

Studying Many-Body Dipolar Spin Systems with Erbium Quantum Gases

PI Name: Bryce Gadway

Address: University of Illinois, 1110 West Green Street, Urbana, IL 61801-3003, USA

Phone: 217-244-9284 Fax: 217-244-7559 Email: bgadway@illinois.edu

Grant number: N00014-16-1-2895

<https://publish.illinois.edu/gadwaylab>

LONG-TERM GOALS

The major long-term goals of this effort are to use dipolar interactions of ultracold atoms with dipole-dipole interactions to explore complex spin Hamiltonians and the physics of quantum magnetism, generally defined. This includes the physics of spin systems with long-range interactions, frustration, disorder, and dynamical Hamiltonian couplings.

OBJECTIVES

The scientific objectives of this effort were to expand the experimental capabilities of controlled atomic matter as it relates to the study of many-body spin systems. This expansion was to be based on the development of scalable systems of atoms with dipolar interactions, as well as the development of new control knobs for interacting spin systems based on cold atoms. This would then help us to “quantum emulate” model Hamiltonians with poorly understood equilibrium phases, as well as study complex many-body dynamics and potentially thermalization.

APPROACH

This project sought to use cold atoms with multiple accessible internal states and dipolar interactions to study quantum magnetism. The original proposed approach was based on magnetically dipolar erbium atoms in their electronic ground state, using spin-resolved quantum gas microscopy. However, due to unforeseen issues related to atomic sources, our original approach was compromised and we have instead sought to realize the same physics on faster timescales and with more easily accommodated spatial resolution in a system based on dipole-dipole interactions of highly-excited Rydberg states of individually trapped potassium atoms.

The key individual participating in this work at my own organization is Jackson Ang’ong’a. He is the lead graduate student contributing to this project, having built up a cold atom apparatus including lasers and ultrahigh vacuum system. He plays the role of technical and design lead on this project.

WORK COMPLETED

We have constructed a cold atom apparatus that loads potassium atomic clouds into an ultrahigh vacuum system with large optical access, following laser-pulsed transfer from a quickly-loaded magneto-optical trap. In this region, we use sub-Doppler (D_1 line) laser cooling to cool potassium-39 atoms to nearly ten microKelvin. We have installed and our finalizing the system for projecting optical

microtraps onto the atoms and imaging individual atoms with micron-scale resolution. The current stage of development is that we are looking for individual atoms in the microtraps, while in parallel developing the capability to project multiple microtraps with tailored patterning. Lastly, we have achieved an error signal for Pound-Drever-Hall locking of one of our two Rydberg lasers to a stable, high-finesse optical cavity. We plan to lock two lasers with disparate frequencies to this cavity in the coming months, to enable coherent optical two-photon transitions from the ground to excited Rydberg level, to enable the population of Rydberg states that can enjoy fast dipole-dipole interactions.

RESULTS

We have learned how to quickly load large clouds of cold atoms into an isolated (UHV) chamber by multi-stage vacuum transfer, and have achieved ultracold temperatures by means of sub-Doppler cooling. We are in the midst of developing the appropriate loading procedure for potassium-39 atoms into optical microtraps, which represents a new atomic species to optical microtrapping (with no previous publications of such a result). Additionally, to my lab, we have learned how to perform cavity-stabilization of lasers for the coherent driving of two-photon transitions, and useful more generation for the use of optical transfer cavities.

On the theory side, we have worked with researchers at Rice University to understand and analyze the possibility for studying complex spin Hamiltonians based on the tailored microwave addresses of internal state transitions (in the context of molecules or Rydberg atoms). Specifically, moving beyond the traditional kinds of experimentally relevant spin models, we have considered systems with many accessible internal states that can be hybridized by spectrally-tailored near-resonant fields. We have shown that new types of quantum phenomena, like the formation of “quantum strings” and “quantum membranes” can occur in such system due to spontaneous symmetry breaking.

IMPACT/IMPLICATIONS

This project has both near-term and long-term implications for the development of tailored model quantum systems for the investigation of open fundamental physics problems. In particular, it promises to enable entirely new levels of Hamiltonian control, based on internal state manipulation, in a many-body quantum system of Rydberg atom arrays. This promises to enable new kinds of study on topics such as thermalization and equilibration in disordered spin models and in driven spin models, on the influence of interactions on flat-band Hamiltonians, and finally on engineering and probing of quantum strings and quantum membranes.

RELATED PROJECTS

None.

REFERENCES

None.

PUBLICATIONS

Papers/technical reports:

Strings of ultracold molecules in a synthetic dimension.

Bhuvanesh Sundar, Matthew Thibodeau, Zhiyuan Wang, Bryce Gadway, Kaden Hazzard
Physical Review A **99**, 013624 (2019)

Synthetic dimensions in ultracold polar molecules.

Bhuvanesh Sundar, Bryce Gadway, and Kaden R. A. Hazzard
Scientific Reports **8**, Article number: 3422 (2018)

Polarization spectroscopy of atomic erbium in a hollow cathode lamp.

Jackson Ang'ong'a and Bryce Gadway
J. Phys. B: At. Mol. Opt. Phys. **51**, 045003 (2018)

Books, or chapters: None

HONORS/AWARDS/PRIZES

Recipient: Bryce Gadway, UIUC; Award: Arnold O. Beckman Research Award; Sponsor: UIUC
College of Engineering Research Board

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to the Department of Defense, Executive Service Directorate (0704-0188). Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ORGANIZATION.

1. REPORT DATE (DD-MM-YYYY) 10-29-2019		2. REPORT TYPE Final Technical Report		3. DATES COVERED (From - To) 08/01/2016-07/31/2019	
4. TITLE AND SUBTITLE Studying Many-Body Dipolar Spin Systems with Erbium Quantum Gases				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER N00014-16-1-2895	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Gadway, Bryce Ang'ong'a, Jackson Liu, Zejun				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) UNIVERSITY OF ILLINOIS 506 S WRIGHT ST STE 364 URBANA IL 61801-3649 UNITED STATES OF AMERICA				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Office of Naval Research 875 N. Randolph Street Suite 1425 Arlington VA 22203-1995				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for Public Release; distribution is Unlimited.					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT This research project developed a neutral atom platform for the exploration of many-body spin systems, based on long-ranged dipolar interactions. In this research we have worked on the development of a system with tunable spins (Rydberg atoms with multiple accessible internal states) that can be controlled and interact via dipole-dipole interactions. The experimental and theoretical work associated with this project will enable the creation of new forms of highly-tunable quantum matter, for investigation of the many-body quantum problem and the exploration of specific new types of phenomena such as the formation of quantum strings in high-spin quantum magnetic systems.					
15. SUBJECT TERMS quantum magnetism; quantum simulation; ultracold atoms; dipole-dipole interactions; quantum strings					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			ONR
U	U	U	UU	4	19b. TELEPHONE NUMBER (Include area code)