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RPPR Final Report

as of 23-Jan-2023

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Final Report for Period Beginning 23-Jul-2021 and Ending 22-Apr-2022

Title: STIR: Toward the exploration of the quantum vacuum optics of metamaterials with the SQCRAMscope

Begin Performance Period: 23-Jul-2021

End Performance Period: 22-Apr-2022

Report Term: 0-Other

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STEM Degrees:

STEM Participants:

Major Goals: The project aimed to use our novel quantum sensor, the SQCRAMscope (Scanning Quantum Cryogenic Atom Microscope), to advance a new field: 'engineered quantum vacuum optics.' The microscope is the first example of the direct marriage of ultracold atomic and optical physics with condensed matter for the imaging of the quantum vacuum. The Casimir effect is an inherently quantum optical manifestation of how the local electromagnetic vacuum environment is modified near materials. We are well-posed to enter into this new realm of optics research, in which Casimir forces can be manipulated through boundary condition engineering and modified by the effect of many-body correlations on optical properties. Manipulating and engineering the quantum vacuum can create novel optical devices for, e.g., eliminating the 'stiction' from MEMS/NEMS technology that causes such devices to fail. We will explore the quantum optics of engineered Casimir-Polder potentials arising from micro-fabricated surfaces like metamaterials. By doing so, the SQCRAMscope will open a new frontier in optical technology. The project addresses the technical challenges underpinning the imaging of Casimir potentials. Specifically, determining whether the SQCRAMscope is capable of imaging potentials of a magnitude we expect for Casimir physics.

Accomplishments: With the SQCRAMscope's high sensitivity, we were able to observe what might be the lateral CP potential directly through the change in atom density across a surface step. We accomplished this by trapping the quasi-1D BEC within 1 μm of a 10- μm periodic structure etched into a thick gold film. We succeeded in fabricating a sample with a wide variety of features, including periodic and random arrays of holes. The difference in the height of these non-translationally invariant conductors should cause the CP potential to spatially oscillate in magnitude, with a lateral component included. The BEC, if its chemical potential is sufficiently low, should exhibit a modulation in density in response to this spatially oscillating force. That modulation should be relatively even across the cloud.

We first tested whether these 10- μm features are resolvable by running electrical current through the sample to create a periodic magnetic potential for the 1D BEC confined nearby. The BEC completely fragmented with 10- μm period. Next, we turned off the current and brought the BEC closer to the sample, within one micron, where the CP force should be strong. There we saw a slight modulation of the BEC density, as expected for the case where the BEC's chemical potential is too large for the CP potential to fragment the matter wave. To test our sensitivity, we then lowered the BEC's chemical potential by lowering its density. This was accomplished by making the longitudinal trap longer and by loading it with fewer atoms. The result is an inhomogeneous modulation of the BEC density. These data are exciting, as they indicate that there is some chance a non-translationally invariant CP force has been detected for the first time. This accomplished the goal of this exploratory STIR.

RPPR Final Report as of 23-Jan-2023

Training Opportunities: This research project explores uncharted regimes of strongly correlated matter by pushing the experimental state-of-the-art in atomic physics, quantum optics, and condensed matter physics. In addition, we actively collaborate with theoretical groups to develop frameworks for understanding these novel tools and complex systems. As such, this research program provides an exceptional training ground for graduate and undergraduate students in the formative scientific environment provided by Stanford University and our state-of-the-art laser lab. The research concerns physics and technical skills that find application in a variety of significant areas of technology, most notably lasers and photonics for telecommunications and advanced novel solid-state materials for electronic devices. The PI currently mentors nine graduate students and two postdocs. Tours of the lab and talks to outside groups are regularly given to spark interest in modern physics ideas and techniques.

Results Dissemination: Nothing to Report

Honors and Awards: Full Professor;
Elected an APS fellow.

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: Graduate Student (research assistant)

Participant: Alec Shelley

Person Months Worked: 9.00

Project Contribution:

National Academy Member: N

Funding Support:

Partners

I certify that the information in the report is complete and accurate:

Signature: Benjamin Lev

Signature Date: 1/19/23 11:38PM

Project Description (Technical Proposal)**STIR: Quantum vacuum optics with the SQCRAMscope****Program Officer:** Dr. James Joseph, ARO**Abstract:**

The project aimed to use our novel quantum sensor, the SQCRAMscope (Scanning Quantum Cryogenic Atom Microscope), to advance a new field: ‘engineered quantum vacuum optics.’ The microscope is the first example of the direct marriage of ultracold atomic and optical physics with condensed matter for the imaging of the quantum vacuum. The Casimir effect is an inherently quantum optical manifestation of how the local electromagnetic vacuum environment is modified near materials. We are well-posed to enter into this new realm of optics research, in which Casimir forces can be manipulated through boundary condition engineering and modified by the effect of many-body correlations on optical properties. Manipulating and engineering the quantum vacuum can create novel optical devices for, e.g., eliminating the ‘stiction’ from MEMS/NEMS technology that causes such devices to fail. We will explore the quantum optics of engineered Casimir-Polder potentials arising from micro-fabricated surfaces like metamaterials. By doing so, the SQCRAMscope will open a new frontier in optical technology.

Objectives for this 9-month grant:

The project addresses the technical challenges underpinning the imaging of Casimir potentials. Specifically, determining whether the SQCRAMscope is capable of imaging potentials of a magnitude we expect for Casimir physics.

Findings:

We now discuss our preliminary results to help motivate the reasons behind the need for a scope change. With the SQCRAMscope’s high sensitivity, we were already able to observe what might be the lateral CP potential directly through the change in atom density across a surface step. We accomplished this by trapping the quasi-1D BEC within $1\ \mu\text{m}$ of a $10\text{-}\mu\text{m}$ periodic structure etched into a thick gold film; see Fig. 1. We succeeded in fabricating a sample with a wide variety of features, including periodic and random arrays of holes. The difference in the height of these non-translationally invariant conductors should cause the CP potential to spatially oscillate in magnitude, with a lateral component included. The BEC, if its chemical potential is sufficiently low, should exhibit a modulation in density in response to this spatially oscillating force. That modulation should be relatively even across the cloud.

We first tested whether these $10\text{-}\mu\text{m}$ features are resolvable by running electrical current through the sample to create a periodic magnetic potential for the 1D BEC confined nearby. Figure 1b shows the result—the BEC is completely fragmented with $10\text{-}\mu\text{m}$ period. Next, we turned off the current and brought the BEC closer to the sample, within one micron, where the CP force should be strong. There we see a slight modulation of the BEC density, as expected for the case where the BEC’s chemical potential is too large for the CP potential to fragment the matter wave; see Fig. 1c. To test our sensitivity, we then lowered the BEC’s

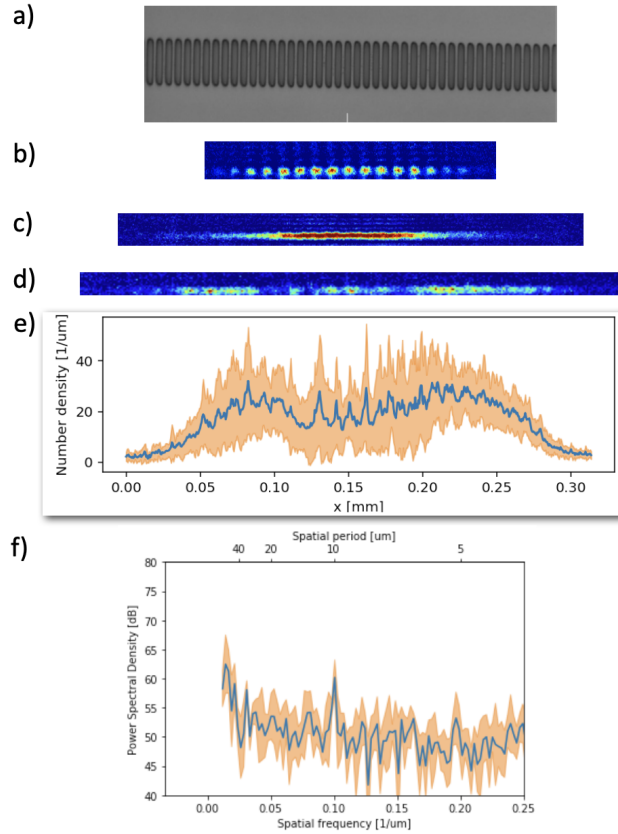


Figure 1. Preliminary data from imaging the CP potential directly through the change in atom density across a surface step. a) The surface steps are created by using photolithography to etch a periodic array of holes in a $1\text{-}\mu\text{m}$ -thick gold film. Shown here are features with a $2\text{-}\mu\text{m}$ periodic structure, to show our capability. We use a $10\text{-}\mu\text{m}$ periodic structure in the data below. b) Demonstration of BEC fragmentation due to the periodic magnetic field from running current through the wire structure. The atoms are absorption imaged. c) Slight corrugation of the BEC density when the BEC is placed within $1\text{ }\mu\text{m}$ of the $10\text{-}\mu\text{m}$ structure without current present. d) BEC fragmentation when its chemical potential is set lower than that in panel c. e) Five averages of data similar to panel d. This shows the $10\text{-}\mu\text{m}$ modulation more clearly. f) Spatial Fourier transform of data in panel e. The peak at $10\text{-}\mu\text{m}$ can be distinguished.

chemical potential by lowering its density. This was accomplished by making the longitudinal trap longer and by loading it with fewer atoms. The result is an inhomogeneous modulation of the BEC density, as shown in Fig. 1d. Figure 1e shows a 5-image average; the $10\text{-}\mu\text{m}$ modulation is more apparent. To confirm, we take the 1D Fourier transform of the image, which is shown in Fig. 1f and exhibits a peak associated with the $10\text{-}\mu\text{m}$ feature. These data are exciting, as they indicate that there is some chance a non-translationally invariant CP force has been detected for the first time. This accomplished the goal of this exploratory STIR.