



## Novel topological properties of matter emerge from an ultra-cold atom-cavity system

An international team of researchers reports on a new method that permits inducing symmetry-protected higher-order topology through a spontaneous symmetry-breaking mechanism in a two-dimensional system of ultra-cold bosonic atoms inside a cavity.

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Topology is a field of mathematics that studies the properties of geometric objects that are preserved under continuous deformations. In physics, topology provides a framework for understanding key properties of physical systems, which has led to the discovery of new materials with unique properties.

Since the discovery of topological materials, which are distinguished by their unique non-local properties, topology has become a central area of research both in fundamental

and applied physics. In recent years, substantial progress has been made in extending the existing paradigm of phases of matter to include the notion of topology and its relation to the underlying symmetries of quantum systems. This resulted in a thorough classification of non-interacting topological systems. Nevertheless, there are still many examples of non-conventional topological phases which escape the current paradigm, presenting challenges and questions that demand new perspectives and solutions. This includes, for example, understanding the interplay of topology with interactions, or the study of higher-order topological insulators, which generalize the bulk-boundary correspondence. Currently, these phases are being proposed and discovered in a wide range of systems, including electronic systems, photonics or cold atoms in optical lattices, among others.

Quantum simulators made of cold atoms in optical lattices have not only been at the center of the study of topological materials because of their versatility, but are used to probe systems in which interactions between particles challenge the capabilities of available computational methods. In fact, the interplay between interactions and topology can result in interesting phenomena. For example, the combination of interaction-induced symmetry breaking and symmetry protection can give rise to delocalized fractional charges, absent in the non-interacting case. Cold atom experiments arise as perfect candidates to study interacting topological systems, but they still need to be benchmarked using advanced numerical methods.

In the recent study published in *Physical Review Letters*, ICFO researcher Joana Fraxanet, led by ICREA Prof. at ICFO Maciej Lewenstein, in collaboration with Daniel Gonzalez-Cuadra from IQOQI, Alexandre Dauphin from PASQAL and Luca Barbiero from Politecnico de Torino, report on a readily available experimental protocol to induce symmetry-protected higher-order topology through a spontaneous symmetry-breaking mechanism in an atom-cavity system.

In their study, the scientists used tensor-network based numerical techniques to investigate a system made of ultra-cold bosonic atoms coupled to two cavities. The atoms are trapped in the lowest energy band of an optical lattice, which is generated by counter-propagating laser beams. By adding two optical cavities, the scientists enhance the probability of photon-mediated interactions between the atoms, leading to effective infinite-range interactions. For the regimes of interest, these interactions induce a Peierls transition, which spontaneously breaks the translational symmetry of the system. The resulting pattern opens a topological gap, leading to a higher-order topological phase hosting corner states. The authors present a detailed protocol for the adiabatic preparation of this higher-order topological phase, which can be readily implemented using existing ultracold atom quantum simulators, therefore opening the path towards the realization of two-dimensional

interaction-induced topological phases and the observation of Peierls transitions in dimensions larger than one.

As Joana Fraxanet comments, *we would like to extend the setup to include multiple cavities, allowing to generate atom-photon topological defects. These defects would generalize the topological solitons and fractionalized quasi-particles found in the Su-Schrieffer-Heeger model to two dimensions. Moreover, by exploring the regime of soft-core bosons, we expect to find plaquette-ordered supersolid phases.* The results presented in this study represent a step forward in understanding interacting topological phenomena, which can have important applications in quantum information processing and the discovery of novel materials. Moreover, the results are relevant to a broad community of theoretical and experimental researchers working on topological matter, ultracold atoms experiments, quantum optics and solid-state physics.

**Reference:** [Higher-Order Topological Peierls Insulator in a Two-Dimensional Atom-Cavity System](#), Joana Fraxanet, Alexandre Dauphin, Maciej Lewenstein, Luca Barbiero, and Daniel Gonzalez-Cuadra, Phys. Rev. Lett. 131, 263001 (2023) - Published 27 December 2023

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**Figure caption:** Atom-cavity experimental setup. Ultracold bosonic atoms are trapped in the lowest band of a 2D optical lattice. The atoms are coupled to two cavity modes created by two optical cavities aligned in the x and y directions, and to a laser pump aligned in the z direction. In each direction, the relative phase between the optical lattice and the cavity mode is chosen such that the nodes of the latter coincide with the sites of the lattice. In this configuration, the effective Hamiltonian describing the atom-cavity system contains correlated-tunneling terms, where atoms can tunnel between nearest neighbor sites by absorbing or emitting a photon from the cavity.