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14. ABSTRACT
This theoretical proposal planned to investigate how to use ultracold polar molecules loaded in optical lattices as quantum simulators of strongly correlated Hamiltonians. The target was to guide experiments to emulate iconic models use to describe solid state materials as well as Hamiltonians without solid state counterpart. The focus was on alkali-metal dimers
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Report Title

Final Report: Exploring New State of Matter with Ultra-cold Polar Molecules

ABSTRACT

This theoretical proposal planned to investigate how to use ultracold polar molecules loaded in optical lattices as quantum simulators of strongly correlated Hamiltonians. The target was to guide experiments to emulate iconic models use to describe solid state materials as well as Hamiltonians without solid state counterpart. The focus was on alkali-metal dimers
given their well characterized hyperfine structure and their close connection to current experiments. The main idea was the use of the rotational degrees of freedom, controllable by dc electric fields and microwave fields to encode a spin degree of freedom. Since direct dipolar interactions couple the rotational states they give rise to spin-spin interactions that can be orders of magnitude stronger than those ones found in generic neutral atoms. We developed probes to characterize the role of dipolar interactions, which lead to the first experimental observation of dipole mediated exchange interactions in the JILA KRb experiment. We studied quantum phases and dynamics of different magnetic models amenable for experimental implementation using numerical and analytical methods. The additional mechanisms for loss and decoherence introduced by the use of rotational freedom and chemical reactions were also investigated.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
02/13/2017	16	Sergey V. Syzranov, Michael L. Wall, Victor Gurarie , Ana Maria Rey. Spin-orbital dynamics in a system of polar molecules , Nature Communication, (07 2014): 5391. doi:
02/13/2017	29	Sergey V. Syzranov, Michael L. Wall, Bihui Zhu, Victor Gurarie, Ana Maria Rey. Emergent Weyl quasiparticles in three-dimensional dipolar arrays, Nature Communication, ( ): 13543. doi:
02/13/2017	24	B Zhu, J Schachenmayer,M Xu, F Herrera, JG Restrepo,MJ Holland, and AM Rey. Synchronization of Interacting Quantum Dipoles, New Journal of Physics, (04 2015): 083063. doi:
02/14/2017	14	Bihui Zhu, John Cooper, Jun Ye, and Ana Maria Rey. Quantum correlations and entanglement in far-from-equilibrium spin systems , PHYSICAL REVIEW A , (07 2014): 023612. doi:
02/14/2017	30	Bihui Zhu, John Cooper, Jun Ye, Ana Maria Rey. Light scattering from dense cold atomic media, Physical Review A, ( ): 023612. doi:
08/03/2016	25	J. G. Bohnet, B. C. Sawyer, J. W. Britton, M. L. Wall, A. M. Rey, M. Foss-Feig, J. J. Bollinger. Quantum spin dynamics and entanglement generation with hundreds of trapped ions, Science, ( ): 1297. doi:
08/03/2016	26	S. L. Bromley, B. Zhu, M. Bishof, X. Zhang, T. Bothwell, J. Schachenmayer, T. L. Nicholson, R. Kaiser, S. F. Yelin, M. D. Lukin, A. M. Rey, J. Ye. Collective atomic scattering and motional effects in a dense coherent medium, Nature Communications, ( ): 11039. doi:
08/06/2016	27	A. Safavi-Naini, M. L. Wall, A. M. Rey. Role of interspecies interactions in the preparation of a low-entropy gas of polar molecules in a lattice, Physical Review A, ( ): . doi:
08/06/2016	28	C Zhang, A Safavi-Naini, Ana Maria Rey, B Capogrosso-Sansone. Equilibrium phases of tilted dipolar lattice bosons, New Journal of Physics, ( ): 123014. doi:

TOTAL: **9**

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

1. Light Scattering in Dense Atomic Samples, Dodd-Walls Centre Symposium, January 25, 2017, Dunedin, New Zealand

2.Quantum spin dynamics, coherences and entanglement in trapped ion arrays,Designer Quantum Systems Out of Equilibrium , KITP, Nov 13, 2016

3. Building with Crystals of Light and Quantum Matter, Colombian Student Association at Purdue (CSAP) 2nd Academic Event, \Latino Research Experience: Talento Local y de Exportacion", Purdue University, West Lafayette, IN, October 2016

4 Building with Crystals of Light and Quantum Matter, The 182nd Institute for Molecular Science Colloquium, National Institutes of Natural Sciences, Okazaki, Japan, October 2016
5 Building with Crystals of Light and Quantum Matter: I. From Superfluids to Magnets; II. From Clocks to Computers; and III. From Atoms to Molecules, Okinawa School of Physics, Okinawa Institute of Science and Technology, Okinawa, Japan, October 2016
6 Quantum Spin Dynamics, Coherences and Entanglement in Trapped Ion Arrays, Long-range Interactions in the Ultracold Workshop, Ercolano, Italy, June 2016
7 Quantum Spin Dynamics, Coherences and Entanglement in Trapped Ions, The 25th International Conference on Atomic Physics, ICAP 2016, Seoul, Republic of Korea, July 2016
8 New perspectives on quantum simulation with ultracold molecules, Quantum Non-Equilibrium Phenomena Workshop, Natal, Brazil, June 2016

Number of Presentations: 8.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received Book

TOTAL:

Received	Book Chapter
08/02/2014 13.00	M. L. Wall, K.R. A Hazzard, A. M. Rey. Quantum magnetism with ultracold molecules, Singapure: World Scientific, (12 2014)

TOTAL: **1**

Patents Submitted

Patents Awarded

Awards

Alexander M. Cruickshank Lecturer award at the Gordon Research Conference on Atomic Physics to be held at Salve Regina University on June 11 – June 16, 2017

Graduate Students

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

This project aimed to perform theoretical investigations for the development of a highly tunable quantum simulator operated with ultra-cold polar molecules. The main idea was to use rotational dressed states of the molecules as the spin (qubit) degrees of freedom and to coupled them by direct dipolar interactions, which can be manipulated and controlled by external dc electric fields and continuous microwave fields.

During this award we not only investigated polar molecules but generic quantum magnetic behavior in systems exhibiting long-range interactions including trapped ions,and radiating dipolar gases.
Specific accomplishments made were:

1. Investigated the implementation of spin-orbit Coupling in ultracold polar molecules: In particular how to generate spin-orbital coupling and non-trivial chiral quasi-particles including Weyl excitations using dipolar interactions.

2. Investigated the dynamics of quantum correlations and entanglement in far-from-equilibrium spin systems realizable by a gas of ultra-cold polar molecule in a lattice or arrays of trapped ions.

3. Developed a new numerical method to investigate the dynamics of correlations in spin models with long-range interactions using phase-space methods
4. Investigated the possibility of achieving quantum synchronization in radiating quantum dipoles
5.Investigated collective emission from coherently driven dipoles. In collaboration with the JILA team, we performed two sets of experiments, using a strong and weak dipole transition that are insensitive and sensitive, respectively, to motion at one microKelvin. We demonstrated that a single, self-consistent, microscopic theory model can provide a unifying picture for the majority of experimental observations.
5. Investigated a disorder-driven transition in systems with power-law hopping.
6. Investigated equilibrium phases of tilted dipolar lattice bosons
7. Proposed an spectroscopic method to investigate signatures of non-equilibrium quantum magnetism in current polar molecule experiments loaded on a 3D optical lattice which are yet not quantum degenerate. The method is based on Ramsey spectroscopy. In collaboration with the polar group molecule at JILA we used this method to observe for the first time signatures of dipolar exchange interactions a lattice spin model with KRb ultracold polar molecules pinned in a deep 3D optical lattice.
8. Developed a novel cluster expansion technique capable of dealing with the non-equilibrium dynamics of spin models with long range interactions and used it to benchmark the JILA experiment.
9. Investigated the role of chemical reactions in dipolar gases and used this understanding to model the JILA experiment and to determined its operating filling fraction. We provided both from theory and experiment compelling evidence of the existence of the quantum Zeno effect in a lattice gas by which by increasing the on-site chemical reaction rate one can actually lower the overall loss rate.
10. Investigated how to use reactive two-body collisions in fermionic polar molecules such as KRb to engineer robust entanglement in those system.
11. Investigated way to use the anisotropic character of dipolar interaction to engineer protected topological phases and other Hamiltonians that are known to exhibit topological phases such as the Kitaev model.

Technology Transfer