

## QUANTUM OPTICS

## Light does matter

Strongly correlated systems are difficult to control or even probe at the level of individual interacting elements. Engineered composites of optical cavities, few-level atoms, and laser light could enable greater insight into their behaviour.

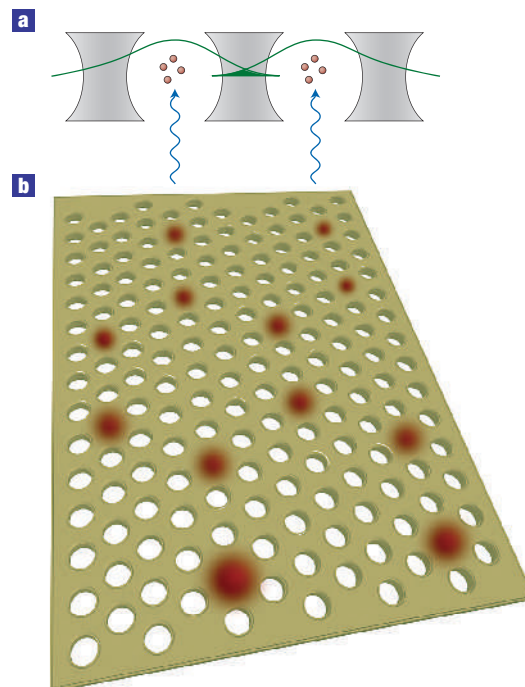
## FABRIZIO ILLUMINATI

is in the Quantum Theory Group, Department of Physics,  
University of Salerno, Baronissi 84081, Italy.

e-mail: illuminati@sa.infn.it

The quest to understand the mechanisms responsible for the behaviour of strongly correlated systems is at the heart of condensed-matter physics. But because of the small distance over which strong correlations persist between the elements of most natural solid-state systems, usually of the order of just a few nanometres or less, manipulating or even just measuring the detailed properties of individual microscopic constituents is challenging, making it difficult to obtain detailed insight into the nuts and bolts operation of such systems. Rather than wait for the development of improved techniques to control and study the behaviour of conventional strongly correlated systems at the deep microscopic level, two studies in this issue — one on page 849 by Hartman and colleagues<sup>1</sup>, and the other on page 856 by Greentree<sup>2</sup> and colleagues — propose to simulate and study this behaviour using a potentially more easily probed physical system, that of an array of coupled optical cavities driven by external laser light.

The past ten years have seen astounding advances in our ability to manipulate the properties and behaviour of atomic systems in interaction with light. Most notably, it has led to the ability to construct an artificial array of ultracold atoms trapped in optical lattices — periodic potentials generated by the controlled interference of multiple laser beams. Systems of atoms trapped in this way can be used to simulate basic systems of condensed matter and to manufacture their mutual interactions with an unprecedented degree of control, purity and isolation from the environment. It has been predicted that interacting neutral bosonic atoms in optical lattices of increasing depth<sup>3</sup>, should exhibit a behaviour that is directly analogous to the archetypal Mott transition, in which a system goes from a coherent, superfluid regime characterized by enhanced atomic tunnelling between lattice sites, to an insulating phase characterized by strong on-site interatomic repulsion<sup>4</sup>. These predictions were verified with spectacular success in experiments conducted just a few years ago, in which a condensate of neutral bosonic atoms was



**Figure 1** Schemes to simulate a strongly correlated system with light. **a**, The interaction of the optical modes of a high-quality optical cavity and the electronic states of atoms contained within these cavities, give rise to a composite optical–atomic state, known as a polariton state. The relatively large distance over which the polaritonic states can overlap allows polaritons to hop between adjacent cavities, whereas the atoms inside each cavity, driven by an external laser field, give rise to on-site self-interaction of the polaritons. **b**, An array of such cavities, as in a photonic crystal (shown) or a matrix of microresonators, should exhibit analogous behaviour to a strongly correlated solid-state system, but should be much easier to study, because the distance between adjacent cavities (sites) can be made much larger than the optical wavelength of the resonant cavity mode, making it possible to discern and manipulate individual sites in the array. (Part **a** reproduced from reference 1. Part **b** reproduced with permission of A. D. Greentree.)

loaded in a three-dimensional cubic optical lattice, and then, by increasing the height of the potential barriers between adjacent sites, the system was driven through a quantum phase transition from a superfluid to a Mott insulator<sup>5</sup>.

Such success has ignited a tremendous burst of theoretical and experimental activity in the simulation of strongly correlated systems using atomic systems in optical lattices. This has led to significant proposals for constructing analogues that exhibit a variety of important solid-state phenomenologies, including: the emergence of superconducting behaviour — involving either BCS-type or *d*-wave pairing transitions — in systems of neutral fermionic atoms in optical lattices<sup>6</sup>; high-temperature atomic superfluidity and other exotic phases in mixtures of fermionic and bosonic atoms in periodic lattice structures<sup>7,8</sup>; and the onset of statistical complexity for atomic systems loaded in disordered and random optical lattice potentials<sup>9,10</sup>.

Despite this progress, and the fact that optical lattices provide a more versatile platform for the

study of strongly correlated behaviour than natural solid-state systems, gaining access to individual elements (sites) of such lattice systems is still difficult. To overcome this difficulty, Hartmann *et al.* and Greentree *et al.* both propose a system whose elements consist of high-quality optical cavities that contain atoms of appropriate level structure. When stimulated with light, the interaction of each cavity with an ensemble of these atoms gives rise to a composite optical–atomic state, known as a polariton. The extended nature of such a state allows tunnelling between adjacent cavities; at the same time, the distance between two adjacent cavities can be made much larger than the optical wavelength of the resonant cavity mode, so that individual cavities can be effectively addressed (see Fig. 1). By constructing a regular array of optical cavities — which could take the form of a grid of whispering-gallery-mode microcavities fabricated in silica<sup>11</sup> or defect cavities formed in a two-dimensional photonic-crystal slab<sup>12</sup> — the authors suggest that a polariton-based simulator of interacting bosonic matter could be realized. Through detailed theoretical analysis they show that by applying an appropriately tuned laser field of increasing strength, the system can be driven to undergo a quantum phase transition from a superfluid to a Mott insulator phase. Most importantly, they show that such a behaviour could be realized in a system

whose elements can be individually probed, and even controlled.

Whether or not a polariton-based system for exploring strongly correlated behaviour proves to be more experimentally tractable than other proposals still remains to be seen. But if it does, it could provide fascinating new insight into a range of fundamental phenomena in condensed-matter physics, and it could also open the way to constructing practical devices for quantum optical and quantum information processing applications.

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