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RPPR Final Report
as of 03-Jan-2023

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Major Goals: In this seedling grant, we embarked on an effort in precision rotation sensing using atomic superfluids. Departing from the atomic beam approach based on single atom physics, the goal was to directly exploit the many-body nature of gaseous quantum matter.

In our quantum matter interferometer, we exploit collective excitations travelling within these quantum liquids as rotation sensing devices: topologically protected vortices and solitons. Propagating within the ideal, uniform background of the superfluid, these are intrinsically insensitive to potential defects and system imperfections, making our approach more robust than conventional "atom-laser based" implementations. This research fit well within Thrust 3 of the MTO BAA, "Decentralized sensors for the DOD". Once miniaturized, a robust, quantum matter interferometer would be well suited for used a decentralized rotation sensor.

The task focused on employing vortex excitations in superfluid Bose-Einstein condensates as rotation sensors. For this, a rapidly rotating Bose gas was created in an extremely round harmonic trap (roundness better than one part in 10000), keeping angular momentum for many tens of seconds. A novel method was developed that enabled the creation of rapidly rotating quantum gases in and near the lowest Landau level – allowing us to directly emulate the quantum behavior of electrons in high magnetic fields.

With this novel method, a new pathway towards the formation of quantized vortices was demonstrated, a crystallization transition from a vortex-less, rapidly rotating, elongated condensate in the lowest Landau level to a regular array of quantized vortices. The crystallization phenomenon we observed is a quantum analogue of the Kelvin-Helmholtz instability of counterflowing liquids in classical fluids.

With this new pathway towards rapidly rotating Bose gases and the formation of vortex arrays, we are in an excellent position to explore in the future the use of these Bose gases as exquisite rotation sensors.

In the following we will shortly summarize the major results of this work, which appeared in Nature and Science 2021 and 2022.

Accomplishments: Please see the attached PDF

Training Opportunities: Please see the attached PDF

Results Dissemination: Please see the attached PDF

Honors and Awards: Please see the attached PDF

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

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Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
National Academy Member: N

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Project Contribution:
National Academy Member: N

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Project Contribution:
National Academy Member: N

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Project Contribution:
National Academy Member: N

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Participant: Richard Fletcher
Person Months Worked: 12.00 **Funding Support:**
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Article Title: Geometric squeezing into the lowest Landau level
Authors: Richard J. Fletcher, Airlia Shaffer, Cedric C. Wilson, Parth B. Patel, Zhenjie Yan, Valentin Crépel, Biswa
Keywords: atomic physics
Abstract: The equivalence between neutral particles under rotation and charged particles in a magnetic field relates phenomena as diverse as spinning atomic nuclei, weather patterns, and the quantum Hall effect. In their quantum descriptions, translations along different directions do not commute, implying a Heisenberg uncertainty relation between spatial coordinates. Here, we exploit the ability to squeeze non-commuting variables to dynamically create a Bose-Einstein condensate occupying a single Landau gauge wavefunction in the lowest Landau level. We directly resolve the extent of the zero-point cyclotron orbits, and demonstrate geometric squeezing of the orbits' guiding centers by more than ${7}~$dB below the standard quantum limit. The condensate attains an angular momentum of more than ${1000}\,{\hbar}$ per particle, and an interatomic distance comparable to the size of the cyclotron orbits. This offers a new route towards strongly correlated fluids and bosonic quantum Hall st
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Article Title: Crystallization of bosonic quantum Hall states in a rotating quantum gas
Authors: Biswaroop Mukherjee, Airlia Shaffer, Parth B. Patel, Zhenjie Yan, Cedric C. Wilson, Valentin Crépel, Ric
Keywords: atomic physics
Abstract: The equivalence between neutral particles under rotation and charged particles in a magnetic field relates phenomena as diverse as spinning atomic nuclei, weather patterns, and the quantum Hall effect. In their quantum descriptions, translations along different directions do not commute, implying a Heisenberg uncertainty relation between spatial coordinates. Here, we exploit the ability to squeeze non-commuting variables to dynamically create a Bose-Einstein condensate occupying a single Landau gauge wavefunction in the lowest Landau level. We directly resolve the extent of the zero-point cyclotron orbits, and demonstrate geometric squeezing of the orbits' guiding centers by more than ${7}~$dB below the standard quantum limit. The condensate attains an angular momentum of more than ${1000}\,{\hbar}$ per particle, and an interatomic distance comparable to the size of the cyclotron orbits. This offers a new route towards strongly correlated fluids and bosonic quantum Hall st
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Partners

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I certify that the information in the report is complete and accurate:
Signature: Martin Zwierlein
Signature Date: 1/3/23   1:26AM

Rotation Sensing with Superfluid Quantum Gases

Final report W911NF1910511 / 76218-PE-DRP

PI: Martin Zwierlein
MIT-Harvard Center for Ultracold Atoms, Research Laboratory of Electronics, and Department of Physics, MIT, Cambridge, MA 02139, USA

A. Accomplishments

1. Research Objectives

In this seedling grant, we embarked on an effort in precision rotation sensing using atomic superfluids. Departing from the atomic beam approach based on single atom physics, the goal was to directly exploit the many-body nature of gaseous quantum matter. In our quantum matter interferometer, we exploit collective excitations travelling within these quantum liquids as rotation sensing devices: topologically protected vortices and solitons. Propagating within the ideal, uniform background of the superfluid, these are intrinsically insensitive to potential defects and system imperfections, making our approach more robust than conventional "atom-laser based" implementations. This research fit well within Thrust 3 of the MTO BAA, "Decentralized sensors for the DOD". Once miniaturized, a robust, quantum matter interferometer would be well suited for used a decentralized rotation sensor.

The task focused on employing vortex excitations in superfluid Bose-Einstein condensates as rotation sensors. For this, a rapidly rotating Bose gas was created in an extremely round harmonic trap (roundness better than one part in 10000), keeping angular momentum for many tens of seconds. A novel method was developed that enabled the creation of rapidly rotating quantum gases in and near the lowest Landau level – allowing us to directly emulate the quantum behavior of electrons in high magnetic fields. With this novel method, a new pathway towards the formation of quantized vortices was demonstrated, a crystallization transition from a vortex-less, rapidly rotating, elongated condensate in the lowest Landau level to a regular array of quantized vortices. The crystallization phenomenon we observed is a quantum analogue of the Kelvin-Helmholtz instability of counterflowing liquids in classical fluids.

With this new pathway towards rapidly rotating Bose gases and the formation of vortex arrays, we are in an excellent position to explore in the future the use of these Bose gases as exquisite rotation sensors.

In the following we will shortly summarize the major results of this work, which appeared in Nature and Science 2021 and 2022.

2. Major activities

2.1 Geometric squeezing into the lowest Landau level

Richard J. Fletcher, Airlia Shaffer, Cedric C. Wilson, Parth B. Patel, Zhenjie Yan, Valentin Crépel, Biswaroop Mukherjee, Martin W. Zwierlein
Science 372, 1318-1322 (2021)
http://dx.doi.org/10.1126/science.aba7202

The equivalence between neutral particles under rotation and charged particles in a magnetic field relates phenomena as diverse as spinning atomic nuclei, weather patterns, and the quantum Hall effect. In their quantum descriptions, translations along different directions do not commute, implying a Heisenberg uncertainty relation between spatial coordinates. Here, we exploit the ability to squeeze non-commuting variables to dynamically create a Bose-Einstein condensate occupying a single Landau gauge wavefunction in the lowest Landau level. We directly resolve the extent of the zero-point cyclotron orbits, and demonstrate geometric squeezing of the orbits' guiding centers by

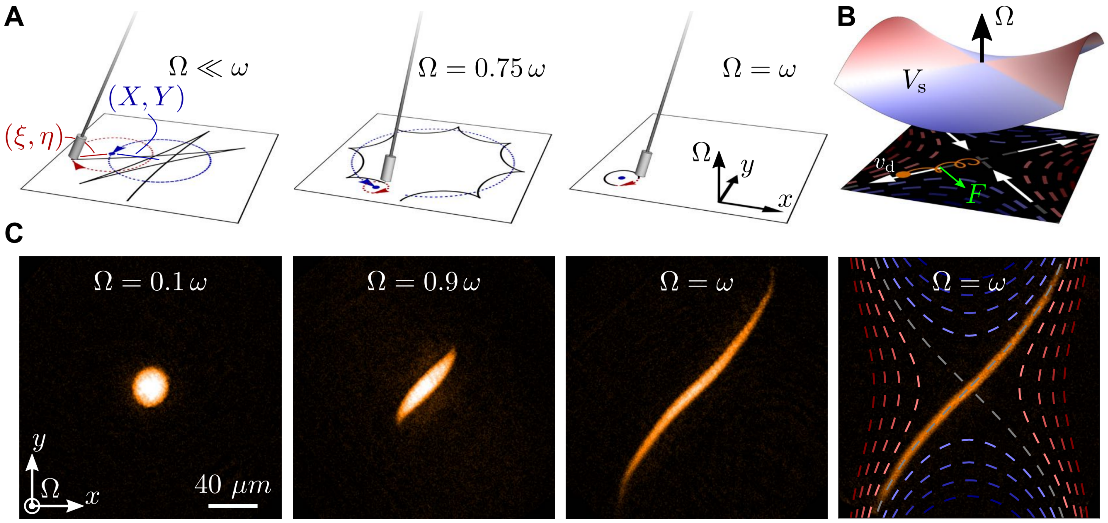

Figure 1: Geometric Squeezing, principal idea and experimental realization. Viewed in a frame rotating at Ω, the motion of a Foucault pendulum with natural frequency ω separates into a slow co-rotating drift of the guiding center (X, Y), shown in blue, and fast counterrotating cyclotron orbits with relative coordinates (ξ, η), shown in red. For $\Omega < \omega$ the pendulum performs skipping orbits, while if $\Omega = \omega$ the guiding center motion is free. (B) Atoms in an elliptical harmonic trap rotating at $\Omega = \omega$ evolve under both a vector potential and a scalar saddle potential, whose isopotentials are shown by red and blue dashed lines. Particles perform cyclotron orbits, whose guiding centers drift along isopotentials. (C) In situ images of the condensate in the rotating frame. During the hold time at $\Omega = \omega$, the atoms flow out along one diagonal and in along the other, mediating squeezing of the distribution in guiding center phase-space. The final image is overlaid with the isopotentials of the scalar saddle potential.

more than 7 dB below the standard quantum limit. The condensate attains an angular momentum of more than $1000\,\hbar$ per particle, and an interatomic distance comparable to the size of the cyclotron orbits. This offers a new route towards strongly correlated fluids and bosonic quantum Hall states.

2.2 Crystallization of Bosonic Quantum Hall States

Biswaroop Mukherjee, Airlia Shaffer, Parth B. Patel, Zhenjie Yan, Cedric C. Wilson, Valentin Crépel, Richard J. Fletcher, Martin Zwierlein
Nature 601, 58-62 (2022)
http://dx.doi.org/10.1038/s41586-021-04170-2

The dominance of interactions over kinetic energy lies at the heart of strongly correlated quantum matter, from fractional quantum Hall liquids, to atoms in optical lattices and twisted bilayer graphene. Crystalline phases often compete with correlated quantum liquids, and transitions between them occur when the energy cost of forming a density wave approaches zero. A prime example occurs for electrons in high magnetic fields, where the instability of quantum Hall liquids towards a Wigner crystal is heralded by a roton-like softening of density modulations at the magnetic length. Remarkably, interacting bosons in a gauge field are also expected to form analogous liquid and crystalline states. However, combining interactions with strong synthetic magnetic fields has been a challenge for experiments on bosonic quantum gases. Here, we study the purely interaction-driven dynamics of a Landau gauge Bose-Einstein condensate in and near the lowest Landau level (LLL). We observe a spontaneous crystallization driven by condensation of magneto-rotons, excitations visible as density modulations at the magnetic length. Increasing the cloud density smoothly connects this behaviour to a quantum version of the Kelvin-Helmholtz hydrodynamic instability, driven by the sheared internal flow profile of the rapidly rotating condensate. At long times the condensate self-organizes into a persistent array of droplets, separated by vortex streets, which are stabilized by a balance of interactions and effective magnetic forces.

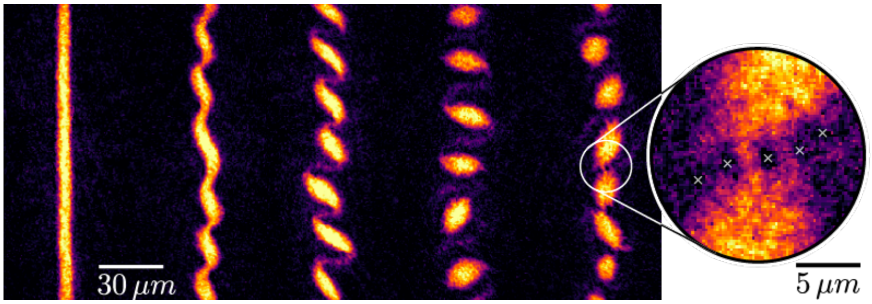

Figure 2: Crystallization of Bosonic Quantum Hall States seen in the laboratory.

3. Dissemination

All results were disseminated on the preprint server https://arxiv.org/ and, for published items, appeared in Nature and Science. In several public talks over the years the PI related the findings to the general public.

B. Impacts

1. Development of the principal discipline of the project

Our experiments realized fundamental models of condensed matter physics in a fully controllable environment, testing them with the precision of atomic physics, atom by atom. The experiment established the equation of state of fermions on a lattice and gave insight into the workings of strongly correlated fermionic matter. These advances are enabling theorists to test their models of strongly-interacting fermions and many-fermion systems, which is imperative if we are to harness the full potential of modern materials. The development of the spin- and density-resolved bilayer imaging represents a major step forward in the field of quantum simulators and is likely to be adapted by other groups.

2. Other disciplines

Experiments in ultracold quantum gases sometimes realize situations that cannot be realized in condensed matter systems. The most prominent example from the above results is the creation of bosonic quantum Hall states, something that had not been achieved in condensed matter experiments, which naturally work with electrons which are fermions.

3. Describe the impact in this reporting period on the development of human resources

Work on ultracold quantum gases of atoms and molecules trains students and postdocs in a wide variety of technical and theoretical skills relevant for the work force. On the experimental side, students and postdocs master ultrahigh vacuum technology, lasers, optics, optomechanics, high-current electromagnets, water cooling, high-voltage electric fields, electronics, computer control, ultra-high-precision laser spectroscopy, frequency standards etc. On the theoretical front, the group learns about many-body quantum theory of atoms and molecules, dipolar interactions, interactions between atoms and light, molecular spectroscopy.

I actively encourage participation from underrepresented minorities in physics. In the present project one female graduate student was involved, who is now doing a postdoc at Princeton. One female postdoc is now professor at Singapore. One african-american student is currently working in my group, soon to finish his PhD.

My students are successful in selections for the finalists of the DAMOP thesis prize (e.g. Lawrence Cheuk) and for the Martin Deutsch Prize of Experimental Physics from MIT (Lawrence Cheuk and

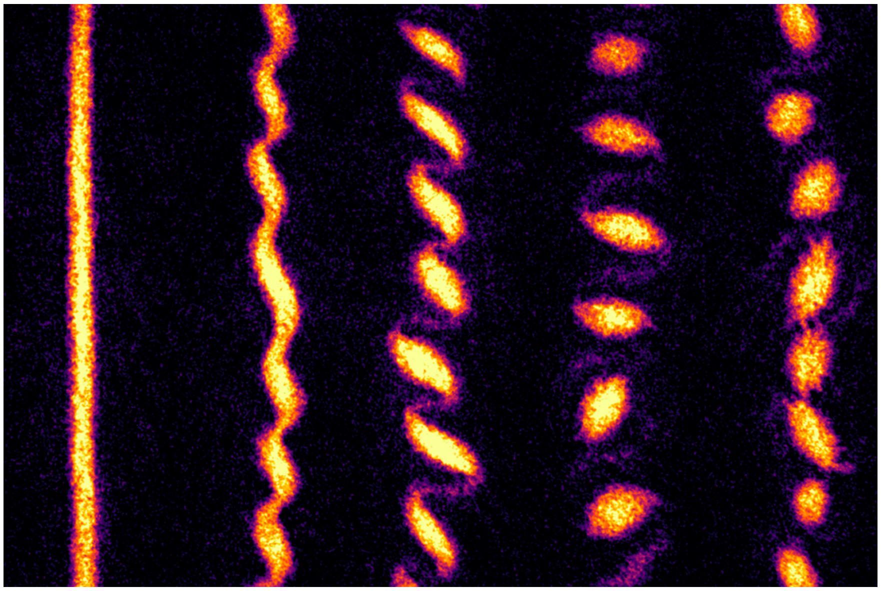

Figure 3: Visualizing the breakup of Landau gauge condensates

Thomas Hartke).

C. Honors

In 2021 the PI was awarded the Toptica Junior BEC award. The citation was "for his pioneering contributions to the field of ultracold quantum gases, specifically Fermi and Bose polarons, rotating condensates, spin and charge transport and the unitary Fermi gas."

1. Describe the impact on teaching and educational experiences

I regularly use material from research in my teaching, in particular the two atomic physics courses at MIT.

D. Technical Updates

We here note a useful news item written up for the public:

1. Physicists watch as ultracold atoms form a crystal of quantum tornadoes

https://news.mit.edu/2022/ultracold-atoms-quantum-0105