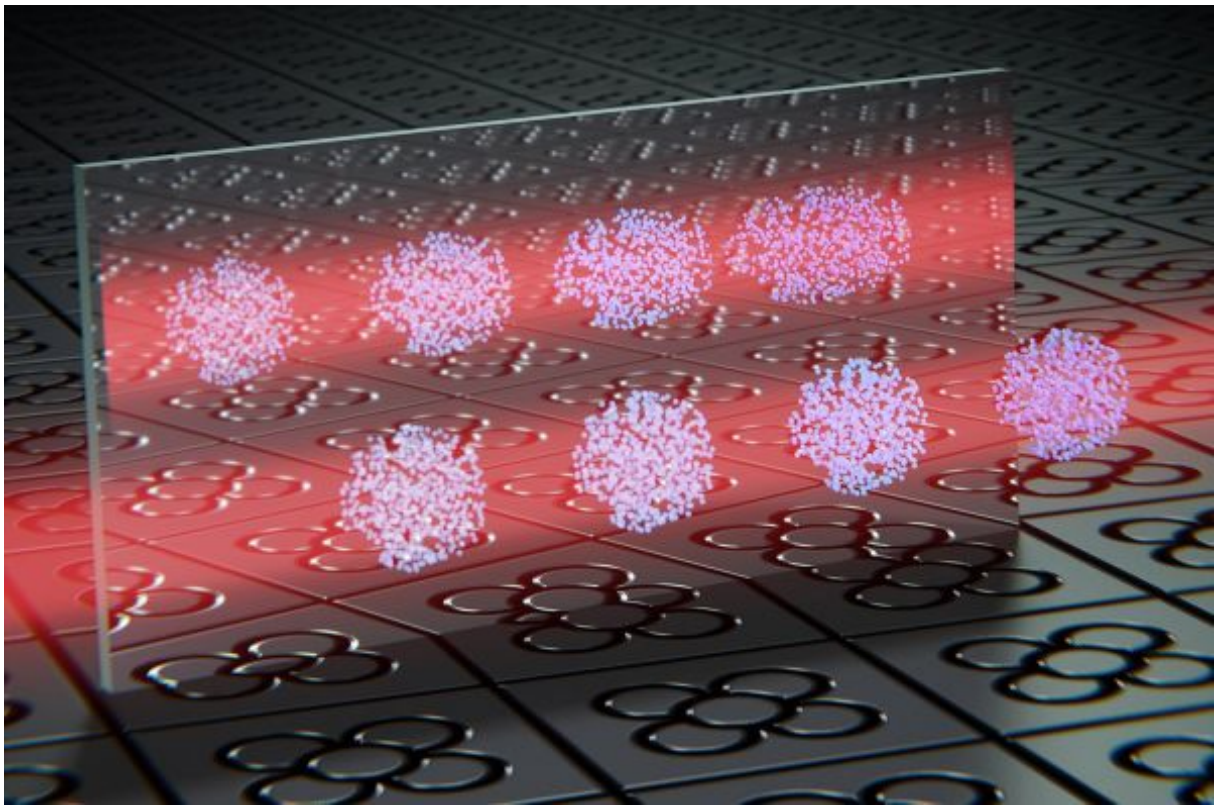


Ultracold atoms dressed by light simulate gauge theories

Researchers at ICFO and UAB, in Barcelona, use the coldest systems in the universe to realize in the laboratory gauge theories, key models of modern physics that describe the fundamental forces of Nature and the behavior of complex quantum materials.

August 11, 2022

Our modern understanding of the physical world is based on gauge theories: mathematical models from theoretical physics that describe the interactions between elementary particles (such as electrons or quarks) and explain quantum mechanically three of the fundamental forces of nature: the electromagnetic, weak, and strong forces. The fourth fundamental force, gravity, is described by Einstein's theory of general relativity, which, while not yet understood in the quantum regime, is also a gauge theory. **Gauge theories** can also be used to explain the exotic quantum behavior of electrons in certain materials or the error correction codes that future quantum computers will need to work reliably, and are the workhorse of modern physics.

In order to better understand these theories, one possibility is to realize them using artificial and highly controllable quantum systems. This strategy is called **quantum simulation** and constitutes a special type of quantum computing. It was first proposed by the physicist Richard Feynman in the 80s, more than fifteen years after being awarded the Nobel prize in physics for his pioneering theoretical work on gauge theories. Quantum simulation can be seen as a quantum LEGO game where experimental physicists give reality to abstract theoretical models. They build them in the laboratory i¿½quantum brick by quantum bricki?½, using very well controlled quantum systems such as ultracold atoms or ions. A ter assembling one quantum LEGO prototype for a specific model, the researchers can mea ure its properties very precisely in the lab, and use their results to understand better the th ory that it mimics. During the last decade, quantum simulation has been intensively exploite to investigate **quantum materials**. However, playing the quantum LEGO game with gauge theories is fundamentally more challenging. Until now, only the electromagnetic force could be investigated in this way.

In a recent study published in **Nature**, **ICFO** experimental researchers **Anika Frolian**, **Craig Chisholm, Ramon Ramos, Elettra Neri, and Cesar Cabrera,** led by **ICREA Prof. at ICFO Leticia Tarruell,** in collaboration with **Alessio Celi,** a theoretical researcher from the **Talent program at the Autonomous University of Barcelona**, were able to simulate a gauge theory other than electromagnetism for the first time, using ultracold atoms.

A gauge theory for very heavy photons

The team set out to realize in the laboratory a gauge theory belonging to the class of topological gauge theories, different from the class of dynamical gauge theories to which electromagnetism belongs.

In the gauge theory language, the electromagnetic force between two electrons arises when they exchange a photon: a particle of light that can propagate even when matter is absent. However, in two-dimensional quantum materials subjected to very strong magnetic fields, the photons exchanged by the electrons behave as if they were extremely heavy and can only move as long as they are attached to matter. As a result, the electrons have very peculiar properties: they can only flow through the edges of the material, in a direction that is set by the orientation of the magnetic field, and their charge becomes apparently fractional. This behavior is known as the **fractional quantum Hall effect**, and is described by the Chern-Simons gauge theory (named after the mathematicians that developed one of its key elements). The behavior of the electrons restricted to a single edge of the material should also be described by a gauge theory, in this case called chiral BF, which was proposed in the 90s but not realized in a laboratory until the ICFO and UAB researchers pulled it out of the

freezer.

An ultracold cloud that does not behave as its mirror image

To give reality to this topological gauge theory and simulate it in their experiment, the team used a cloud of atoms cooled down to temperatures about a billionth of a degree above absolute zero. As atomic species they chose potassium, because one of its isotopes has two states that interact with different strengths and can be used as the quantum bricks to construct the chiral BF gauge theory. They then shone laser light to combine the two states into a single new one. This technique, called i¿½**dressing the atoms with light**i¿½, made th m acquire peculiar interactions whose strength and sign depended on the velocity of the clou . Finally, they created an optical waveguide that would restrict the motion of the atoms to a line, and used additional lasers to kick the cloud and make it move at different velociti s along i

In normal conditions, letting the atoms evolve freely in the waveguide would have resulted n the cloud expanding. However, with the dressing light on, the images of the atoms taken n the laboratory showed a completely different behavior. A**Ramon Ramos** explains, i¿½in o r system, when the atoms move to the right their interactions are attractive and cancel t e behavior of the atoms trying to expand. So, what you actually see is that the shape of t e cloud remains the same. In technical words, we realized a soliton. But, if the atoms move o the left, these atoms expand like normal gasi¿½. The observation of atoms that be ave differently when moving in opposite directions demonstrates that the system is chiral, that is, different from its mirror image. i¿½When we observed for the first time the effect of hiral interactions in our atomic cloud, we were not trying to simulate a gauge theory. But th data was so beautiful and intriguing that we felt that we really needed to understand bett r its meaning. It made me change completely the research plans of the teami¿½, s**Leticia Tarruell**.

The team quickly figured out that their observations were connected to a theoretical article published ten years earlier, which proposed to use an almost identical setup to study a modified type of electromagnetism. However, the results of the experiment never seemed to agree with their expectations. As **Craig Chisholm** recalls, initially i¿½the results that we we e obtaining did not seem at all aligned with any of the theory. The challenge was to understa d which regime you had to be in to actually see the correct effect coming from the corre t place and to eliminate the effect coming from the wrong placei?

?. For the experimental team, the meaning of the modified electromagnetism mentioned in

the paper was also very unclear. It cited mathematical physics papers from the 90s, w
ich established the connection with the gauge theories used to described the fractional qua
tum Hall effect. However, as Tarruell says, i¿½for experimental atomic physicists like u
, the content of these works was very hard to grasp, because they were written in a mathem
tical physics language that was completely different from ours. It was really frustrating t
know that the answer to our questions was there, but we were not being able to understand it
This is when we decided that we needed to bring a theorist into the pictu

A very fruitful experiment-theory collaboration

For theoretical physicist **Alessio Celi**, who had worked for many years on high energy physics and gravity before switching to quantum simulation, reading the original gauge theory papers was easy. At the same time, he could understand the regime in which the experiments could be performed, and their challenges. He sat down with the experimental team, and after several discussions came up with a model that could properly explain the experimental results. As he explains, i¿½the main problem we had was to enter in the right framewor
. Once you knew where to look, it became an easy problem to solvei¿½. Remarkably, there was a regime of parameters where this model was exactly the topological gauge theory prop
sed 30 years earlier to describe the behavior of electrons at the edges of fractional quantum
all materi

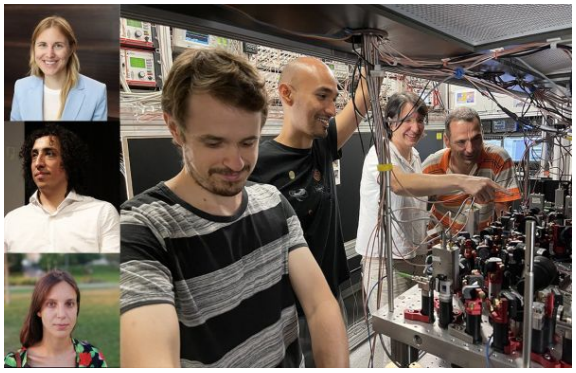
s. i¿½I think that this project shows us the strength of interdisciplinary collabora
ions. Combining experimental tools of ultralow temperature physics and theoretical tool
from high energy physics has made all of us better physicists, and resulted in the first q
antum simulation of a topological gauge theoryi¿½, concludes T

ruell. The team is already set to explore the new research directions opened by this projec
. Their goal now is to try to expand the experiments and the theory from a line to a plan
, which would allow them to observe the fractional quantum Hall effect without the n
ed of a quantum material. This would give access to exotic quasi-particles, called anyons,
hich in the future could be used for more robust forms of quantum co

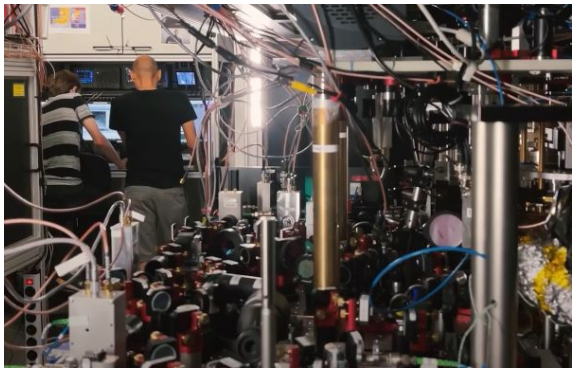
uti

Reference: Realizing a 1D topological gauge theory in an optically dressed BEC, Anika Frolian, Craig S. Chisholm, Elettra Neri, Cesar R. Cabrera, Ramon Ramos, Alessio Celi, and Leticia Tarruell, 2022, Nature, DOI: 10.1038/s41586-022-04943-3

Acknowledgements: This work was supported by funding from the European Union (ERC CoG-101003295 SuperComp), Ministerio de Ciencia e Innovacion and Agencia Estatal de Investigacion (LIGAS projects PID2020-112687GB-C21 at ICFO and PID2020-112687GB-C22 at UAB, and Severo Ochoa CEX2019-000910-S at ICFO), Deutsche Forschungsgemeinschaft (Research Unit FOR2414, Project No. 277974659), Fundacion Ramon Areces (project CODEC), Fundacio Cellex, Fundacio Mir-Puig, and Generalitat de Catalunya (ERDF Operational Program of Catalunya, Project QUASICAT/QuantumCat Ref. No. 001-P-001644, AGAUR and CERCA program). A. F. acknowledges support from La Caixa Foundation (ID 100010434, PhD fellowship LCF/BQ/DI18/11660040) and the European Union (Marie Sklodowska-Curie-713673), C. S. C. from the European Union (Marie Sklodowska-Curie-713729), E. N. from the European Union (Marie Sklodowska-Curie-101029996 ToPIKS), C. R. C. from an ICFO-MPQ Cellex postdoctoral fellowship, R. R. from the European Union (Marie Sklodowska-Curie-101030630 UltraComp), A. C. from the UAB Talent Research program, and L. T. from Ministerio de Ciencia e Innovacion, Agencia Estatal de Investigacion and the European Social Fund (RYC-2015-17890).



Left pictures (from top to bottom): ICFO Alumni Anika Frolian, Cesar Cabrera, Elettra Neri. Right picture (from left to right): ICFO researchers Craig Chisholm, Ramon Ramos, Leticia Tarruell, together with UAB researcher Alessio Celi, in the lab at ICFO w



Ultracold atoms dressed by light simulate gauge theories