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Lattice geometry gives rise to anomalous fluctuations in Bose-Einstein condensates

Fluctuations lie at the core of our universe, from thermal phase transitions to cosmic evolution. Scientists study these fluctuations using Bose-Einstein condensates (BECs), in which the number of atoms in the condensate naturally fluctuates over time.

In a new *Physical Review Letters* study, ICFO researchers and collaborators have investigated, for the first time, the particle-number fluctuations in a BEC placed in a triangular optical lattice. Combining theoretical modelling and experimental measurements, the team has observed strongly anomalous fluctuations and demonstrated the central role of lattice geometry. These results deepen our understanding of atom-number fluctuations in BECs.

February 25, 2026

Fluctuations are central for physical systems, driving phase transitions and limiting control of quantum systems. It is therefore not surprising that scientists are so interested in studying such fluctuations. One of the most suitable platforms is atomic Bose-Einstein condensates (BECs), where a large number of atoms occupy the lowest-energy state and naturally exhibit intriguing fluctuations.

A recent article in *Physical Review Letters* reports the first investigation of particle-number fluctuations in **a BEC embedded in an optical lattice**. By combining the theoretical expertise of Donostia International Physics Center in San Sebastian Spain, Adam Mickiewicz University in Poznan Poland and ICFO researchers **Dr. Zahra Jalali-Mola** and **Dr. Utso Bhattacharya**, led by **ICREA Prof. Maciej Lewenstein**, with the experimental support of the University of Hamburg and TU Dortmund University in Germany, the team observed **strongly anomalous fluctuations in the condensate's number of atoms**, while also revealing that **the confinement in a lattice deeply influences such fluctuations**.

Unlike previous work on continuous BECs, where the atoms move freely within a harmonic trap, the current study traps the atoms at discrete sites forming a triangular pattern through an optical lattice. The lattice is combined with a 3D harmonic potential, which confines the atoms in each site into elongated, tube-like regions. $i\frac{1}{2}$ This geometry alters the way ato

s move and interact, leading to an unusual scaling of fluctuations with the total particle number, states Prof. Christof Weitenberg from TU Dortmund University, lead author of the article.

To observe this effect, the experimentalists cooled, trapped, and loaded rubidium atoms into the lattice. By varying temperature and initial atom number, they monitored the phase transition from a normal gas to a BEC. They then used matter-wave microscopy to image the condensate and subsequently determine atom number, temperature, and condensate fraction. In parallel, ICFO, Donostia International Physics Center and Adam Mickiewicz University led the theoretical effort, performing numerical simulations that combined two different frameworks, and whose results closely matched the experimental observations. According to first author Dr. Zahra Jalali-Mola, these results substantially advance our understanding of the role of interactions and trap geometry on the condensate fluctuations. This brings us one step closer to reveal new quantum many-body phenomena in lattice systems and, in the long-term, could enable applications in quantum metrology.

Reference:

Zahra Jalali-Mola, et. al., Anomalous fluctuations of Bose-Einstein condensates in optical lattices, *Phys. Rev. Lett.* **136**, 083401 (2026)

DOI: <https://doi.org/10.1103/95pq-6r5g>

Acknowledgements:

This work was funded by Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) via Research Unit FOR 5688, Project No. 521530974, and via the cluster of excellence AIM, EXC 2056-project ID 390715994 as well as by 'Hamburg Quantum Computing', financed by the city of Hamburg and the European Union. U.B. acknowledges financial support of the IBM Quantum Researcher Program. R.W.C. acknowledges support from the Polish National Science Centre (NCN) under Maestro Grant No. DEC-2019/34/A/ST2/00081. T.G. acknowledges funding by the Department of Education of the Basque Government through the IKUR Strategy, through BasQ (project EMISGALA), and through PIBA_2023_1_0021 (TENINT), as well as by the Agencia Estatal de Investigación (AEI) through Proyectos de Generación de Conocimiento PID2022-142308NA-I00 (EXQUSMI), and that this work has been produced with the support of a 2023 Leonardo Grant for Researchers in Physics, BBVA Foundation. ICFO-QOT group acknowledges support from: European Research Council AdG NOQIA; MCIN/AEI (PGC2018-0910.13039/501100011033, CEX2019-000910-S/10.13039/501100011033, Plan National FIDEUA PID2019-106901GB-I00, Plan National STAMEENA PID2022-139099NB, I00, project funded by

MCIN/AEI/10.13039/501100011033 and by the European Union NextGenerationEU/PRTR & quot; (PRTRC17. I1), FPI); QUANTERA DYNAMITE PCI2022- 132919, QuantERA II Program e co-funded by European Union's Horizon 2020 program under Grant Agreement o 101017733; Ministry for Digital Transformation and of Civil Service of the Spanish Governme t through the QUANTUM ENIA project call - Quantum Spain project, and by the Europe n Union through the Recovery, Transformation and Resilience Plan - NextGenerationEU with n the framework of the Digital Spain 2026 Agenda; MICIU/AEI/10.13039/501100011033 and U (PCI2025-163167); Fundacio Cellex; Fundacio Mir-Puig; Generalitat de Catalunya (Europe n Social Fund FEDER and CERCA program; Barcelona Supercomputing Center MareNostr m (FI-2023-3-0024); Funded by the European Union. (HORIZON-CL4-2022-QUANTUM-02-S A PASQuans2.1, 101113690, EU Horizon 2020 FET-OPEN OPTologic, Grant No 89979 , QU-ATTO, 101168628), EU Horizon Europe Program (This project has received funding fr m the European Union's Horizon Europe research and innovation program under gra t agreement No 101080086 NeQSTGrant Agreement 101080086 -NeQST); ICFO Intern l i½QuantumGaudii½ project.