Instituto de Física Teórica
UAM-CSIC

Quantum Matter

The new states of matter

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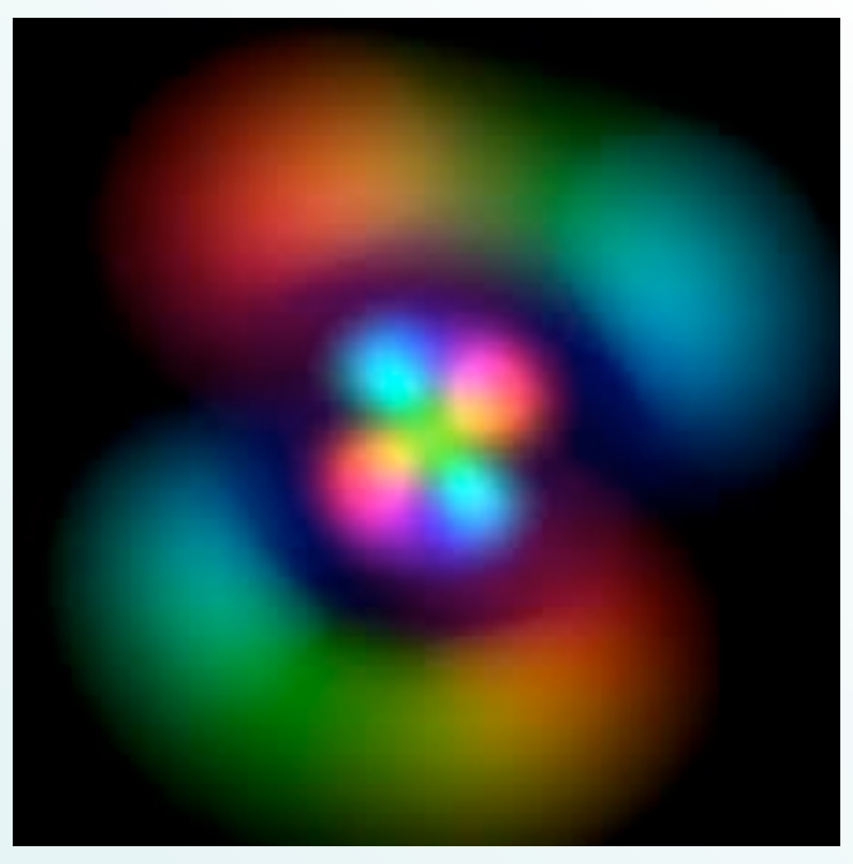
Consejo Superior de Investigaciones Científicas

Quantum Physics

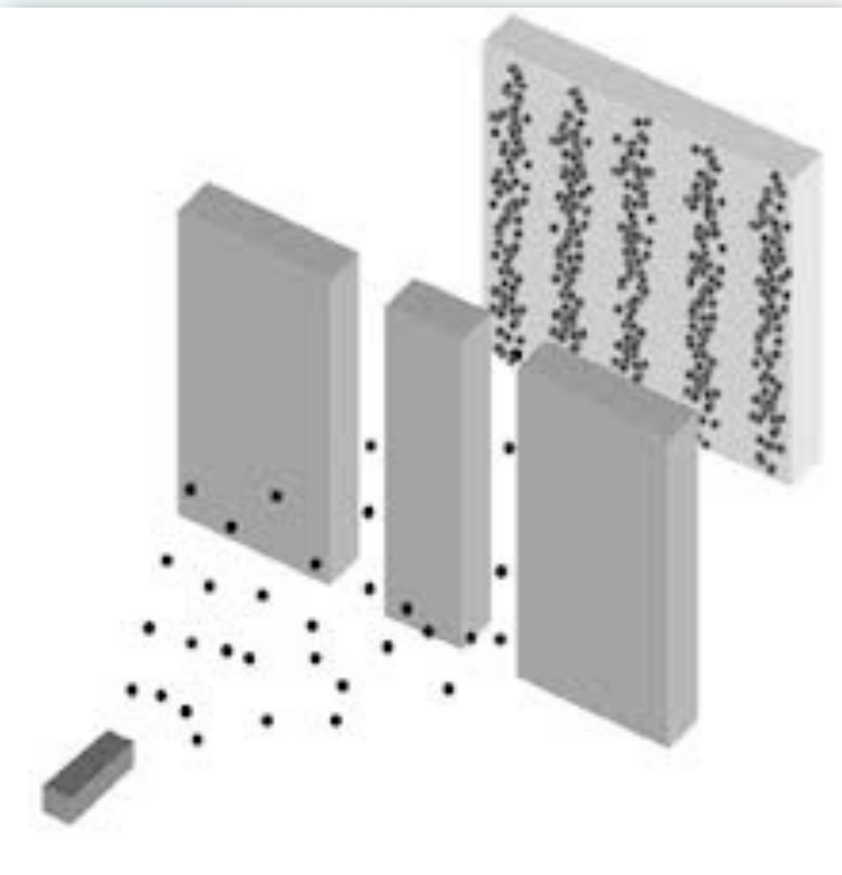
The quantum atom

The dynamics of subatomic particles is ruled by Quantum Mechanics. One fundamental quantum law is the superposition principle, which allows a quantum system to simultaneously exist in (a superposition of) several states. For instance, electrons in an atom do not describe orbits with well-defined positions and velocities; actually, each electron is in a quantum superposition of all the different positions. These orbitals are quantum superpositions in which the position and the momentum are not well-defined (but other quantities, like their energy and angular momentum, are), and are properly described in terms of wavefunctions.



The double slit experiment

The superposition principle is manifest in the phenomenon of interference. If you imagine shooting quantum particles to a double slit, the impact probability on a screen behind shown an interference pattern, with regions of high and low impact probability. This phenomenon works like the diffraction of light, but for the wavefunctions of particles (and underlies wave-particle duality). The interference implies that each particle crosses the two slits simultaneously; in other words, it is in a superposition of the states of having crossed each of the two slits in their way to the screen.



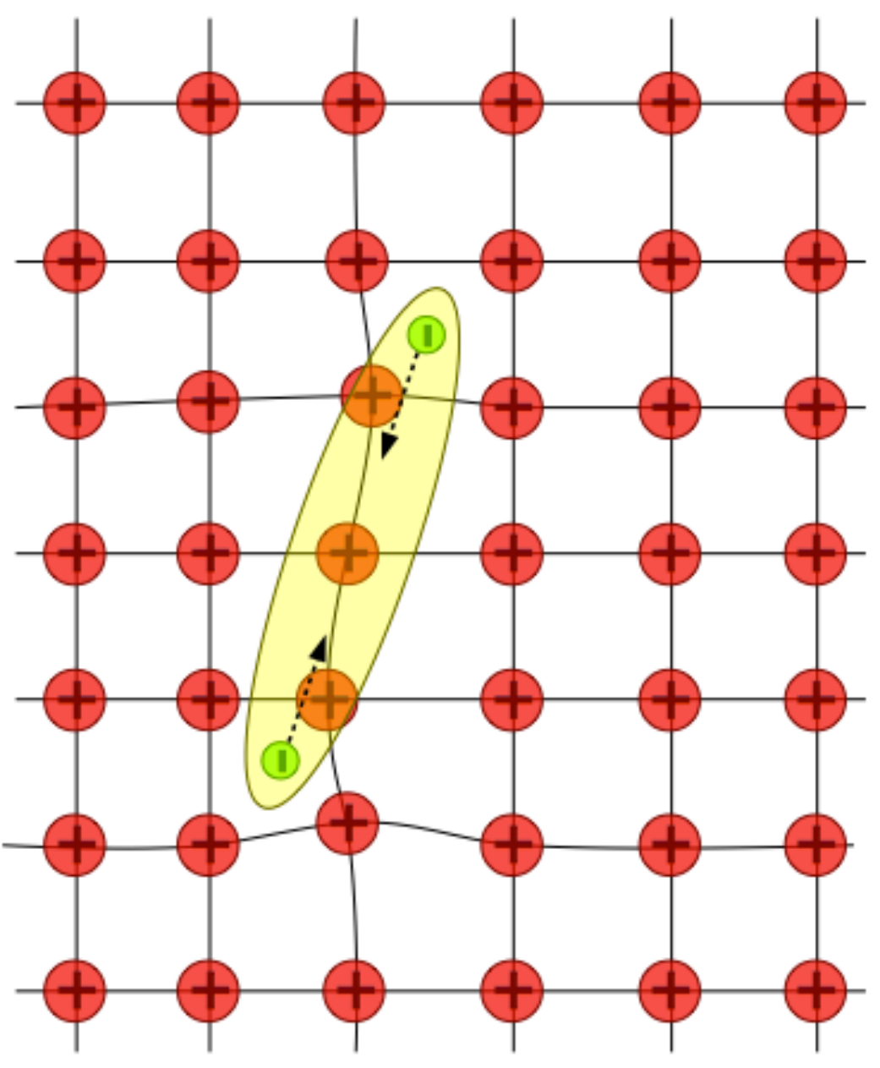
Emergence of collective phenomena and quasiparticles

Quantum Mechanics also has surprising implications when applied to many-body systems, as in the field of Condensed Matter Physics (which studies the properties of materials from the dynamics of their constituent particles). Oftentimes, there is **emergence of collective phenomena** involving **entanglement** or correlation of many particles, and which modify the macroscopic properties of the material.

An analogy of collective phenomena and emergent properties is a chess game: the very simple rules to move each piece can correlate to form strategies of enormous complexity and beauty, with their own set of properties.

An example of collective behavior is **superconductivity**, in the BCS model. When certain materials are cooled below a critical temperature, their electrons can feel an attractive force due to a collective motion of the underlying lattice, which allows pairs of electrons to bing into a so-called Cooper pair. Cooper pairs subsequently experience Bose-Einstein condensation, so all pairs in the material move coherently and can transport electrical current without dissipation or resistence.

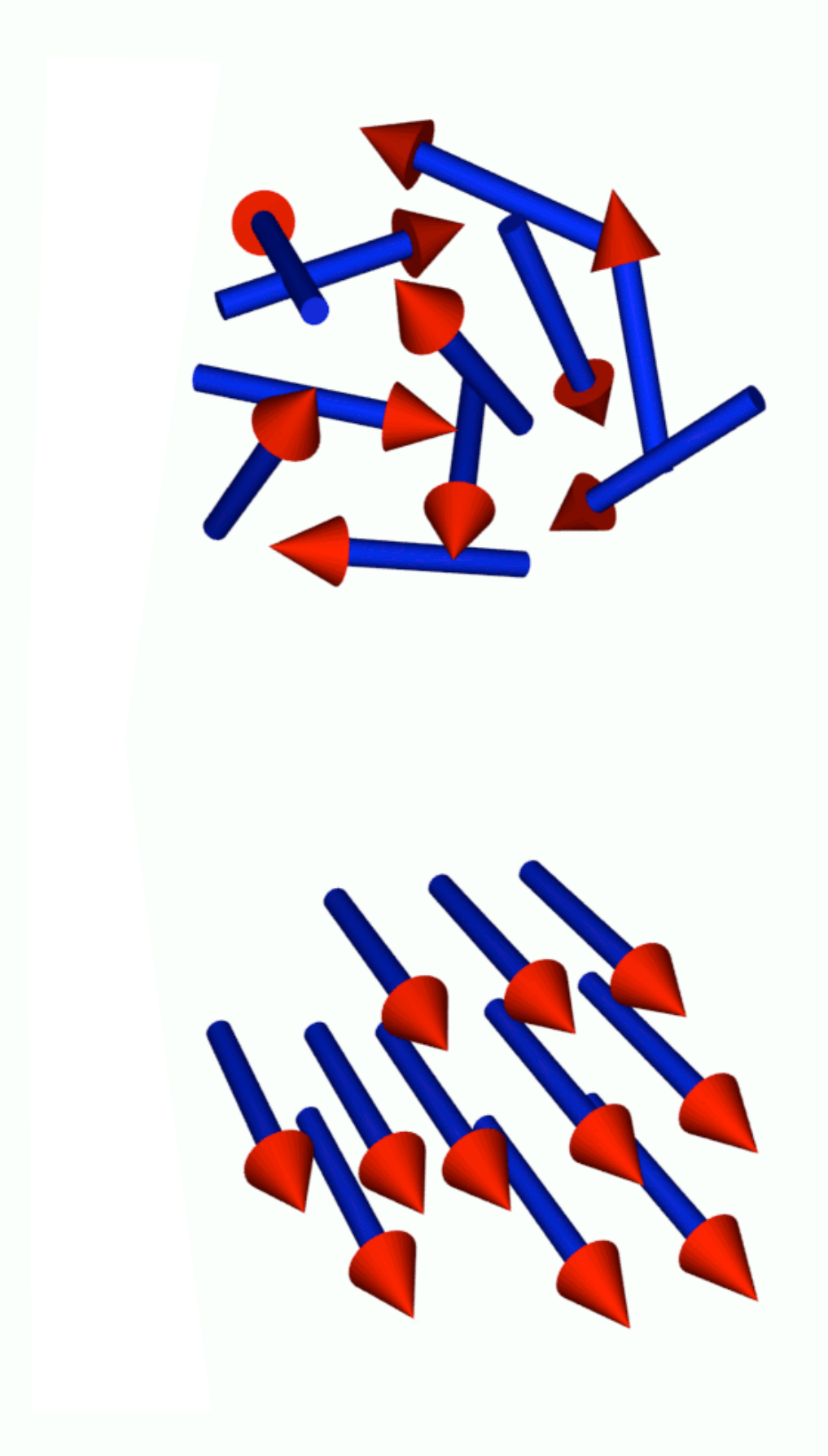
The effective excitation in a system with collective behavior are known as **quasi-particles**. In an oridnary metal, the quasiparticles are electrons of the same electric charge and spin as free electrons, but with a different mass due to interactions. On the other hand, in a two-dimensional electron gas subject to a strong magnetic field, the quasiparticles are collective excitation with fractional electric charge (quantum Hall effect).



Symmetry breaking vs. topological order

Many properties of materials and their phase transitions can be understood in terms of spontaneous symmetry breaking. For instance, a permanent magnet is characterized by the fact that the magnetic moment of its constituent particles is not distributed randomly (thus in a rotationally invariant way, from the macroscopic viewpoint), but rather they aligh in a specific direction (thus breaking rotational symmetry). Also, the superconducting phase in the BSC model is characterized by the fact that the Cooper pair condensate breaks spontaneously the symmetry associated to the electromagnetic interaction (and gives the photon an effective mass, in an analogue of the Higgs mechanism in Particle Physics).

However, there exist materials with phases which cannot be characterized in this fashion, and require the introduction of a new concept: topological order. This characterizes new states of matter (*quantum matter*) not according to symmetries broken by condensates, but in terms of topological invariants of the quantum state of the constituent particles. The notion of “topological invariant” means that the corresponding property does not change when the system is perturbed (for instance, by the thermal fluctuations due to the finite temperature).

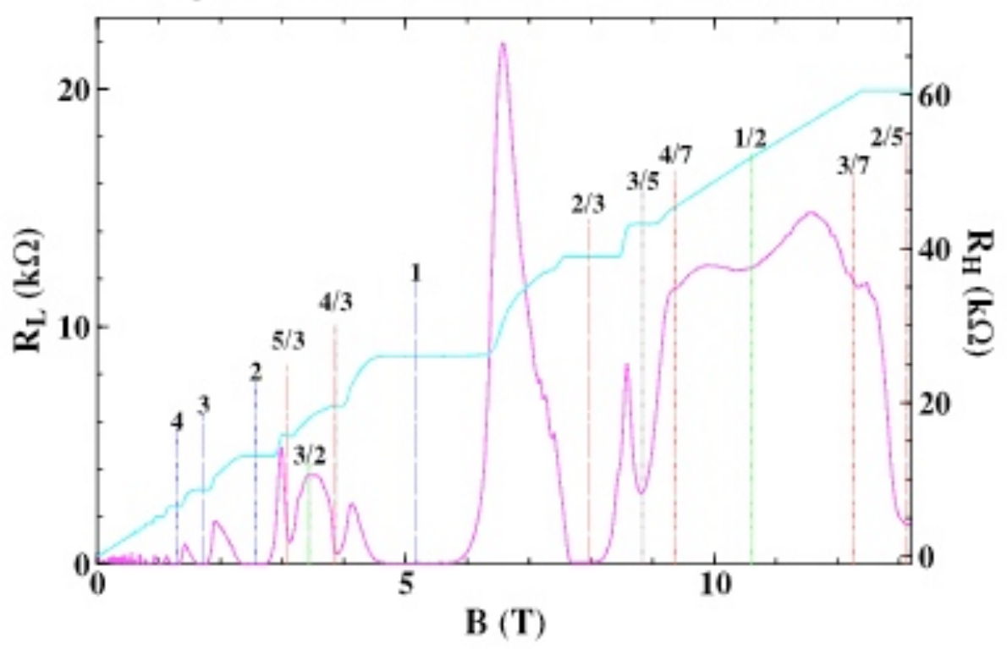


Quantum matter

The theoretical formulation and experimental study of systems with topological order is a most active field of research. Some of these systems are related to quantum versions of the Hall effect. This occurs when a magnetic fields, applied on a 2-dimensional material carrying an electric current, induces a second electric current in a transverse direction.

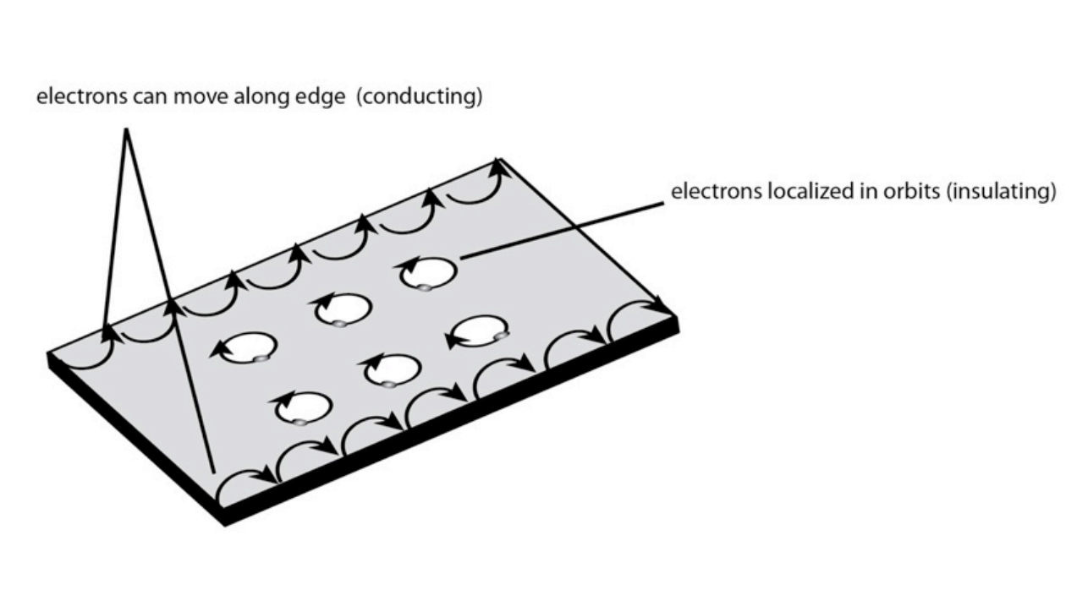
- In the integer quantum Hall effect, the conductivity in the transverse direction is quantized and can take values only in integer multiples of a basic unit (or quantum). It arises at low temperatures and sufficiently high magnetic fields. It is interpreted in terms of quasiparticles formed by bound states of electrons and magnetic field flux quanta.

-In the fractional quantum Hall effect, the conductivity is quantized in fractions of the earlier quantum. It is interpreted in terms of a new kind of quasiparticles, the **anyons**, which have the property of behaving neither like bosons nor fermions, something possible only in two (or lower) dimensions.



Other interesting systems with topological order are topological insulators. These materials are isolators in their bulk, but conductors on their surface, due to the presence of localized quasiparticles which can carry electric current. The existence of these “edge states” is associated to certain topological invariants.

Topological instulators include diverse material of timely interest, like graphene.



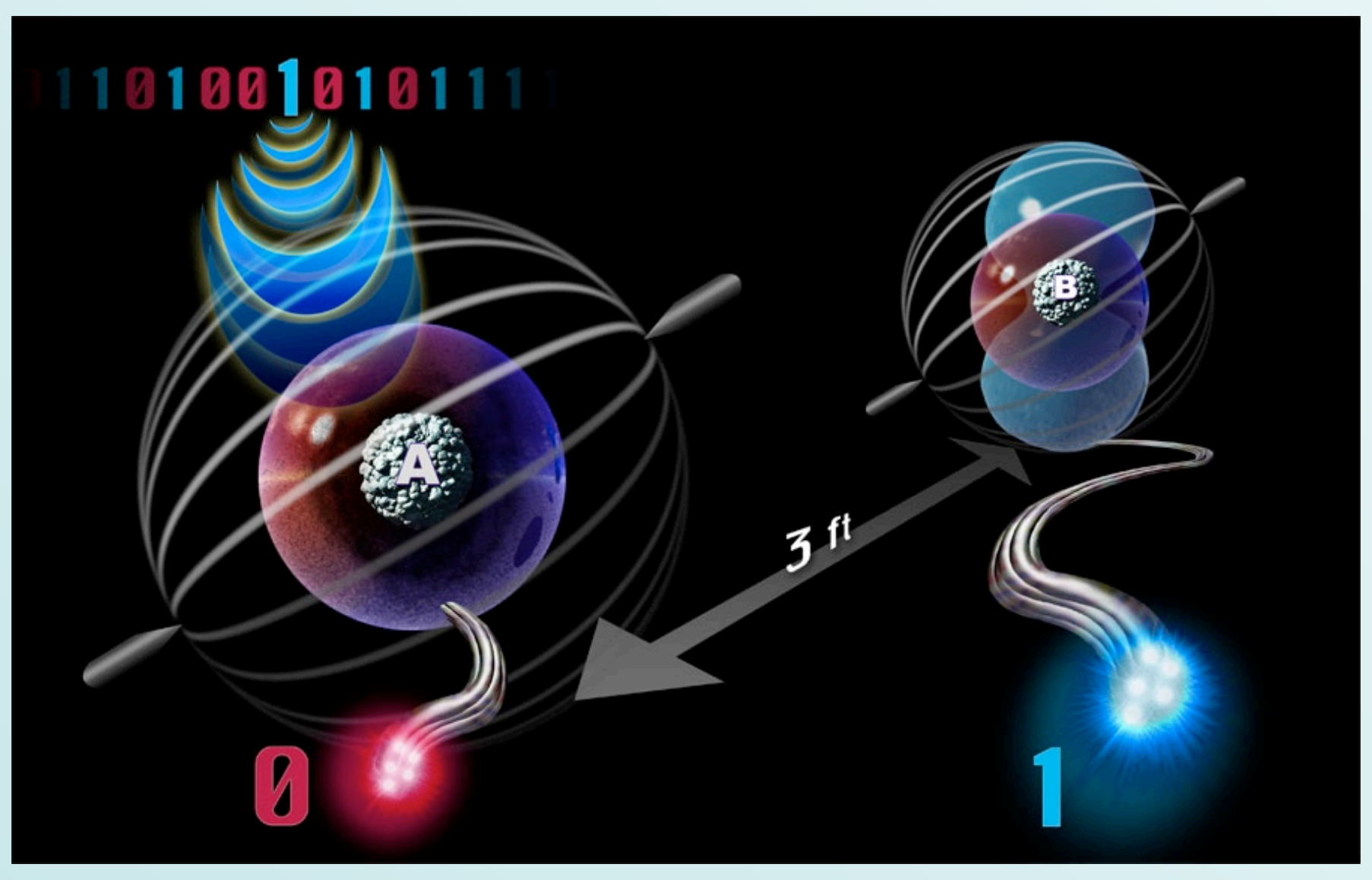
Entanglement and qubits

The property of quantum entanglement refers to systems with several particles which are in a quantum superposition which cannot be decomposed into a product of states for the individual particles.

In entangled states, the set of particles is in a combination of the possible states for the system. This observation has triggered the birth of the very active field of Quantum Computing. It puts forward the use of quantum devices to carry out computations. Its advantage, as compared with traditional computers, is that, thanks to the quantum superposition of states, it can carry out many different computations simultaneously. The basic unit of quantum information is called a qubit, and corresponds to a quantum object in superpositions of two states (0 and 1).

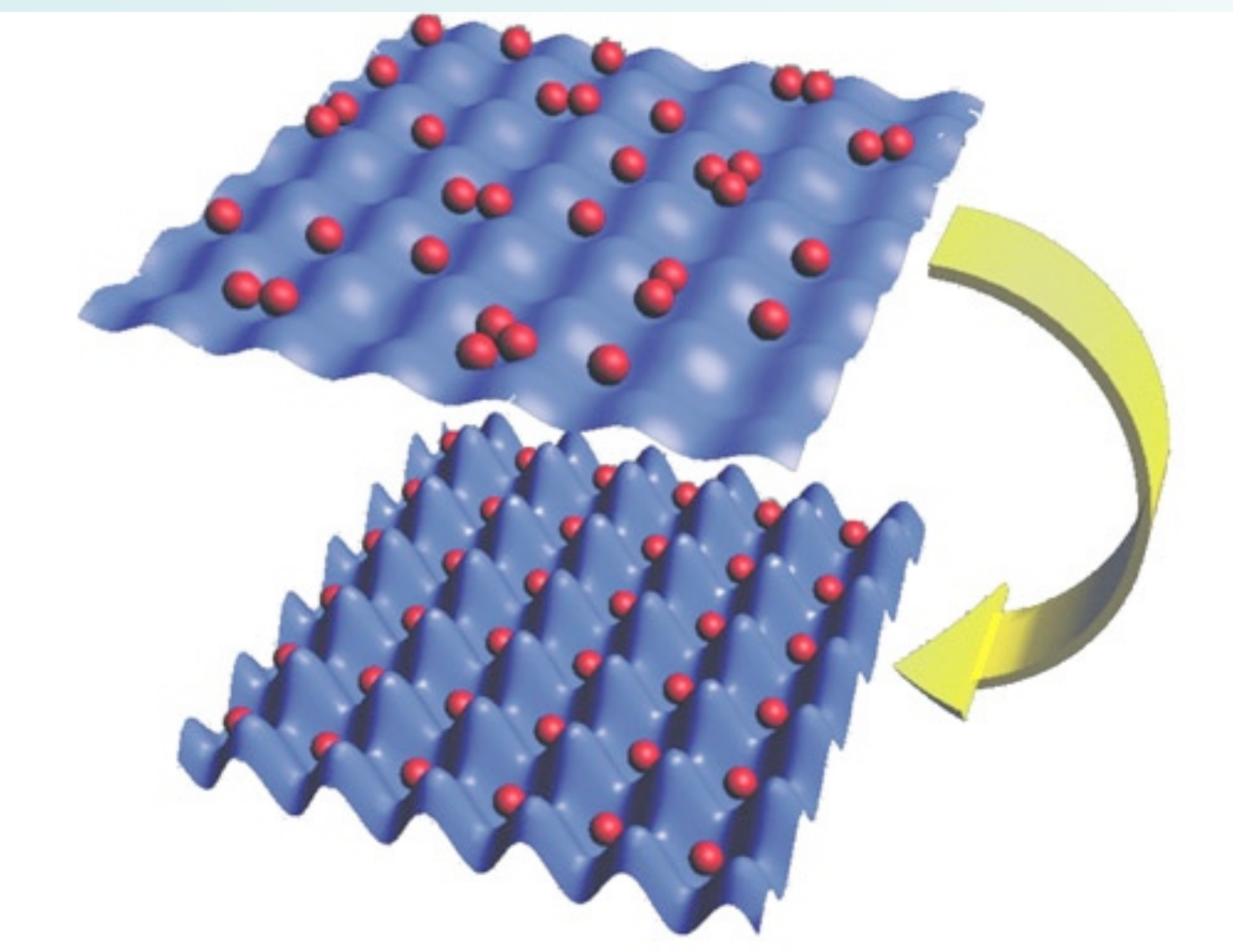
There are quantum algorithms which allow to solve certain problems at a speed substantially higher than classical algorithms. For instance, the decomposition of a number into prime factors (a problem of enormous relevance in the field of cryptography and digital security).

Another examples is the quantum state formed by the superposition of prime numbers, which would allow to test the Riemann hypothesis beyond any classical algorithm.



Quantum simulators

Using crossed lasers and their interference pattern, it is possible to device and realize *optical lattices* in which sets of individual atoms can be trapped. The parameters of the system, like the lattice geometry and spacing, and the potential barriers between neighboring nodes, are adjustable. This technique allows to device quantum systems simulating materials with novel properties, and to study their phase transitions as parameters are tuned (quantum phase transitions at zero temperature).

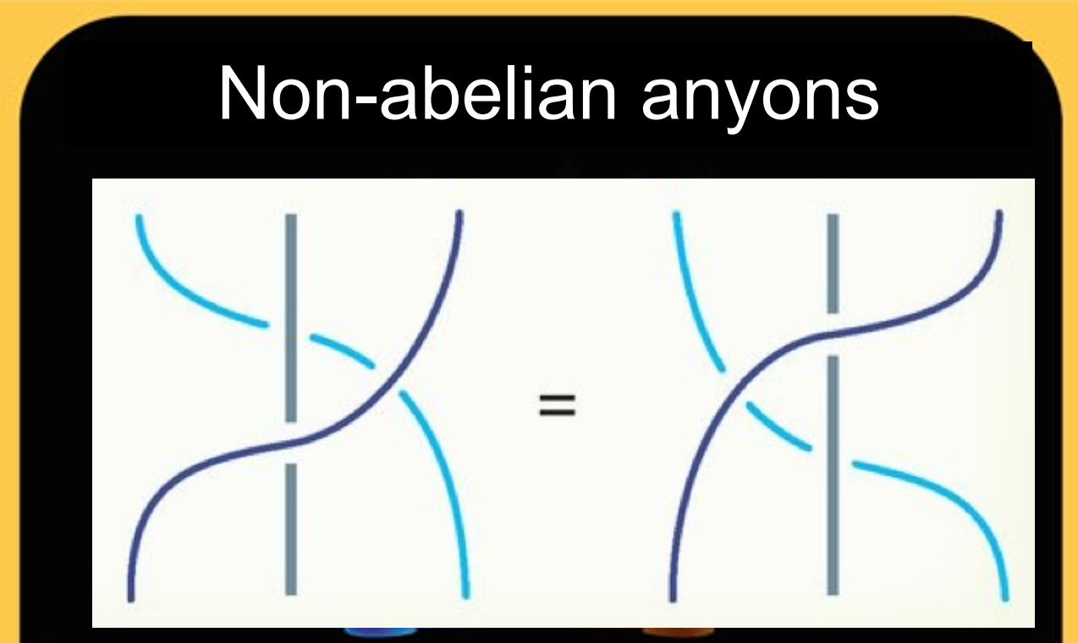


Open puzzles

Topological Quantum Computation

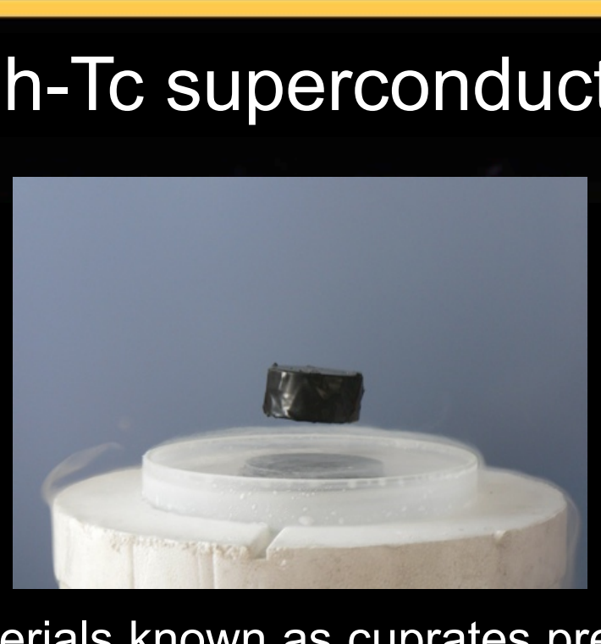
The construction of qubits in systems with topological order would allow storage and use of quantum information in a robust way under perturbations spoiling the quantum coherence, improving over other realizations of qubits.

Non-abelian anyons



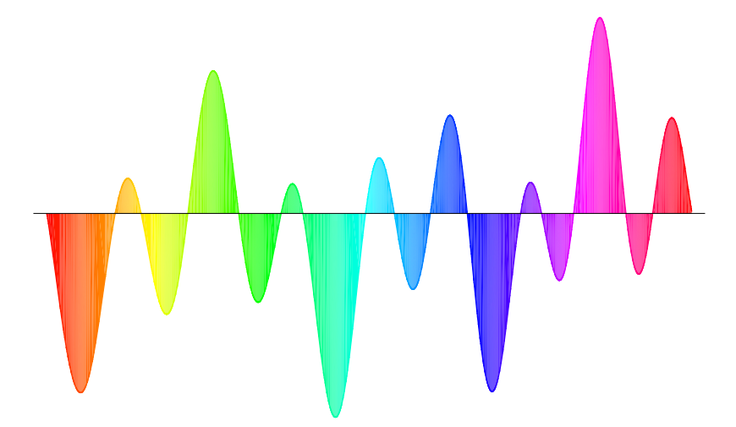
There are theoretical formulations of non-abelian anyons, for which the operations of pairwise exchange of particles are non-commuting, but obey braiding. The experimental search of materials with such quasiparticles is a promising entreprise.

High-Tc superconductors



The materials known as cuprates present a n intricate phase diagram, with superconductor phases, along with antiferromagnet and strange metal phases, whose quasiparticles present unusual behaviors. The characterization of these systems remains an open problem.

The Riemann hypothesis



There are reasons to expect that zeroes of Riemann’s zeta function are the spectrum of a quantum Hamiltonian. This would provide a physical proof of Riemann’s hypothesis, which has deep implications in branches of Mathematics, like Number Theory and Quantum Chaos.

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