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Major Goals: The broad goal of the project is to develop a versatile toolbox for quantum simulation of two-dimensional lattice spin models with ultracold atoms. To date, the most elusive element of such a toolbox has been a means of engineering coherent and tunable long range interactions. We aim to fill this gap by building upon recent advances in coherent manipulation of Rydberg states -- highly excited electronic states featuring long-range dipole-dipole and van der Waals interactions. In particular, we will harness the method of Rydberg dressing, introducing long-range interactions among ground-state atoms pinned in an optical lattice by off-resonantly coupling the atoms to Rydberg states.

Rydberg dressing theoretically offers versatile control over the form of interactions, including their sign, range, and [an]isotropy in spin and in real space. The method is ideally suited to generating frustration in antiferromagnetic models, thanks to a plateau shaped interaction potential that gives rise to many degenerate or near-degenerate ground states. Such frustrated anti-ferromagnets are of interest for the pursuit of topological order. Rydberg dressing also promises new opportunities for accessing non equilibrium topological phases of matter by optically controlling the strength or sign of interactions. Yet another prospect is to engineer spin-spin interactions that change sign as a function of distance, mimicking a paradigmatic model for spin-glass physics.

Tapping into these opportunities requires advancing the state of the art in control and coherence of the interactions generated by Rydberg dressing. An initial goal is to identify optimal parameter regimes for attaining coherent interactions in the many-body system, namely, a two-dimensional plane of a hundred spins or more. In particular, we will seek to maximize the interaction-to-decay ratio by choosing Rydberg states near a Foerster resonance and by tuning the lattice spacing according to the resulting interaction range. We will then test the capability for simulating well understood phase transitions in transverse-field Ising models, initially on a dilutely filled lattice analogous to a magnet with quenched disorder in the solid state. We will furthermore expand the capabilities of Rydberg dressing to encompass Heisenberg models by engineering flip-flop processes, in which spin excitations hop from one site to another on the lattice.

Successful simulations of disordered quantum magnets by Rydberg dressing will pave the way to engineering designer Hamiltonians on honeycomb and kagome lattices in future extensions to the current project. These geometries are ideally suited to generating frustration that thwarts magnetic ordering, and accordingly feature prominently in the growing list of models with putative spin-liquid ground states. Motivated by these models, our apparatus will already feature a triangular lattice, ready for extension to the honeycomb and kagome geometries by suitable positioning of the atoms.

The project milestones were divided into three phases:

1. Apparatus design and construction
[a] Three-chamber vacuum system
[b] Magneto-optical trap
[c] Optical dipole trap and lattice laser system
[d] Rydberg laser system: spectroscopy and locking

2. Preparation and imaging of 2D atomic lattice
[a] Optical transport to science chamber
[b] Loading atoms into a single 2D plane of lattice
[c] High-resolution, state-sensitive imaging

3. Physics with Rydberg-dressed atoms
[a] Spectroscopy and verification of dressing
[b] Site-disordered Ising models
[c] Site-disordered Heisenberg models

Accomplishments: See attached PDF.

Training Opportunities: The project provided training for four graduate students, one postdoctoral researcher, and several undergraduate students who participated in the research. These project participants developed expertise in techniques of experimental atomic and optical physics, quantum simulation and relevant aspects of condensed-matter theory, numerical techniques for simulation of quantum many-body dynamics, as well as widely applicable analytical and problem-solving skills. The students and postdoctoral researcher also had the opportunity to present their research results in talks and posters at conferences including the APS DAMOP Meeting, KITP Workshop on Open Quantum Systems, Gordon Research Conference on Atomic Physics, and the International Conference on Quantum Fluids and Solids.

Results Dissemination: Results from the project have been published in (or accepted by) Physical Review Letters [Potirniche et al (2017); Borish et al (2020); Hines et al. (to appear)] and PRX Quantum [Anikeeva et al. (2021)]. In addition, results from the project were disseminated in invited conference presentations and colloquia by the PI, as well as conference talks and posters by graduate students participating in the project. Conferences and colloquia featuring our work in invited presentations included:

1. APS DAMOP Meeting [Milwaukee, WI, 2019]
2. Many Facets of Non-Equilibrium Physics [Mazara, Italy, 2019]
3. Otto Stern Fest [Frankfurt, Germany, 2019]
4. Israeli Physical Society Annual Meeting [Rehovot, Israel, 2020]
5. Simons Foundation Workshop on Ultra Quantum Matter [virtual, 2020]
6. Princeton University Physics Colloquium [virtual, 2020]
7. IBM Qiskit Quantum Information Science Seminar [virtual, 2020]
8. International Conference on Quantum Fluids and Solids (QFS) [virtual, 2021]

Honors and Awards: PI Schleier-Smith received the Presidential Early Career Award for Scientists and Engineers (PECASE), the I. I. Rabi Prize of the American Physical Society, a MacArthur Foundation Fellowship, and an American Physical Society Fellowship. Graduate student Tori Borish received a DARE Doctoral Fellowship and Stanford's Centennial Teaching Award. Undergraduate student Simon Evered received Stanford's Firestone Award for Excellence in Undergraduate Research.

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PARTICIPANTS:

Participant Type: PD/PI

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Person Months Worked: 10.00 **Funding Support:**
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Project Contribution:
National Academy Member: N

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Authors: Ionut-Dragos Potirniche, Andrew C. Potter, Monika Schleier-Smith, Ashvin Vishwanath, Norman Y. Yao
Keywords: quantum physics, topological phases, Rydberg atoms
Abstract: We propose two distinct routes toward realizing interacting symmetry-protected topological (SPT) phases via periodic driving. First, we demonstrate that a driven transverse-field Ising model can be used to engineer interactions which enable the emulation of an equilibrium SPT. This phase remains stable only within a parametric time scale controlled by the driving frequency. To overcome this issue, we consider an alternate route based upon an intrinsically Floquet SPT phase that does not have any equilibrium analogue. In both cases, we show that disorder, leading to many-body localization, prevents runaway heating and enables the observation of coherent quantum dynamics at high energy densities. We clarify the distinction between the equilibrium and Floquet SPT phases by identifying a unique micro-motion-based entanglement spectrum signature of the latter. Finally, we propose a unifying implementation in a chain of Rydberg-dressed atoms and show that protected edge modes are observable.
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Authors: V. Borish, O. Markovic, J. A. Hines, S. V. Rajagopal, M. Schleier-Smith
Keywords: cold atoms, long-range interactions, spin dynamics, Floquet systems
Abstract: We report on the realization of long-range Ising interactions in a cold gas of cesium atoms by Rydberg dressing. The interactions are enhanced by coupling to Rydberg states in the vicinity of a Förster resonance. We characterize the interactions by measuring the mean-field shift of the clock transition via Ramsey spectroscopy, observing one-axis twisting dynamics. We furthermore emulate a transverse-field Ising model by periodic application of a microwave field and detect dynamical signatures of the paramagnetic-ferromagnetic phase transition. Our results highlight the power of optical addressing for achieving local and dynamical control of interactions, enabling prospects ranging from investigating Floquet quantum criticality to producing tunable-range spin squeezing.
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Authors: Galit Anikeeva, Ognjen Markovic, Victoria Borish, Jacob A. Hines, Shankari V. Rajagopal, Eric S. Coope
Keywords: Quantum algorithms, atomic physics, quantum optics, spin dynamics, Rydberg atoms
Abstract: Numerous conceptually important quantum algorithms rely on a blackbox device known as an oracle, which is typically difficult to construct without knowing the answer to the problem that the algorithm is intended to solve. A notable example is Grover's search algorithm. Here we propose a Grover search for solutions to a class of NP-complete decision problems known as subset sum problems, including the special case of number partitioning. Each problem instance is encoded in the couplings of a set of qubits to a central spin or boson, which enables a realization of the oracle without knowledge of the solution. The algorithm provides a quantum speedup across a known phase transition in the computational complexity of the partition problem, and we identify signatures of the phase transition in the simulated performance. Whereas the naive implementation of our algorithm requires a spectral resolution that scales exponentially with system size for NP-complete problems, we also present a ...
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Authors: Jacob Hines, Shankari Rajagopal, Gabriel Moreau, Michael Wahrman, Neomi Lewis, Ognjen Markovic,
Keywords: quantum metrology, Rydberg atoms

Abstract: We report on the creation of an array of spin-squeezed ensembles of cesium atoms via Rydberg dressing, a technique that offers optical control over local interactions between neutral atoms. We optimize the coherence of the interactions by a stroboscopic dressing sequence that suppresses super-Poissonian loss. We thereby prepare squeezed states of N = 200 atoms with a metrological squeezing parameter 0.77(9) quantifying the reduction in phase variance below the standard quantum limit. We realize metrological gain across three spatially separated ensembles in parallel, with the strength of squeezing controlled by the local intensity of the dressing light. Our method can be applied to enhance the precision of tests of fundamental physics based on arrays of atomic clocks and to enable quantum-enhanced imaging of electromagnetic fields.

Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
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Partners

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I certify that the information in the report is complete and accurate:
Signature: Monika Schleier-Smith
Signature Date: 7/12/23 11:04PM

Quantum Simulation of Frustrated Magnets by Rydberg Dressing

Monika Schleier-Smith
Stanford University

Motivated by applications in quantum simulation of frustrated lattice spin models, this project aimed to advance methods of Rydberg dressing for optical control of long-range spin interactions. The approach of Rydberg dressing was selected because it produces a plateau-shaped interaction potential conducive to generating frustration and offers a route to optically tuning the strength, sign, and anisotropy of spin-spin interactions, where the spins are encoded in hyperfine ground states. Objectives included demonstrating dynamic optical control of the interactions and characterizing the interactions via quench dynamics; investigating the use of near-Förster-resonant Rydberg dressing to enhance the range of the Rydberg-dressed potential and facilitate switching their sign; and observing phase transitions in transverse-field Ising models. Specifically, we applied Floquet engineering to realize a transverse-field Ising model in a Rydberg-dressed atomic gas and observed signatures of a paramagnetic-ferromagnetic phase transition in the resulting mean-field dynamics [1]. We furthermore developed a technique of stroboscopic Rydberg dressing to maximize the coherence of the interactions [2]. In related theoretical work, we proposed applications of Rydberg dressing to realizing Floquet topological phases [3] and to implementing a quantum optimization algorithm for the NP hard problem of number partitioning [4].

I. MAJOR GOALS AND OBJECTIVES

Following is a description of the project objectives as stated in the grant proposal.

The broad goal of the project is to develop a versatile toolbox for quantum simulation of two-dimensional lattice spin models with ultracold atoms. To date, the most elusive element of such a toolbox has been a means of engineering coherent and tunable long range interactions. We aim to fill this gap by building upon recent advances in coherent manipulation of Rydberg states—highly excited electronic states featuring long-range dipole-dipole and van der Waals interactions. In particular, we will harness the method of Rydberg dressing, introducing long-range interactions among ground-state atoms pinned in an optical lattice by off-resonantly coupling the atoms to Rydberg states.

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Tapping into these opportunities requires advancing the state of the art in control and coherence of the interactions generated by Rydberg dressing. An initial goal is to identify optimal parameter regimes for attaining coherent interactions in the many-body system, namely, a two-dimensional plane of a hundred spins or more. In particular, we will seek to maximize the interaction-to-decay ratio by choosing Rydberg states near a Foerster resonance and by tuning the lattice spacing according to the resulting interaction range. We will then test the capability for simulating well understood phase transitions in transverse-field Ising models, initially on a dilutely filled lattice analogous to a magnet with quenched disorder in the solid state. We will furthermore expand the capabilities of Rydberg dressing to encompass Heisenberg models by engineering "flip-flop" processes, in which spin excitations hop from one site to another on the lattice.

Successful simulations of disordered quantum magnets by Rydberg dressing will pave the way to engineering designer Hamiltonians on honeycomb and kagome lattices in future extensions to the current project. These geometries are ideally suited to generating frustration that thwarts magnetic ordering, and accordingly feature prominently in the growing list of models with putative spin-liquid ground states. Motivated by these models, our apparatus will already feature a triangular lattice, ready for extension to the honeycomb and kagome geometries by suitable positioning of the atoms.

The project milestones were divided into three phases:

1. Apparatus design and construction (a) Three-chamber vacuum system (b) Magneto-optical trap (c) Optical dipole trap and lattice laser system (d) Rydberg laser system: spectroscopy & locking

2. Preparation and imaging of 2D atomic lattice (a) Optical transport to science chamber (b) Loading atoms into a single 2D plane of lattice (c) High-resolution, state-sensitive imaging

3. Physics with Rydberg-dressed atoms (a) Spectroscopy and verification of dressing (b) Site-disordered Ising models (c) Site-disordered Heisenberg models

II. ACCOMPLISHMENTS

Major accomplishments included the construction of the experimental apparatus, the realization of a transverse-field Ising model by Rydberg dressing [1], and the development of a stroboscopic dressing technique for maximizing the coherence of the interactions [2]. We also conducted supporting theoretical work, publishing proposals for leveraging Rydberg dressing to access Floquet topological phases [3] and to enable a quantum optimization algorithm [4].

A. Experimental Apparatus for Rydberg Dressing

The project began with the construction of an experimental apparatus designed for quantum simulations of lattice spin models with Rydberg-dressed cesium atoms. We constructed a three-chamber vacuum system comprised of a 2D MOT, a 3D MOT, and a science chamber featuring in-vacuum electrodes and a high-numerical-aperture objective designed to enable single-site addressing and imaging. Atoms are transported from the 3D MOT to the science chamber in an optical dipole trap controlled by a focus-tunable lens. While our long-term science goals will require transferring these atoms into a two-dimensional optical lattice, we proceeded directly to investigating the physics of Rydberg-dressed interactions in the setting of a bulk gas, first in a single-beam optical dipole trap [Borish et al, PRL (2020)] and subsequently in an array of optical microtraps [Hines et al, PRL (accepted)].

To enable Rydberg dressing, we installed an ultraviolet laser system for single-photon coupling to cesium Rydberg states. The laser system consists of a 1280 nm diode laser which is locked to a stable reference cavity, amplified by a 7 W Raman Fiber Amplifier, and subjected to two stages of resonant frequency doubling to produce an output power of up to 900 mW at a wavelength of 320 nm.

B. Transverse-Field Ising Dynamics

As a demonstration of dynamical optical control of interactions via Rydberg dressing, we engineered a Floquet transverse-field Ising model in a dilute gas of cesium atoms [1]. Here, the spin degree of freedom is encoded in the hyperfine clock states of cesium, one of which is off-resonantly coupled to a Rydberg P state to induce interactions. To generate Ising interactions while canceling any additional ac Stark shift from the dressing light, we apply a pair of dressing pulses in a spin echo sequence incorporating a microwave π pulse on the clock transition. To introduce an effective transverse field, we insert additional microwave pulses of tunable angle in between periods of Ising interactions. For sufficiently fast alternation between the interactions and the transverse field, the result is a trotterized transverse-field Ising model.

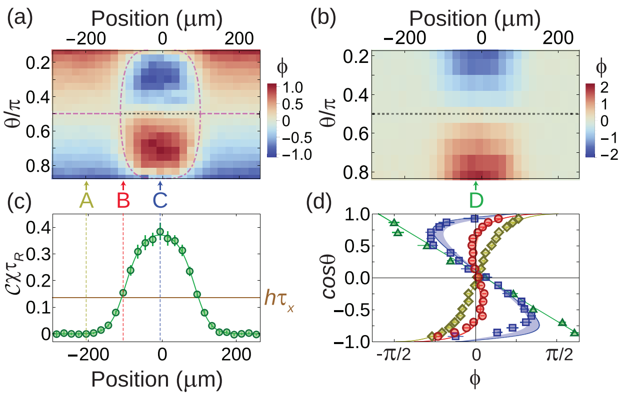

FIG. 1: **Dynamical signature of paramagnetic-to-ferromagnetic phase transition (from Ref. [1]).** (a-b) Phase ϕ of the average Bloch vector as a function of initial tilt θ of Bloch vector and position in the atomic cloud, for (a) Ising interactions with transverse field or (b) Ising interactions only. The $\phi = 0$ contour reveals fixed points of the mean-field dynamics, showing a bifurcation at the paramagnetic-to-ferromagnetic phase transition. Fitting the phase evolution in (b) yields the average mean-field interaction per cycle, shown in (c) by green points and fit curve. (d) Final phase ϕ vs. initial tilt θ for cuts labeled A (yellow diamonds), B (red circles), C (blue squares), and D (green triangles), in order of increasing increasing interaction strength.

The transverse-field Ising model possesses a well-studied phase transition between a paramagnet (in the limit of a strong transverse field) and a ferromagnet (for strong interactions of the appropriate sign). In our experiment, we observed signatures of this phase transition in the mean-field dynamics of a gas prepared in different initial spin-polarized states. In particular, the paramagnetic ground state manifests in the dynamics as a stable fixed point, which undergoes a bifurcation into two stable fixed points as the interaction strength is increased to enter the ferromagnetic phase. By imaging the magnetization dynamics in a spatially extended atomic gas subject to an inhomogeneous intensity of the dressing light, we were able to directly observe this bifurcation as a function of position in the gas (Fig. 1). We published these results in *Physical Review Letters* [1].

C. Maximizing the Coherence of Rydberg Dressing

Crucial to enabling goals in quantum simulation is achieving a large ratio $J/\gamma \gg 1$ of the interaction strength J to the decay rate γ of the Rydberg-dressed state. Past experiments have observed an interaction-to-decay ratio substantially lower than a naive estimate would predict, due to multibody loss processes arising from the fact that a single atom excited to the Rydberg state can shift the dressing light onto resonance for neighboring atoms, triggering an avalanche of subsequent excitation and decay. A key accomplishment of the present project was to develop a method of stroboscopic Rydberg dressing [1, 2] that maximizes the coherence of interactions. Here, the light is applied in a sequence of short pulses separated by a delay to ensure that, should any atom be excited to the Rydberg manifold, it decays before the application of additional dressing light. We optimized the stroboscopic dressing technique with the aid of sensitive projection-noise-limited measurements in ensembles of $10^2 - 10^3$ atoms, which allowed us to probe the super-Poissonian statistics of percent-level loss.

In early experiments, we additionally investigated Rydberg dressing near a Förster resonance as a means of enhancing the range and controlling the sign of interactions, as originally proposed in the project goals. However, we observed increased loss for this near-Förster-resonant dressing (at principle quantum number $n = 43$), compared to choosing a state of higher principle quantum number ($60P_{3/2}$) with a similar strength C_6 of the van der Waals interaction. The excess loss in the vicinity of the Förster resonance may be attributable to molecular potentials at short distances $\lesssim 500$ nm; thus, whether it poses a limitation should be reexamined in future experiments in the more controlled setting of a lattice or tweezer array. Suppressing this loss would allow for leveraging the Förster resonance to dynamically control the sign of the Rydberg-dressed interactions, as envisaged in our theoretical proposal for realizing a Floquet symmetry-protected topological (SPT) phase [3]. As a step in this direction, we have already demonstrated control over the sign of the Rydberg dressed potential via the laser detuning and principle quantum number in Ref. [1].

D. Theoretical Results

Floquet Topological Phases: Together with theory collaborators including N. Yao and A. Vishwanath, we proposed an approach to realizing a newly predicted topological phase of matter by Rydberg dressing [3]. The Floquet symmetry-protected topological phase is predicted to arise in a one-dimensional spin chain subject to a Hamiltonian that is modulated periodically in time. The modulation gives rise to a symmetry under discrete translations in time, and this symmetry protects the coherence of two spin-1/2 degrees of freedom localized at the ends of the chain. This work was published in *Physical Review Letters* [3].

Quantum Optimization: Inspired by our experimental work on Rydberg dressing, we also developed a theoretical proposal for harnessing these optically controlled interactions in a quantum optimization algorithm for the NP hard problem of number partitioning. Each instance of this problem is specified by a set of integer weights, and the objective is to partition the weights into two groups that would balance a scale. In our algorithm, the weights are encoded in the couplings between a group of spins and a central ancilla atom. This configuration allows for implementing Grover's algorithm—a paradigmatic quantum search algorithm—to obtain a quantum speedup in searching for solutions to the number partitioning problem. In contrast to past proof-of-principle demonstrations of Grover's algorithm, which have relied on hard-coding the solution to the search problem into a quantum circuit, our proposed application to number partitioning can be implemented without knowledge of the solution, by directly encoding the problem in the optically controlled interactions between Rydberg-dressed atoms and the central Rydberg atom. Our theoretical proposal, including a detailed analysis of the performance expected in realistic experiments, was published in *PRX Quantum* [4].

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[1] V. Borish, O. Marković, J. A. Hines, S. V. Rajagopal, and M. Schleier-Smith, Phys. Rev. Lett. **124**, 063601 (2020).

[2] J. A. Hines, S. V. Rajagopal, G. L. Moreau, M. D. Wahrman, N. A. Lewis, O. Marković, and M. Schleier-Smith, arXiv:2303.08805 (2023), to appear in Phys. Rev. Lett.

[3] I.-D. Potirniche, A. C. Potter, M. Schleier-Smith, A. Vishwanath, and N. Y. Yao, Phys. Rev. Lett. **119**, 123601 (2017).

[4] G. Anikeeva, O. Marković, V. Borish, J. A. Hines, S. V. Rajagopal, E. S. Cooper, A. Periwal, A. Safavi-Naeini, E. J. Davis, and M. Schleier-Smith, PRX Quantum **2**, 020319 (2021).