A new Hall for Quantum protection

Long-range vacuum fluctuations break the integer quantum Hall topological protection

By **Angel Rubio**

Cavitronics—a portmanteau of cavity, materials, and photonics—are devices whose electronic properties can be controlled by the light waves bouncing inside the cavity the device sits in. In quantum mechanical terms, this interaction between light and matter is done via the so-called vacuum field-states (that are standing-light wave modes inside the cavity). A major advantage of this setup for generating light-matter coupling is the ability to induce certain properties inside a material that otherwise require the use of a strong external electric or magnetic field. On page XXX of this issue, Appugliese *et al.* [1] provide a unique case of cavitronics. Their experimental setup modifies one of the most prominent quantum phenomena in materials known as the quantum Hall effect. They found a drastic change in its Hall resistance, opening the path to designing materials functionalities by vacuum-field engineering.

When an electric current is passed through a conductor under the influence of a magnetic field, an electrical voltage perpendicular to the current is induced by the magnetic field. This is known as the Hall effect. However, this "sideways" voltage sometimes happens in steps rather than linearly as function of magnetic field [2,3]. This constitutes the quantum Hall effect (QHE), namely a quantized version of the classical Hall effect [2], where the Hall conductance exhibits steps, or Hall plateaus, at precisely integer and fractional multiples of the inverse of the quantum of resistance [4].

Whereas conventional resistance depends on the material's geometry and external factors, the quantum Hall resistance depends only on fundamental constants and can be reproduced with extraordinarily precision. Not surprisingly, the QHE has become the primary standard of resistance metrology. The robustness of the QHE to structural defects, disorder, and other perturbations is a striking manifestation of "topological protection", a desirable and advantageous property for many emerging quantum information applications. Without this protection, quantum states of materials are subjected to changes caused by temperature-dependent scattering and dissipative processes. To protect certain quantum states from external disturbances, materials with specific symmetries can decouple some quantum-states from interacting with the rest of the sample. Those are the so-called topological protected states, which are robust to external perturbations and have long lifetimes.

How robust can this topological quantum protection be, with respect to perturbations acting on the entire device, i.e., spatially long-range perturbations? To answer this question, Appugliese *et al.* created a two-dimensional electron-gas device embedded in a split-ring cavity resonator (see figure). Vacuum field states, that span the whole space inside the cavity, provide the sought spatially long-range interactions inside the device. This interaction creates new light-matter hybrid states, referred to as polaritonic states, with characteristics that neither the original material nor the cavity field state possesses. This hybridization effect is proportional to the strength of the light-matter coupling inside the cavity and can be better detected if the device is brought to a strong coupling regime [5-9], but this is often not the case as light-matter coupling is generally weak. By confining the light field in a small region of space, the cavity, the probability of photon absorption and therefore the light-matter coupling strength, increases. Recent advances in cavity design have enabled the practical realization of this strong light-matter coupling regime [10].

The device created by Appugliese et al., realize a strong-light matter coupling regime Surprisingly, the authors observed that a dark cavity, without external illumination, breaks the quantization of the Hall conductivity over a wide range of applied magnetic fields. They measured up to eleven integer Hall plateaus for the device outside the cavity. The shape of those plateaus is modified when immersed in the cavity, with especially strong changes for odd-numbered plateaus. The authors also found that the fractional Hall plateaus are much less affected by the cavity, which seems to be consistent with the observation that fractional plateaus couple weakly to light[3,4]. Those findings offer a new route to control quantum materials.

Why does the cavity modify the otherwise topologically protected integer quantum Hall conductivity in quantum Hall devices? To answer this, it is important to bring up the connection between topological protection and the physical path taken by the physical Hall current, which is localized at the edges of the device. The robustness of the QHE is linked to the fact that this edge-current is physically separated from the bulk of the sample. However, the vacuum field states of the cavity facilitate the hopping of electrons between the states carrying the edge-current and the bulk states of the sample. This new coupling channel give rise to the breakdown of the topological protection of the QHE. The microscopic process behind this coupling involves several intermediate states in which the defects in the sample play an important role [*11*]. The demonstration that the cavity vacuum field states circumvent the QHE topological protection supports recent predictions on the cavity modification of the quantum of Hall resistance in defect-free two-dimensional devices [12] when the cavity field is larger than the external applied magnetic field.

Experimental and theoretical research on the control of materials by engineering cavity vacuum fields is destined to considerably accelerate and expand. Controlling the environment surrounding a material inside a cavity can alter its properties enabling the design of quantum materials and phenomena [7]. Recent theoretical predictions for material's quantum phenomena mediated by cavity photons include photon-mediated superconductivity, ferroelectricity, and magnetism as well as the control of many body interactions and topological phenomena in multi-layer two-dimensional materials. These are among the lines of research that may soon come under the umbrella of "cavity materials engineering" which can be used to induce specific functional properties, such as superconductivity, in materials. For example, it may be possible to control, in twisted bilayer graphene and transition metal dichalcogenides, the low energy scales of their moiré electronic bands and electron-correlated phases with engineered cavity vacuum field states to create new exotic states of matter (13,14), increasing the impressive portfolio of materials phenomena in two-dimensional heterostructures.

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