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Quantum Manybody Physics with Rydberg Polaritons

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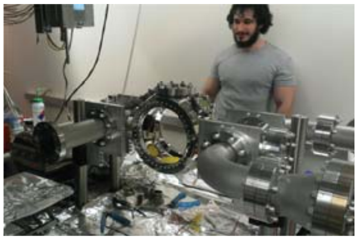
Abstract

Over the course of this grant, we have seen tremendous progress, both theoretically and experimentally, in our control of photonic Hamiltonians. We have developed near-degenerate optical resonators to manipulate the single-particle sector, and coupled the photons in these resonators to small, optically thick samples of Rubidium Rydberg atoms to eventually mediate strong photon-photon interactions and build photonic materials.

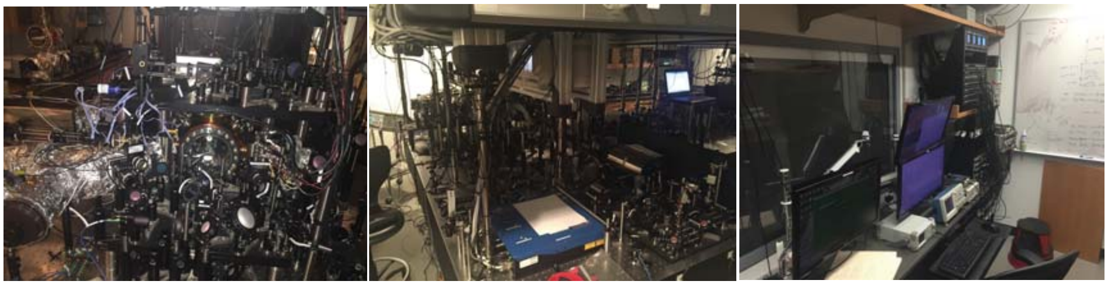
This document summarizes these various efforts, and progress towards achieving the listed scientific goals. In short, we have built a one-of-a-kind apparatus to laser-cool ^{87}Rb atoms, load them into an optical lattice, and transport them, within ~10ms, 2cm into the small (12 μm) waist of a running-wave optical resonator. The atoms are then Rydberg-dressed with a narrow laser at 480nm, and the structure of the resulting cavity-polaritons is spectroscopically probed. We find that the individual cavity-Rydberg-polaritons behave in quantitative agreement with models that we have developed. In conjunction with synthetic magnetic fields generated through non-planar cavities, we are now poised to explore fractional quantum hall physics of photonic quasi particles.

Our approach to engineering photonic materials relies heavily on coupling our photons to *both* Rydberg atoms to mediate interactions, and a high-finesse optical resonator to control the single particle properties (Sommer *et al.,* ***NJP*** 18, 035008, 2016). This combination has proven unexpectedly challenging, as the cavity structure produces stray fields which perturb the Rydberg atoms very strongly. As such, a large portion of this document is dedicated to exploring these effects, and the final solution which we have ultimately reached, based on an even more exotic type of optical resonator, to keep the resonator mirrors as far as possible from the atomic sample.

Apparatus



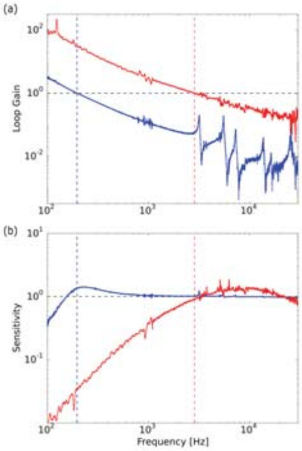
Over the course of the grant, we have built a cold atom machine combining the challenges of Rydberg physics with the challenges of cavity quantum electrodynamics. The apparatus, shown in multiple stages of construction at left and below, spans three optical tables in two rooms: One for the experimental control system, comprised of two computers, that control sequenced 32 analog outputs, 32 digital outputs, 12x3.5GHz FPGA-controlled DDS channels, 4x500MHz static DDS channels, and a four-channel FPGA-based pulse timer.

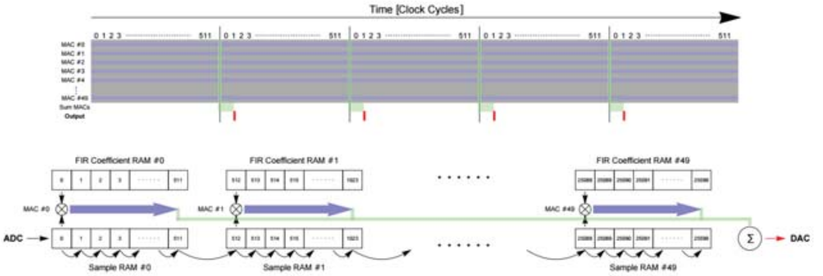


The optical setup is split into two tables: one for laser preparation, and one (primarily) for the vacuum system. On the laser table, reference, MOT, and Repumper DFB lasers are frequency stabilized, with agile, real-time control of their wavelength across the ^{87}Rb D2 line. The MOT laser is amplified with a fiber-coupled tapered amplifier, and combined with the Repumper laser, to generate the magneto-optical trap. The remainder of this table is employed for a 783nm neardetuned transport lattice laser, generated from an electronically narrowed DFB sent through a tapered amplifier, as well as a 1560nm fiber laser employed for cavity locking with a few kHz linewidth, which is fiber-amplified, and single-pass-doubled to provide our ultra-narrow probe laser for Rydberg EIT experiments. The 480nm laser for exciting from the P-state to the Rydberg state is housed on the second optical table, along with an ultrastable vacuum cavity employed to lock it, and the 1560nm fiber laser. We employ a novel sideband-on-sideband laser locking scheme to achieve agile control of the experimental cavity wavelength, along with the probe and cavity locking lasers.

The heart of the apparatus is the optical resonator which resides within a UHV chamber. Because our experiments occur on millisecond timescales rather than the second timescales of a typical lattice experiment (the photons move a lot faster than atoms tunnel), we are able to get away with a vacuum of only ~10^{-9} Torr (background-gas limited lifetime of ~2 sec), permitting a much wider array of materials in our vacuum chamber than ultracold-atom/lattice experiments. This has enabled us to employ exotic resonators relying upon numerous in-vacuum electrodes, heating elements, and piezo-electric transducers. While the cavity has now undergone several iterations, its qualitative form is shown at left, immediately prior to installation into the vacuum system.

To stabilize this resonator, we employ a electro-optic sideband FM transmission lock, similar in spirit tothe Pound-Drever-Hall scheme. This approach, while successful, has suffered from the mechanical floppiness of our optical resonator mounting structure. Such floppiness (low frequency mechanical resonances) is unavoidable in exotic resonator geometries, and will need to be resolved in the long-term. To this end, we have developed a state-of-the-art FPGA-based finite-impulse-response filter to precisely electronically cancel mount resonances up to ~100 kHz. This first-of-its-kind device performs a 60000 point fixed-point convolution 250000 times per second, employing 50 parallel multiply-and-accumulate channels each operating at over 100 MHz (as shown below right). The results of employing this device, shown at left, are striking. The mechanical resonances and anti-resonances in the piezo transfer function have been completely cancelled out up to 100 kHz, enabling a factor of ten increase in noise suppression bandwidth. This technique promises to be extremely useful for rapidly switching the resonant frequency, as well as stabilization of higher finesse cavities, more rapid turn-off of the MOT coils (which otherwise induce eddy currents in the piezos and shake the resonator). It appears likely that the technology will also find application in LIGO, as well as optomechanical squeezing experiments.

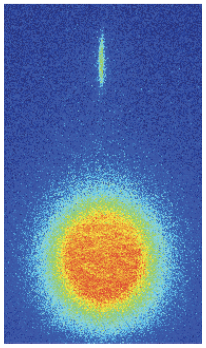




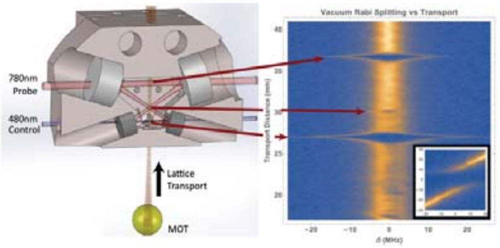
Towards Manybody Physics with Rydberg Polaritons

Over the coarse of the grant, we have succeeded in exploring the properties of cavity Rydberg polaritons, and along the way have learned quite a bit about stray electric fields and their impact upon Rydbergs.

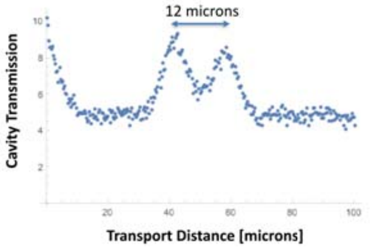
The first step in our experiments is to load a MOT, and polarization gradient cool it, and load it into an optical transport lattice. In the fluorescence image at left, only a small fraction of the atoms (upper pencil-shaped cloud) are loaded into our transport lattice. The majority remain in the MOT (large, bright disk). We have since loaded our lattice at densities beyond $10^{10}/cm^3$, capturing nearly half of our MOT.

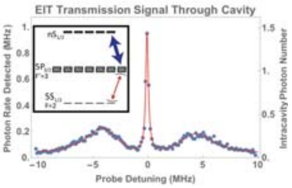


We then adiabatically transport the atoms into the optical resonator by ramping (via DDS) the relative frequency of the lattice beams. In the figure below right, the cavity transmission is plotted versus probe frequency (x-axis) and atom transport distance (y axis). The appearance of an atomic vacuum Rabi splitting at 27mm of transport and 36mm of transport reveals the presence of the atomic cloud in the lower- and upper- waists of our optical resonator, respectively. The inset reveals the avoided crossing when the cavity and probe are tuned.



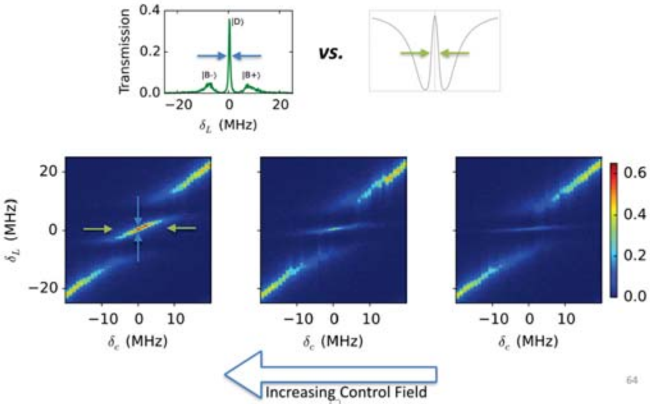
To mediate interactions between the photons, it will eventually be essential that the polaritonic quasi-particles are localized to distances where their Rydberg components can interact substantially. For n=70~100 Rydbergs, an interaction of a few MHz requires separations less than approximately 10 microns. Our first experiments treat a single-mode resonator as a sort of polaritonic "quantum dot" that photons can tunnel into and out of, and so the size of this island should be of order 10 microns. We achieve this, first and foremost, by employing a resonator whose designed mode-waist is 12 microns. We verify experimentally that the waist is 12 microns by blowing away atoms by sending light through the resonators TEM10 mode, thus imprinting the inverse of the shape of the TEM10 mode on the atomic cloud. We then transport the atoms through the cavity (using the lattice) and observe the transmission as a function of location. As the atoms detune the resonator, the shape of the TEM10 mode is apparent in the transmission spectrum, as shown at right.



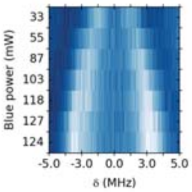


We next explored Rydberg EIT in the single-mode case by dressing the atomic cloud in the lower waist with a 480nm laser field, tuned to the 5P-nS transition, where n is 40~68. A typical probe scan, shown at left, reveals the vacuum Rabi doublet characteristic of a medium resonantly coupled to an optical cavity, as well as a dark resonance characteristic of an ensemble of three-level emitters. This dark resonance may be narrower than the optical resonator itself, as it is largely Rydberg-like, and the atomic Rydberg state can live longer than the resonator photons (Ningyuan *et al.*, **PRA** 93, 041802, 2016).

The narrowing of the resonator line due to the coupling to the Rydbergs is characteristic of a *dynamical slowdown* of polaritonic dynamics, relative to their photonic counterparts. It is also manifest as a reduced sensitivity to the resonator frequency, and most broadly reflects a compression of the single particle spectrum of the polaritons compared with the photons. We explore this first with a single isolated cavity mode, by mimicking the different frequencies of different modes by detuning the cavity, at right. It is apparent that, as the control field is reduced, the EIT feature becomes spectrally narrower, and its dependence upon the resonator frequency, δ_c, is reduced. One might be inclined to associate the width of the EIT feature with the width of the free-space EIT window; this is a false equivalence, as the width of the EIT feature has more to do with how long the photon lives in the cavity, than the spectral range over which EIT persists. Indeed, width of the free-space (corrected for the cavity-finesse-enhancement to the OD) is *precisely reflected* in the range of resonator frequencies over which the polariton lifetime is not reduced.

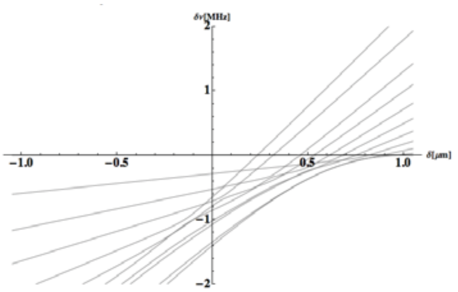


To explore the dynamical slowdown effect more thoroughly, we engineered our resonator to have manifolds of modes which are nearly degenerate, given by $\mathrm{TEM}_{(n,0)}$ and $\mathrm{TEM}_{(0,2n)}$. In the figure at right, we explore the spectrum of TEM10 and TEM02 dark polariton modes, as the blue control field power is reduced; we observe the expected mode compression. This indicates that once we have a cavity with a larger degenerate manifold of modes, reflecting the physics of either a massive harmonically trapped particle, a particle in a magnetic field, or a particle on a curved surface, the mode compression will behave as our simple theoretical models predict.

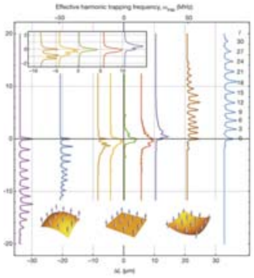


Quite recently, we managed to create a degenerate, twisted optical resonator within which photons behave as massive particles in a synthetic magnetic field ("Synthetic Landau levels for photons", Schine *et al.,* **Nature** 2016: doi:10.1038/nature17943). This groundbreaking result is the first demonstration of a bulk magnetic field for optical photons, all prior work having been conducted in a lattice. Furthermore, it is completely consistent with the requirements for introducing strong Rydberg-EIT based photon-photon interactions, for exploration of FQH/Laughlin physics, and the properties of anyonic quasi-particles.

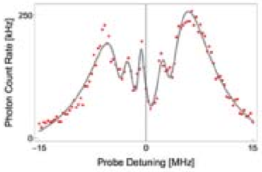
Perhaps most importantly, we have demonstrated that as we tune the resonator to precisely cancel the harmonic confinement induced by the resonator twist, the massively degenerate lowest Landau level that we produce is *exquisitely* flat. Consistent with modeling performed for the initial grant proposal (see right), we observe more than 10 states in the LLL compressed into a few MHz of bandwidth (see below), less than the bandwidth of the typical EIT window for our cavity-enhanced OD. Equally important is that Laughlin states *remain* nearly-zero energy states, *even in the presence of strong interactions.* This should be contrasted with crystalline states, whose interaction energy scales strongly with system size



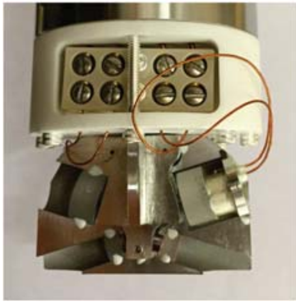
(particularly for a harmonically trapped crystal). This means that photonic Laughlin states will be less constrained by the EIT width than crystalline states, and should be easier to produce, more robustly.

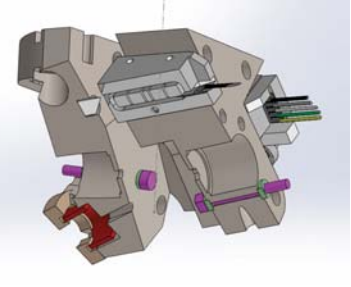


The next step, then, is to explore interactions between polaritons. To this end, we have begun attempting to operate at higher principal quantum numbers for the Rydberg state, where the interactions between the atoms becomes stronger. What we have found is that stray electric fields become prohibitive before the interactions between the atoms are strong enough to observe in the optical field. Initially, we contended with a constant offset field of ~0.5V/cm, induced by a metal electric field filter placed next to the atoms to shield them from charges built up on the dielectric mirrors. As best we can tell, this field arises from Rubidium atoms adsorbed onto the metallic surface forming patches of electric dipoles. We observed this field first as an EIT-splitting of Rydberg D-states (see right).



To compensate this offset field, we moved from a resonator with only a passive electric field *filter* (see below, left), to one with 8 segmented electrodes (see below, second from left). This enabled us to compensate for stray fields, but still left us with large gradients and field curvatures that, while perhaps possible to correct in principle, in practice we were unable to control before they drifted due to additional Rubidium deposition.

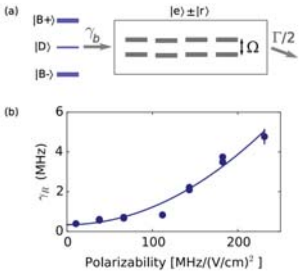




Moving forward, we have designed and built an exotic resonator employing both convex *and* concave supermirrors, exhibiting a similarly small ~12 micron waist, but with the closest surface nearly a cm from the atomic cloud, rather than a mm (see above, second from right). In conjunction with a re-orientation of our atomic source to prevent line-of-site access to the metal structure, we anticipate 1000x suppression of stray fields, and 10000x suppression of gradients, and 100000x suppression of field curvature. In truth, so long as the fields are stable, even a 10x suppression in the fields, and corresponding suppresion in gradients and curvatures, will be more than sufficient to perform all desired experiments up to n=100S.

In parallel, we have begun to develop a UHV-compatible twisted resonator whose length is broadly tunable with slip-stick piezo actuators (see above, right). This resonator *also* boasts a minimum separation between atoms and all resonator structures of nearly a cm, relying again upon convex supermirrors.

In keeping with our initial proposal, we have also explored the collective suppression of inhomogeneous broadening in cavity EIT. This is important because, to lowest order, it is in fact electric field *gradients* and *curvature* which decohere Rydberg polaritons, and not the constant offset field, which simply shifts the polariton resonance, and in any event may be compensated. In the initial grant proposal, we anticipated that the dominant source of inhomogeneous broadening would be atomic motion (so-called *Doppler broadening*), arising from the k-vector mismatch between cavity photon (at 780nm) and control field (at 480nm). Fascinatingly, this broadening mechanism takes the same form as that arising from inhomogeneous electric fields:



Shown at left is the extracted decay rate of the collective Rydberg excitation, as a function of its polarizability (adjusted by changing principal quantum number). While the single particle inhomogeneous linewidth scales linearly with the polarizability of the Rydberg state, the observed broadening scales quadratically. This indicates that there is in fact a detuning between the inhomogeneously broadened manifold of single particle states, and the cavity polariton state of interest. As mentioned above, this was anticipated in the original grant proposal, arising from the absence of a cavity coupling of the broadened single particle states. The demonstrated existence of this suppression is fantastic news for our next generation of experiments, indicating that not only will we be insensitive to doppler broadening, but a modest improvement in stray fields will lead to a marked improvement in polariton coherence.

1.

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Jonathan Simon

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Abstract

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"Observation and characterization of cavity Rydberg polaritons," Ningyuan et al., Physical Review A 93 (4), 041802.

"Engineering photonic Floquet Hamiltonians through Fabry–Pérot resonators," Sommer et al., New Journal of Physics 18 (3), 035008.

"Active Cancellation of Acoustical Resonances with an FPGA FIR Filter," Ryou et al., arXiv:1604.04668.

"Time-and site-resolved dynamics in a topological circuit," Ningyuan et al., Physical Review X 5 (2), 021031.

"Quantum Crystals and Laughlin Droplets of Cavity Rydberg Polaritons", Sommer et al., arXiv preprint arXiv:1506.00341.

"Engineering topological materials in microwave cavity arrays," Anderson et al., arXiv preprint arXiv:1605.03177.

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