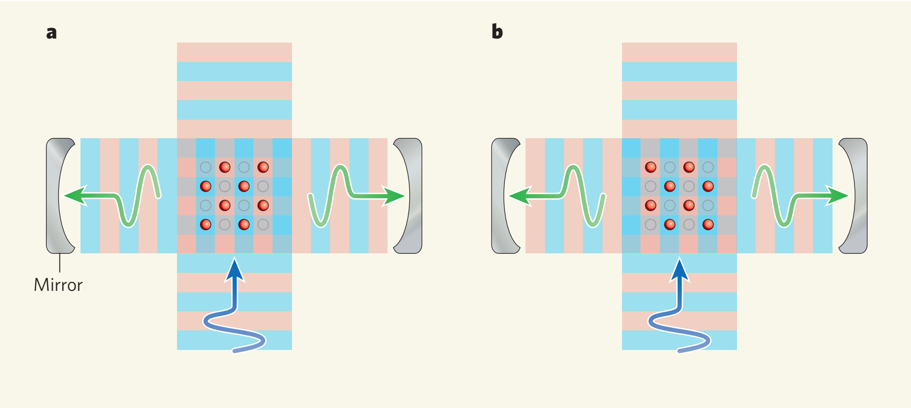

Figure 1 | Chequerboard ordering of atoms in an optical cavity. Baumann and colleagues[3] show that, when a Bose–Einstein condensate of atoms is placed between two highly reflective mirrors (an optical cavity) and is illuminated with laser light (blue arrows) of sufficiently strong intensity, it 'superradiates' light into the cavity (green arrows). Depending on whether the superradiated light waves' peaks line up exactly with those of the incident light (**a**; compare blue and green waveforms) or whether the peaks lie in the incident light's troughs (**b**), the condensate's atoms self-organize into one of two distinct chequerboard patterns, **a** or **b**, of a square lattice formed by the combination of the incident and superradiated light. Red filled circles denote higher atomic density, and open circles represent lower density.

50 & 100 YEARS AGO

50 YEARS AGO

'A possible fundamental in the behaviour of young nidifugous birds' — One of the most significant behaviour patterns observed is one which occurs immediately upon hatching. I propose to call this the 'brooding reflex' because it seems to be the mechanism whereby the newly hatched duckling orientates itself to the position of optimum warmth and mechanical protection beneath the female. It involves an active search by the duckling for a feeling of enclosure around the head or part of the head ... Thus, a duckling a few seconds after hatching on my hand would actively follow my other hand once I had held its head between finger and thumb. A state of rest, or even of sleep, could be released in the ducklings merely by providing this contact stimulus on two sides of the head or bill ... I found that I could release a similar quiescence in wild juveniles ... To date, this response has been positive in every nidifugous juvenile I have handled ... It would appear to be a fundamental behaviour activity which has been previously overlooked.

From *Nature* 30 April 1960.

100 YEARS AGO

'The total solar eclipse of May 8, 1910' — This eclipse, which can be observed from Tasmania, is not a very favourable one, because the sun at the critical time is only about 8° above the horizon. Mr. Frank McClean, however, who has made considerable preparations for observing it, is already in Tasmania ... Little is known at present about the site, but in a letter ... he writes that one of his party "is as strong as a horse," and will be exceedingly useful "when we have to clear the 200-feet high trees out of the way and carry the packing cases up a 600-feet hill." It will thus be seen that he is making every endeavour to secure as good a site as possible, and it is hoped that his energy will be rewarded with success.

From *Nature* 28 April 1910.

GEOCHEMISTRY

The mystery of Don Juan Pond

Naturally occurring nitrous oxide, a potent greenhouse gas, is mainly produced by biological processes. So how can it have formed in high concentrations in one of the harshest environments on Earth, a place where attempts at finding life have failed? Writing in *Nature Geoscience*, Vladimir Samarkin *et al.* provide the answer: an unexpected abiotic mechanism for nitrous oxide production (V. Samarkin *et al. Nature Geosci.* doi:10.1038/NGEO847; 2010).

The authors report their discovery of nitrous oxide emissions from the soil around Don Juan Pond in Antarctica (pictured), a lake that is so salty it almost never freezes, even in the cold Antarctic winter. Surprisingly, Samarkin and colleagues found that the flux of gas from the lifeless soil was comparable to that of certain tropical soils that teem with microorganisms. An abiotic process must be the source, but no such process was known.

Samarkin *et al.* realized that the environment of Don Juan Pond

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contains chemical ingredients that might take part in reactions that produce nitrous oxide: nitrate and nitrite salts in the brine, and iron(II) salts in the rocks around the pond's edges. Back in the laboratory, they found that nitrous oxide was indeed immediately produced when they mixed sterile brine from the pond with minerals found in the pond's vicinity, and at temperatures as low as −20 °C. Hydrogen gas was also produced.

The newly discovered process for nitrous oxide production might well occur elsewhere on Earth. More intriguingly, the authors propose that it may also occur on Mars, which harbours minerals, brine geochemistry and sub-zero temperatures remarkably similar to those at Don Juan Pond.

Andrew Mitchinson

all atoms in one chequerboard pattern. This macroscopic dominance of one optical phase demonstrates that a spatial symmetry in the condensate's underlying optical lattice is spontaneously broken. This symmetry breaking was also observed in an earlier experiment based on thermal atoms in a cavity[4].

The strong coupling between photons and the condensate that can be achieved in the cavity suggests that the symmetry breaking must also be accompanied by the appearance of a new symmetry by means of a quantum phase transition in the condensate. Baumann and colleagues[3] present an intuitive picture of the process. They describe the superradiant light as a means of introducing long-range interactions between the atoms. As photons traverse the condensate multiple times, they introduce effective atomic interactions of nearly infinite range that ultimately drive the system to undergo a 'Dicke quantum phase transition'[5] into a supersolid state. Unlike conventional phase transitions (for example, liquid to solid transitions and Bose–Einstein condensation), which are driven by thermal fluctuations at finite temperatures, quantum phase transitions such as the Dicke phase transition observed by the authors are triggered by quantum fluctuations.

To observe the chequerboard density pattern and the emergence of the supersolid phase, Baumann *et al.* used time-of-flight imaging. This technique consists of releasing the condensate into free space, letting it expand and taking images of its atoms at a much later time, which reveal the so-called diffraction pattern. The authors observe a clear diagonal diffraction pattern in the images after the onset of superradiance. This pattern is in full agreement with the expected chequerboard density order and signals the appearance of a new symmetry by means of a quantum phase transition in the condensate. Taken together with the images' high contrast, the observed diagonal pattern makes a strong case that a Bose–Einstein condensate in an optical cavity develops supersolid order through a superradiance-induced quantum phase transition.

Many questions remain to be addressed, including the dynamics of both the symmetry breaking and the Dicke quantum phase transition and especially the robustness of the supersolid phase of atoms in the cavity. However, Baumann and colleagues' demonstration of a fascinating interplay between superradiance, spontaneous symmetry breaking, a quantum phase transition and supersolidity in a condensate inside a cavity portends an exciting future for research in quantum optics. Although much is to be learned about quantum phase transitions in open systems, as well as about supersolidity, the authors' work[3] represents a milestone in the quantum wonderland of ultracold atoms enclosed in a cavity. ■

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NEUROSCIENCE

Each synapse to its own

Nicholas J. Priebe and David Ferster

A neuron can receive thousands of inputs that, together, tell it when to fire. New techniques can image the activity of many inputs, and shed light on how single neurons perform computations in response.

Synaptic communication between neurons is fundamental to how the brain processes and transforms information. Uncovering the neural circuitry has therefore been a major endeavour for neuroscientists, to understand the neural basis of perception and action. In this issue (page 1307), Jia *et al.*[1] present one of the most detailed views of synaptic integration within the brain so far, addressing a classic and vigorously debated question in sensory system physiology: how do neurons in the primary visual cortex acquire orientation selectivity?

For the past two decades, mammalian brain slices have been an essential tool for studying neural circuitry. Slice experiments have revealed the functional diversity of synapses, synaptic integration within the neuronal branches that constitute a dendritic tree, how voltage-gated currents in the dendrites shape integration, and how activity-dependent changes in synaptic strength might contribute to memory formation and to development. But the physiological model that the brain slice provides comes at a cost, as natural neural connections are lost when the slice is prepared. It has therefore been difficult to determine which of the above features are crucial to the function of neurons in the intact brain, and how they would interact in response to naturally driven activity.