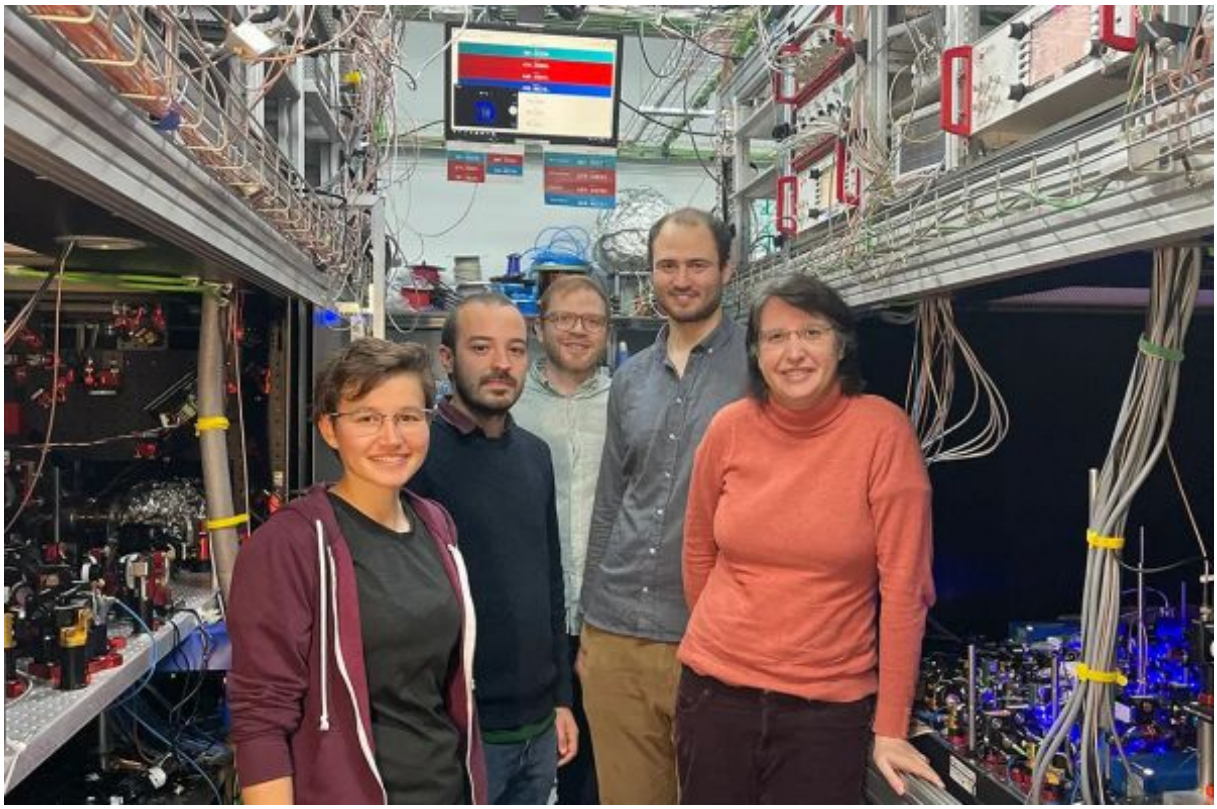


QUIONE: Announcing the birth of a unique analog quantum processor in the world

ICFO researchers build QUIONE, a quantum simulator capable of observing individual atoms in a strontium quantum gas.

April 22, 2024

Quantum physics needs high-precision sensing techniques to delve deeper into the microscopic properties of materials. From the analog quantum processors that have emerged recently, the so-called quantum-gas microscopes have proven to be powerful tools for understanding quantum systems at the atomic level. These devices produce images of quantum gases with very high resolution: they allow individual atoms to be detected. Now, ICFO researchers (Barcelona, Spain) **Sandra Buob**, **Jonatan Hoschele**, **Dr. Vasiliy Makhalov** and **Dr. Antonio Rubio-Abadal**, led by **ICREA Professor at ICFO Leticia Tarruell**, explain how they built their own quantum-gas microscope, named QUIONE after the Greek goddess of snow. **The group's quantum-gas microscope is the only one imaging individual atoms of strontium quantum gases in the world, as well as the first of its kind in Spain.**

Beyond the impactful images in which individual atoms can be distinguished, the goal of QUIONE is quantum simulation. As ICREA Prof. Leticia Tarruell explains: i¿½**Quantum simulation** can be used to boil down very complicated systems into simpler models to then understand open questions that current computers cannot answer, such as why some **materials conduct electricity without any losses** even at relatively high temperaturesi¿½. T e research of the group at ICFO in this area has received support at national level (award fr m the Royal Spanish Society of Physics, and projects and grants from the BBVA Foundatio , Ramon Areces Foundation, La Caixa Foundation and Cellex Foundation) and European lev l (including an ERC project
. The singularity of this experiment lies in the fact that they have managed to bring the **strontium gas** to the **quantum regime**, place it in an **optical lattice** where the atoms could interact by collisions and then apply the single atom imaging techniques. These three ingredients altogether make **ICFO's strontium quantum-gas microscope unique** in its kind.

Why strontium?

Until now, these microscope setups relied on alkaline atoms, like lithium and potassium, which have simpler properties in terms of their optical spectrum compared to alkaline-earth atoms such as **strontium**. This means that strontium offers more ingredients to play with in these experiments.

In fact, in recent years, the unique properties of strontium have made it a very popular element for applications in the fields of **quantum computing** and **quantum simulation**. For example, a cloud of strontium atoms can be used as an **atomic quantum processor**, which could solve problems beyond the capabilities of current classical computers.

All in all, ICFO researchers saw great potential for quantum simulation in strontium, and they set to work to build their own quantum-gas microscope. This is how QUIONE was born.

QUIONE, a quantum simulator of real crystals

To this end, they first lowered the temperature of the strontium gas. Using the force of several laser beams, the speed of atoms can be reduced to a point where they remain almost motionless, barely moving, reducing their temperature to almost absolute zero in just a few milliseconds. Then, the laws of quantum mechanics rule their behavior, and the atoms display new features like **quantum superposition** and **entanglement**.

After that, with the help of special lasers, the researchers activated the optical lattice, which keeps the atoms arranged in a grid along space. i¿½You can imagine it like an egg carto , where the individual sites are actually where you put the eggs. But instead of eggs we ha e atoms and instead of a carton we have the optical latticei¿½, explains Sandra Buob, f rst author of the arti
le. The atoms in the egg cup interacted with each other, sometimes experiencing qua tum tunnelling to move from one place to another. This quantum dynamics between a

oms mimics that of electrons in certain materials. Therefore, the study of these systems can help **understand the complex behavior of certain materials**, which is **the key idea of ??quantum simulation**.

As soon as the gas and the optical lattice were ready, the researchers took the images with their microscope and could finally observe their strontium quantum gas atom by atom. At this point, the construction of QUIONE had already been a success, but its creators wanted to get even more out of it.

Thus, in addition to the pictures, they took videos of the atoms and were able to observe that, while the atoms should remain still during the imaging, they sometimes jumped to a nearby lattice site. This can be explained by the phenomenon of **quantum tunnelling**. i¿½The ato s were i¿½hoppingi¿½ from one site to another. It was something very beautiful to see, as we were literally witnessing a direct manifestation of their inherent quantum behaviori¿½ shar s Buob. Finally, the research group used their quantum-gas microscope to confirm that the **strontium gas** was a **superfluid**, a quantum phase of matter that flows without viscosity. i¿½We sudden y switched off the lattice laser, so that the atoms could expand in space and interfere wi h each other. This generated an interference pattern, due to the wave-particle duality of t e atoms in the superfluid. When our equipment captured it, we verified th**presence of superfluidity in the sample**i¿½, explains Dr. Antonio Rubio-Abada . i¿½It is a very exciting moment for quantum simulationi¿½, shares ICREA professor L ticia Tarruell. i¿½Now that we have added strontium to the list of available qua tum-gas microscopes, we might be able to simulate more complex and exotic materials so n. Then new phases of matter are expected to arise. And we also expect to obtain m ch more computational power to use these machines as **analog quantum computers**i¿?

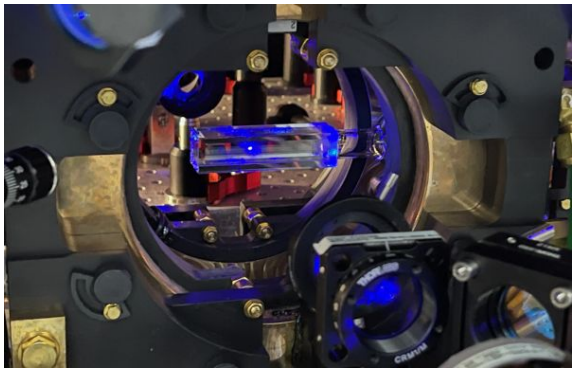
About QUIONE and Quantum Technologies in Barcelona

QUIONE is a program created by ICFO that aims at using quantum processors based on individually controlled and detected ultra-cold atoms to solve problems hard for classical computers. The program includes the analog quantum processor QUIONE I, the quantum-gas microscope mentioned in the study, and a hybrid analog-digital processor named QUIONE II, which is currently under construction. QUIONE is part of the eight major programs that the Government of Catalonia, through the Secretary of Digital Policies, is addressing to include Quantum Technologies as part of the Strategy of Catalonia, and establish Barcelona as a Core Innovation Hub for these technologies.

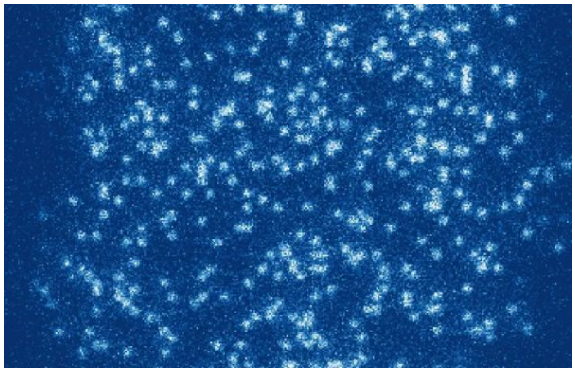
Acknowledgements

We acknowledge discussions with S. Blatt, A. Kaufman, V. Klüsener, A. Park, P. SchauSs, A Young, J. Zeiher, and the other members of the ICFO Quantum Gases Experimental group We thank M. Miranda for the band-structure calculations and S. Hirthe for contributions t

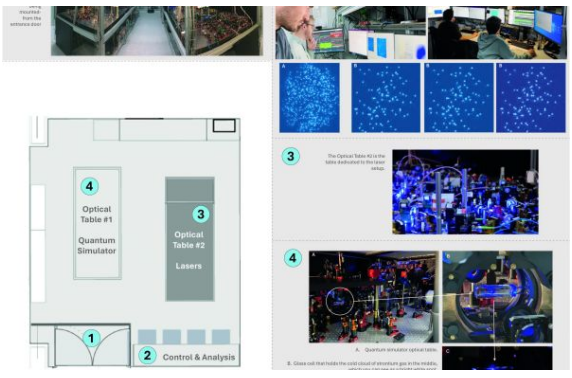
the reconstruction algorithm and for a careful reading of the manuscript. We acknowledg funding from the European Union [HORIZON-CL4-2022-QUANTUM-02-SGA through **PASQuanS2.1** (Grant Agreement No. 101113690); **DAALI** (Grant Agreement No. 899275); **ERC SuperComp** (Grant Agreement No. 101003295)], Ministry of Science and Innovation of Spain, and State Research Agengy MCIN/AEI/10.13039/501100011 (LIGAS project PID2020-112687GB-C21, DYNAMITE QuantERA project PCI2022-132919 with funding from European Union NextGenerationEU, Equipamiento Cientifico Tecnico EQC2018-005001-P, EQC2019-005699-P, and EQC2019-005706-P, Severo Ochoa CEX2019-000910-S, and **PRTR-C17.I1 - Plan Complementario de Comunicaciones Cuanticas** -with funding from European Union NextGenerationEU and Generalitat de Catalunya), Fundacio Cellex, Fundacio Mir-Puig, and Generalitat de Catalunya (i¿½**Quantica - Vall de la Mediterrania de les Ciencies i les Tecnologies Quantiques**i¿½ Government Agreement GOV/51/2022, promoted y Secretary of Digital Policies of the Government of Catalonia, AGAUR SGR 2021-SGR-014 8 and CERCA program). S.B. acknowledges support from MCIN/AEI/10.13039/5011000110 3 and **ESF** (Grant No. PRE2020-094414), J.H. acknowledges support from the European Union (**Marie Sk?odowska-Curie Actions**, Grant No. 713729), V.M. acknowledges support from the **Beatriu de Pinos** Program and the Ministry of Research and Universities of the Government of Catalonia (Grant No. 2019-BP-00228), and A.R. acknowledges support from the MCIN/AEI/10.13039/501100011033 (**Juan de la Cierva** Formacion Grant No. FJC2020-043086-I).



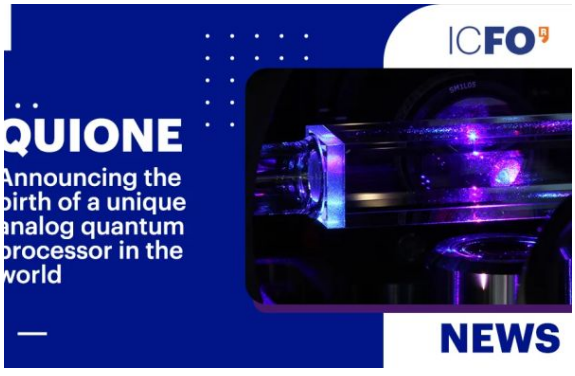
The cloud of strontium atoms in the middle of the glass cell



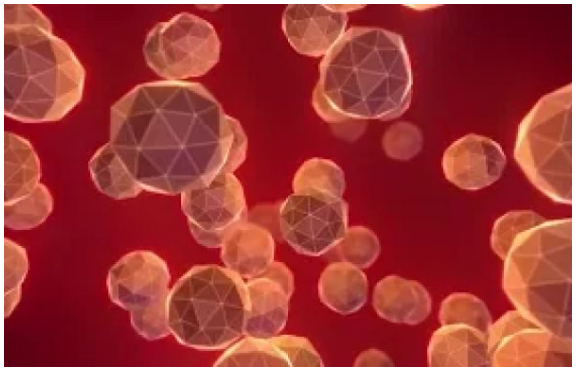
Snapshot of the individual atoms of strontium in the optical lattice



map of the lab and location of the quantum simulator



Video interview



QUIONE: a quantum simulator