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INVESTIGATOR(S):

Name: Monika Schleier-Smith
Email: schleier@stanford.edu
Phone Number: 6504973069
Principal: Y

Organization: **Stanford University**
Address: 3160 Porter Drive, Stanford, CA 943048445
Country: USA
DUNS Number: 009214214
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Report Date: 08-Aug-2018
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Final Report for Period Beginning 09-May-2016 and Ending 08-May-2018

Title: Ultraviolet Laser System for Quantum Many-Body Physics with Rydberg-Dressed Atoms

Begin Performance Period: 09-May-2016
End Performance Period: 08-May-2018
Report Term: 0-Other

Submitted By: Monika Schleier-Smith
Email: schleier@stanford.edu
Phone: (650) 497-3069

STEM Degrees: 0 **STEM Participants:** 5

Major Goals: A high-power, narrow-linewidth ultraviolet laser system will be employed to induce long-range interactions among laser-cooled atoms by the method of Rydberg dressing. Two broad areas of scientific inquiry will be enabled by the Rydberg dressing laser: the study of frustrated quantum magnets; and the investigation of many-body spin dynamics as a route to generating metrologically useful entanglement. We will generate the requisite magnetic interactions by using light of 320-nm wavelength to off-resonantly couple two ground hyperfine states of cesium to highly polarizable Rydberg states. The resulting pair of Rydberg-dressed ground states, which form the effective spin degree of freedom for simulations, will acquire tunable interactions extending over a range of several microns. The commercial laser system enabling the Rydberg dressing outputs 150 mW of single-mode 320-nm light, obtained via two stages of resonant frequency doubling seeded by the amplified output of a 1280-nm diode laser. By electro-optic modulation of the fundamental radiation, it will be possible to generate two output frequencies, separated by 9 GHz, for indepedent dressing of two distinct hyperfine states. This capability is crucial for varing the isotropy of the spin-spin couplings to implement not only Ising but also Heisenberg spin models of interest for the study of topologically ordered many-body states. Besides enabling fundamental research in many-body quantum physics, the long-range interactions obtained by Rydberg dressing can be harnessed to generate specific entangled states with applications in quantum metrology.

Accomplishments: The high-power ultraviolet laser system purchased under the DURIP grant has enabled advances in control and coherence of long-range interactions among cold atoms. Our experiments have focused on optically inducing interactions among cesium atoms by the method of Rydberg dressing, in which one of two hyperfine ground states is off-resonantly coupled to a Rydberg state. Such optically controlled interactions open new opportunities in areas ranging from quantum simulation to quantum state engineering for metrology. Motivated by these two directions, we demonstrated local and dynamical control of Ising interactions, which we have applied to study a mean-field phase transition in a transverse-field Ising model [1] and as a mechanism for generating entanglement in the form of spin squeezing [2].

A major milestone was the realization of a Floquet transverse-field Ising model in a gas of Rydberg-dressed cesium atoms [1]. We observed signatures of a paramagnetic-ferromagnetic phase transition by imaging the magnetization dynamics in a spatially extended atomic cloud. Here, an optically induced gradient in the interaction strength allowed for directly observing a bifurcation in the mean-field dynamics, associated with the transition from a single paramagnetic ground state to two degenerate ferromagnetic ground states, as a function of position in the atomic cloud.

A notable effect of the Ising interactions induced by Rydberg dressing, in the setting of a gas where each atom

interacts with many neighbors, is to produce one-axis twisting dynamics, i.e., a spin precession rate that depends on the longitudinal magnetization of the surrounding spins. Such dynamics are well established as a mechanism for squeezing in globally interacting spin systems. Motivated by the prospect of local, optical control of metrologically useful entanglement, we investigated spin squeezing via Rydberg-dressed Ising interactions. For this application, a crucial requirement is to maximize the coherence of the interactions. As past experiments applying Rydberg dressing in 2D and 3D systems have suffered from super-Poissonian loss processes, we undertook sensitive, projection-noise limited measurements of percent-level loss induced by the dressing in ensembles of N = 1000 atoms to optimize the choice of Rydberg state and the dressing pulse sequences. This optimization has allowed us to achieve spin squeezing, with a metrological squeezing
parameter (quantifying the phase variance relative to the standard quantum limit) of 0.70(5). We are currently preparing a manuscript on these results [2].

The experimental work enabled by the ultraviolet laser system has also served as an inspiration for theoretical developments in the areas of quantum simulation and quantum computation. In collaboration with the groups of N. Yao and A. Vishwanath, we showed that a driven transverse-field Ising chain realizable by Rydberg dressing in an optical tweezer array provides access to Floquet symmetry-protected topological phases, including a phase with no analog in equilibrium [3]. In the area of computation, we showed theoretically that a central spin model realizable by Rydberg dressing enables application of Grover's search
algorithm to achieve a quantum speedup in solving the NP hard optimization problem of number partitioning [4]. Both of these theoretical works lay crucial groundwork for future experiments that will continue to leverage the laser system supported by the DURIP grant.

[1] V. Borish, O. Marković, J. A. Hines, S. V. Rajagopal, and M. Schleier-Smith, Physical Review Letters 124, 063601 (2020).
[2] J. A. Hines, S. V. Rajagopal, G. Moreau, M. Wahrman, N. Lewis, O. Markovic, and M. Schleier-Smith (2022), in preparation.
[3] I.-D. Potirniche, A. C. Potter, M. Schleier-Smith, A. Vishwanath, and N. Y. Yao, Physical Review Letters 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).

Training Opportunities: The laser system supported by the grant has been crucial to the training of four graduate students and one undergraduate student. These students gained experience in high-bandwidth feedback control for stabilizing the laser frequency and intensity, non-linear optics involved in the two stages of resonant frequency doubling, as well as vacuum technology and electronics required to build a temperature-stabilized vacuum chamber housing a stable reference cavity to which the laser system is locked. The graduate students participating in the experiments, as well as two additional undergraduate students, have furthermore received training in wide-ranging aspects of quantum information and quantum metrology, by conducting supporting theoretical work in these areas inspired by our Rydberg dressing experiments.

Results Dissemination: Results obtained using the ultraviolet laser system, as well as supporting theoretical work inspired by our Rydberg dressing experiments, have been published in Physical Review Letters and PRX Quantum [see Products section]. In addition, results from the project have been disseminated in colloquia and invited talks by the PI and postdoctoral researcher Shankari Rajagopal, as well as in posters by project participants at conferences including the APS DAMOP Meeting, International Conference on Atomic Physics [ICAP], and Gordon Research Conferences.

Honors and Awards: Awards received by the PI during the reporting period:
* Research Corporation Cottrell Scholar Award [2017]
* NSF CAREER Award [2018]

In addition, undergraduate student Simon Evered received Stanford's Firestone Award for Excellence in Undergraduate Research [2019] for thesis work initiated during the reporting period.

Protocol Activity Status:

Technology Transfer: Nothing to Report

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PARTICIPANTS:

Participant Type: PD/PI
Participant: Monika Helene Schleier-Smith
Person Months Worked: 2.00 **Funding Support:**
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Participant Type: Graduate Student (research assistant)
Participant: Victoria Borish
Person Months Worked: 6.00 **Funding Support:**
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Participant Type: Graduate Student (research assistant)
Participant: Ognjen Markovic
Person Months Worked: 6.00 **Funding Support:**
Project Contribution:
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Participant Type: Graduate Student (research assistant)
Participant: Jacob Hines
Person Months Worked: 6.00 **Funding Support:**
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Participant Type: Undergraduate Student
Participant: Simon Evered
Person Months Worked: 5.00 **Funding Support:**
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Participant Type: Undergraduate Student
Participant: Michelle Chong
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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: Rydberg atoms, spin dynamics, Floquet systems, atomic physics
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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Article Title: Number Partitioning With Grover's Algorithm in Central Spin Systems
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
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 ...
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I certify that the information in the report is complete and accurate:
Signature: Monika Schleier-Smith
Signature Date: 8/16/22 1:26AM

Ultraviolet Laser System for Quantum Many-Body Physics with Rydberg-Dressed Atoms

Monika Schleier-Smith, Stanford University

The high-power ultraviolet laser system purchased under the DURIP grant has enabled advances in control and coherence of long-range interactions among cold atoms. Our experiments have focused on optically inducing interactions among cesium atoms by the method of Rydberg dressing, in which one of two hyperfine ground states is off-resonantly coupled to a Rydberg state. Such optically controlled interactions open new opportunities in areas ranging from quantum simulation to quantum state engineering for metrology. Motivated by these two directions, we demonstrated local and dynamical control of Ising interactions, which we have applied to study a mean-field phase transition in a transverse-field Ising model [1] and as a mechanism for generating entanglement in the form of spin squeezing [2].

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

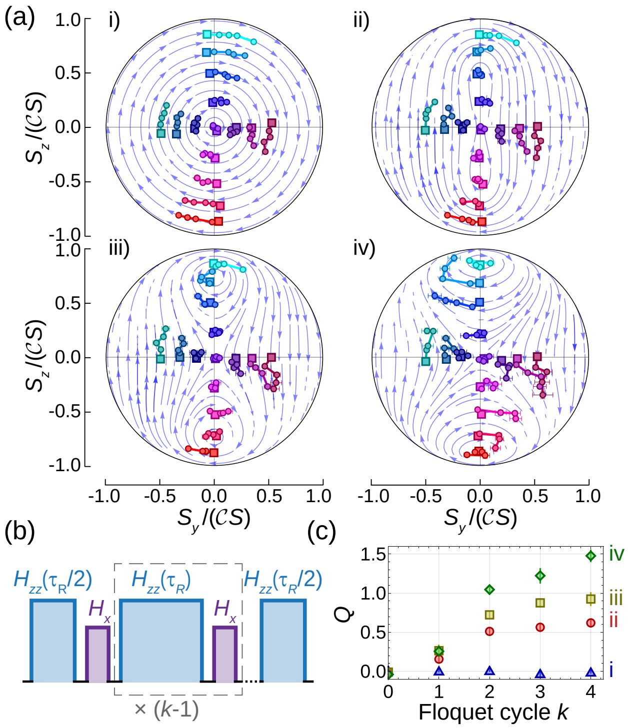

FIG. 1: **Mean-field dynamics of the transverse-field Ising model (from Ref. [1]).** In the absence of interactions (a.i), the average magnetization precesses about a single fixed point along the x-axis, the paramagnetic ground state. With increasing strength of Ising interactions (a.ii)-(a.iv), the fixed point bifurcates into the two ferromagnetic ground states located above and below the x-axis. (b) Floquet sequence for emulating the transverse-field Ising model by alternate application of interactions H_{zz} and a microwave drive H_x. (c) Integrated interaction strength over k Floquet cycles, measured by one-axis twisting dynamics in the absence of the transverse field.

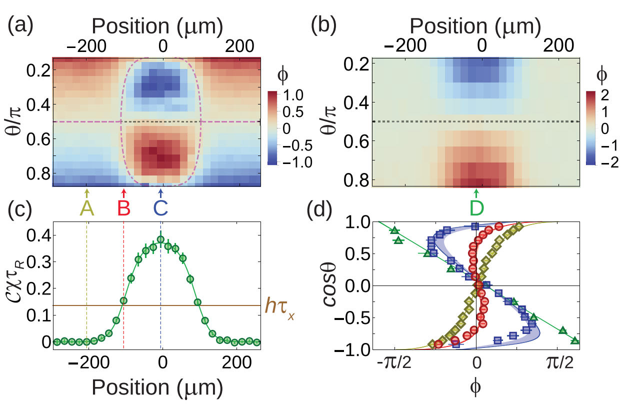

FIG. 2: **Dynamical signature of paramagnetic-to-ferromagnetic phase transition in a cloud of Rydberg-dressed atoms (from Ref. [1]).** (a-b) Phase ϕ of the average Bloch vector after the Floquet sequence of Fig. 1, as a function of initial tilt θ of Bloch vector and position in the atomic cloud, for (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.

[2] J. A. Hines, S. V. Rajagopal, G. Moreau, M. Wahrman, N. Lewis, O. Markovic, and M. Schleier-Smith (2022), in preparation.

[3] I.-D. Potirniche, A. C. Potter, M. Schleier-Smith, A. Vishwanath, and N. Y. Yao, Physical Review Letters **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).