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RPPR Final Report

as of 29-Mar-2023

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Final Report for Period Beginning 22-May-2020 and Ending 21-Aug-2021

Title: Condensed Matter Physics (CMP)

Begin Performance Period: 22-May-2020

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STEM Degrees:

STEM Participants:

Major Goals: We propose to develop the tools to implement high-fidelity fluorescence detection of single cavity Rydberg polaritons, which are the central ingredient of the Simon Lab's photonic quantum materials platform. This new tool will not only enable us to prepare and study substantially more sophisticated quantum many-body states, but is indeed the essential ingredient standing between the cavity Rydberg polariton platform and its application as a truly scalable quantum repeater.

Accomplishments: During the funding period we explored ways to employ Rydberg blockade to detect single polaritons. Our proposed approach:

- 1) using polariton blockade to coherently excite a single cavity polariton in the system via a polaritonic pi-pulse.
- 2) shelve the polariton as a Rydberg atom in a different rydberg state via a microwave pi-pulse between Rydberg states.
- 3) probe the cavity through Rydberg EIT, and observe that, if we shelved a rydberg atom in steps (1) & (2) then we expect to observe blockaded transmission of the resonator; on the other hand if we did not shelve a Rydberg than we expect to observe transmission through the cavity.
- 4) If we can probe the cavity for long enough, the transmitted photon-number difference in a single measurement can be larger than the noise level (typically photon shot noise, so we need more than 1 - photon transmitted on average), then we can deterministically detect a single polariton.

We were able to observe (1)-(3) in the lab on average, but unfortunately were unable to probe for long enough to detect even a single transmitted photon in a single run of the experiment. As a consequence, we were not able to achieve deterministic detection of a single polariton.

What we learned is that the key challenges are:

- (1) cavity impedance matching -- if the photons are predominantly lost due to mirror scattering rather than mirror transmission, we lose most of our signal photons. <A transmission-dominated cavity is thus crucial>
- (2) interactions between the probe photons: if the probe polaritons interact with one another as strongly as they interact with the shelved rydberg, only a single probe polariton can go through the cavity at a time, strongly limiting the number of photons that may be collected during the lifetime of the shelved Rydberg. <to improve on this axis, either (a) a forster resonance or (b) enough control field intensity to reduce the polariton-polariton interactions compared to shelved Rydberg-polariton interactions will be required).

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Training Opportunities: Graduate students Lukas Palm and Claire Baum worked on this project as their first independent experimental work. Claire has now received her PhD and is now a postdoc in neuroscience. Lukas is now a senior student, having developed a new experimental apparatus with a blue buildup cavity to provide larger contrast between the polariton-shelved rydberg interaction and polariton-polariton interaction. We expect to revisit the deterministic polariton detection in the coming year.

Results Dissemination: In the process of developing the new apparatus with a blue buildup cavity, we learned a lot about both beyond paraxial optics:

<https://opg.optica.org/viewmedia.cfm?uri=optica-9-8-878&seq=0>

and back-reflection in optical resonators:

<https://arxiv.org/pdf/2105.05235.pdf>

Honors and Awards: Nothing to Report

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: Graduate Student (research assistant)

Participant: Lukas Palm

Person Months Worked: 6.00

Funding Support:

Project Contribution:

National Academy Member: N

Partners

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

Signature: Jonathan Simon

Signature Date: 3/29/23 11:22AM

Final Report: Microscopy of Individual Rydberg Polaritons

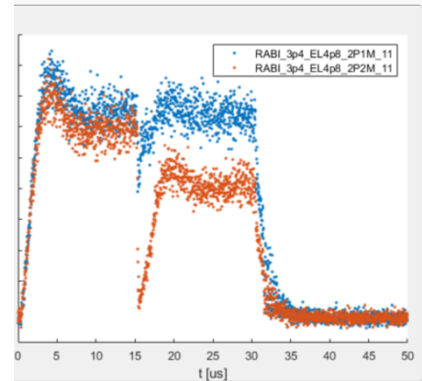
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We propose to develop the tools to implement high-fidelity fluorescence detection of single cavity Rydberg polaritons, which are the central ingredient of the Simon Lab's photonic quantum materials platform. This new tool will not only enable us to prepare and study substantially more sophisticated quantum many-body states, but is indeed the essential ingredient standing between the cavity Rydberg polariton platform and its application as a truly scalable quantum repeater.

In this program we planned to focus on non-destructive detection of polaritons by shelving them in an auxiliary Rydberg level, and then detecting that shelved Rydberg via cavity transmission. An early measurement of this effect is shown below, where, from time 0 to 15 microseconds polaritons are optically excited through the cavity end-mirror, and optical leakage of polaritons through the other end-mirror are detected. At 15 microseconds, a fast microwave Rabi π -pulse is/is not (orange/blue) applied to shelve the Rydberg-part of the polariton in a P-state; a subsequent optical excitation pulse reveals that subsequent to shelving the cavity emission rate decreases, as anticipated if the shelved Rydberg *blocks* the excitation of future polaritons. This is a proof-of-concept of the blockade-enhanced detection, though our narrow polariton linewidth, poor cavity mode-matching, and finite atomic optical depth limited the number of photons that we detect per polariton to less than one in the current iteration of the machine.



In order to *drastically* improve this situation we have undertaken a number of very substantial upgrades, resulting in an essentially new in-vacuum system and atom loading protocol:

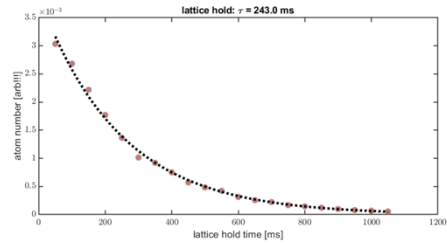
1. A new, higher-finesse and in-vacuum-alignable Rydberg-control-field build-up cavity, based upon vacuum manipulation of the mirrors; *this will allow for rapid increase in the polariton linewidth to more efficiently detect many photons within the polariton lifetime.*
2. Better impedance matching to the cavity by making the new resonator single-ended, requiring additional coating runs to produce a higher-transmission outcoupling mirror in addition to the high-reflection mirrors used for the rest of the physics cavity. This should provide a factor of ~ 2 in detected photon number per polariton, barring other losses.
3. Substantially higher optical depth of the atomic sample producing the polaritonic quantum dynamics of interest, and the blockaded readout. This will both allow more polariton collisions/quantum gates, depending upon application, and provide a stronger

blockade in the shelved readout regime and thus allow for faster blockade-enhanced detection.

The work in this STIR focused on challenge #3. The upshot is that, through introduction of additional degenerate Raman sideband cooling and atomic compression techniques harnessing intracavity dipole traps, we have achieved an optical depth within our $w=19\ \mu\text{m}$ cavity mode waist of $OD \approx N\eta \approx 2500$; this is an improvement over prior work from our group of a factor of ~ 20 , in the state-of-the-art in free-space by a factor of ~ 100 . Because photonic gate infidelity $\epsilon \approx \frac{\pi}{\sqrt{N\eta}}$, the number of collisions in a photonic quantum material $N_{coll} \approx \sqrt{N\eta}$, and the on/off contrast of a polariton switch/polariton detector $C_{switch} \approx N\eta$, it is apparent that this increase in optical depth will be absolutely transformative for the science accessible in our platform.

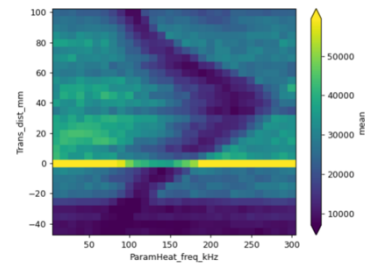
To achieve this increase in optical depth we:

1. Improved our lattice lifetime to $\sim 200\text{ms}$ (see Figure at right) through a combination of reduced spontaneous scattering of stray resonant light; narrower trapping laser linewidth; and reduced intensity noise induced acousto-optic modulators.

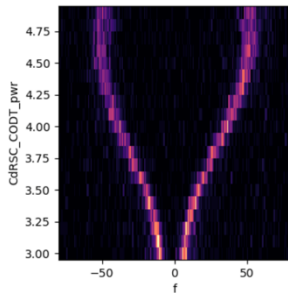


by

2. Optimization of transport lattice alignment through precision transport-distance dependent atom-loss spectroscopy (see Figure at right).



3. Introduction of an intra-cavity optical dipole trap to adiabatically compress the atom cloud, in conjunction with additional Raman-cooling stages to remove extra energy introduced by the adiabatic compression. The left Figure shows the vacuum Rabi splitting



(reflecting the square root of the atom number) in the cavity optical dipole trap as a function of the trapping power, reaching a maximum above 100MHz. By loading atoms into the MOT for longer, we can increase this number even further, indicating that we are not yet density limited, and could further increase the optical depth ($OD = N\eta = \frac{Ng^2}{\kappa\Gamma}$) by loading the MOT from multiple getter atom sources; loading the transport lattice more efficiently; or compressing more of the transported atoms into the intra-cavity lattice.

With these advances in hand, we anticipate demonstrating high fidelity polariton-by-polariton switching (equivalent to blockade-enhanced polariton detection) in the coming year, once our fully updated apparatus comes online and is fully commissioned.