REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY): 11-03-2023

2. REPORT TYPE: Final Report

3. DATES COVERED (From - To): 15-Aug-2012 - 14-May-2013

4. TITLE AND SUBTITLE: Final Report: High power optical lattices for a lithium-7 quantum simulator

5a. CONTRACT NUMBER: W911NF-12-1-0435

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER: 611102

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHORS

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES

Massachusetts Institute of Technology (MIT
77 Massachusetts Avenue
NE18-901
Cambridge, MA 02139 -4307

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)

U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S): ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S): 62542-PE-II.4

12. DISTRIBUTION AVAILIBILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
UU	UU	UU	UU		Wolfgang Ketterle
					19b. TELEPHONE NUMBER: 617-253-6815

Standard Form 298 (Rev 8/98)
Prescribed by ANSI Std. Z39.18

RPPR Final Report
as of 16-Mar-2023

Agency Code: 21XD

Proposal Number: 62542PEII

Agreement Number: W911NF-12-1-0435

INVESTIGATOR(S):

Name: Ph.D. Wolfgang Ketterle
Email: ketterle@mit.edu
Phone Number: 6172536815
Principal: Y

Organization: **Massachusetts Institute of Technology (MIT)**
Address: 77 Massachusetts Avenue, Cambridge, MA 021394307
Country: USA

DUNS Number: 001425594 EIN: 042103594

Report Date: 14-Aug-2013 Date Received: 11-Mar-2023

Final Report for Period Beginning 15-Aug-2012 and Ending 14-May-2013

Title: High power optical lattices for a lithium-7 quantum simulator

Begin Performance Period: 15-Aug-2012 **End Performance Period:** 14-May-2013

Report Term: 0-Other

Submitted By: Ph.D. Wolfgang Ketterle Email: ketterle@mit.edu
Phone: (617) 253-6815

Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: 0 **STEM Participants:**

Major Goals: This grant was for the development of high-power optics and fiber coupling for a lithium-7 experiment which requires high laser power for optical lattices.

Accomplishments: The goal of the proposal was achieved: We have performed several experiments with lithium-7 in optical lattices.

Training Opportunities: This grant was only for equipment, but it was crucial for the research of several graduate students.

Results Dissemination: Results were disseminated via theses and publications.

Honors and Awards: Nothing to Report

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: PD/PI
Participant: Wolfgang Ketterle
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
National Academy Member: Y

ARTICLES:

RPPR Final Report
as of 16-Mar-2023

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Nature
Publication Identifier Type: DOI Publication Identifier: 10.1038/s41586-020-3033-y
Volume: 588 Issue: 7838 First Page #: 403
Date Submitted: 3/11/23 12:00AM Date Published: 12/1/20 3:00PM
Publication Location:
Article Title: Spin transport in a tunable Heisenberg model realized with ultracold atoms
Authors: Paul Niklas Jepsen, Jesse Amato-Grill, Ivana Dimitrova, Wen Wei Ho, Eugene Demler, Wolfgang Ketter
Keywords: spin transport, Heisenberg model
Abstract: Simple models of interacting spins have an important role in physics. They capture the properties of many magnetic materials, but also extend to other systems, such as bosons and fermions in a lattice, gauge theories, high-temperature superconductors, quantum spin liquids, and systems with exotic particles such as anyons and Majorana fermions1,2. To study and compare these models, a versatile platform is needed. Realizing such systems has been a long-standing goal in the field of ultracold atoms. So far, spin transport has only been studied in systems with isotropic spin–spin interactions3,4,5,6,7,8,9,10,11,12. Here we realize the Heisenberg model describing spins on a lattice, with fully adjustable anisotropy of the nearest-neighbour spin–spin couplings (called the XXZ model). In this model we study spin transport far from equilibrium after quantum quenches from imprinted spin-helix patterns. When spins are coupled only along two of three possible orientations (the XX model), we find
Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review X
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevX.11.041054
Volume: 11 Issue: 4 First Page #:
Date Submitted: 3/11/23 12:00AM Date Published: 12/1/21 10:00AM
Publication Location:
Article Title: Transverse Spin Dynamics in the Anisotropic Heisenberg Model Realized with Ultracold Atoms
Authors: Paul Niklas Jepsen, Wen Wei Ho, Jesse Amato-Grill, Ivana Dimitrova, Eugene Demler, Wolfgang Ketter
Keywords: spin transport, Heisenberg model
Abstract: In Heisenberg models with exchange anisotropy, transverse spin components are not conserved and can decay not only by transport, but also by dephasing. Here, we utilize ultracold atoms to simulate the dynamics of 1D Heisenberg spin chains and observe fast, local spin decay controlled by the anisotropy. However, even for isotropic interactions, we observe dephasing due to a new effect: an effective magnetic field created by superexchange. If spatially uniform, it leads only to uniform spin precession and is, therefore, typically ignored. However, we show through experimental studies and extensive numerical simulations how this superexchange-generated field is relevant and leads to additional dephasing mechanisms over the exchange anisotropy: There is dephasing due to (i) inhomogeneity of the effective field from variations of lattice depth between chains; (ii) a twofold reduction of the field at the edges of finite chains; and (iii) fluctuations of the effective field due to the presenc
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support: **Y**

RPPR Final Report
as of 16-Mar-2023

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Nature Physics
Publication Identifier Type: DOI Publication Identifier: 10.1038/s41567-022-01651-7
Volume: 18 Issue: 8 First Page #: 899
Date Submitted: 3/11/23 12:00AM Date Published: 7/1/22 4:00AM
Publication Location:
Article Title: Long-lived phantom helix states in Heisenberg quantum magnets
Authors: Paul Niklas Jepsen, Yoo Kyung 'Eunice' Lee, Hanzhen Lin, Ivana Dimitrova, Yair Margalit, Wen Wei Ho,
Keywords: spin, phantom states, Bethe ansatz, Heisenberg model
Abstract: Exact solutions for quantum many-body systems are rare but provide valuable insights for the description of universal phenomena such as the non-equilibrium dynamics of strongly interacting systems and the characterization of new forms of quantum matter. Recently, specific solutions of the Bethe ansatz equations for integrable spin models were found. They are dubbed phantom Bethe states and can carry macroscopic momentum yet no energy. Here, we show experimentally that there exist special helical spin patterns in anisotropic Heisenberg chains which are long-lived, relaxing only very slowly in dynamics, as a consequence of such states. We use these phantom spin-helix states to directly measure the interaction anisotropy, which has a major contribution from short-range off-site interactions. We also generalize the theoretical description to higher dimensions and other non-integrable systems and find analogous stable spin helices, which should show non-thermalizing dynamics associated with
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support: **Y**

Partners

,

I certify that the information in the report is complete and accurate:
Signature: Wolfgang Ketterle
Signature Date: 3/11/23 11:11PM

Final report

Title: High power optical lattices for a lithium-7 quantum simulator

Sponsor: ARO, STIR program, contract W911NF-12-1-0435

Location: MIT

Award Amount: $ 50,000

Period: Aug. 15, 2012 to May 14, 2013

This grant was for the development of high-power optics and fiber coupling for a lithium-7 experiment. Those components were purchased, tested and integrated into the experimental setup.

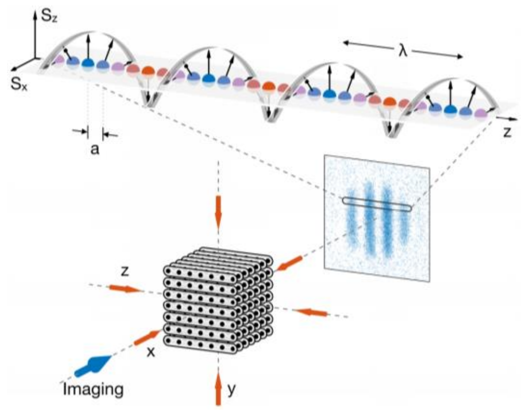
However, the experiment suffered from major delays. They were caused by a postdoc leaving early, equipment failures (in particular lasers) and a major problem with thermal lensing of an optical viewport. Furthermore, the main part of the experiment had to be disassembled and baked out again, since we had to exchange viewports and the magnetic trap (which had a design flaw in its winding pattern).

Eventually, everything worked well. Our studies of spin dynamics in Heisenberg spin chains resulted in major new discoveries and a series of impactful papers which are summarized here.

1. Simulation of the Anisotropic Spin-1/2 Heisenberg Model

N. Jepsen, J. Amato-Grill, I .Dimitrova, W.W. Ho, E. Demler, and W. Ketterle, *Spin transport in a tunable Heisenberg model realized with ultracold atoms,* Nature 403–407 (2020), https://doi.org/10.1038/s41586-020-3033-y

Simple models of interacting spins play an important role in physics. They capture the properties of many magnetic materials, but also extend to other systems, such as bosons and fermions in a lattice, systems with gauge fields, high-T_c superconductors, and systems with exotic particles such as anyons and Majorana fermions. In order to study and compare these models, a versatile platform is needed. Realizing such a system has been a long-standing goal in the field of ultracold atoms. So far, spin transport has only been studied in the isotropic Heisenberg model. Here we implement the Heisenberg XXZ model with adjustable anisotropy and use this system to study spin transport far from equilibrium after quantum quenches from imprinted spin helix patterns (see figure).



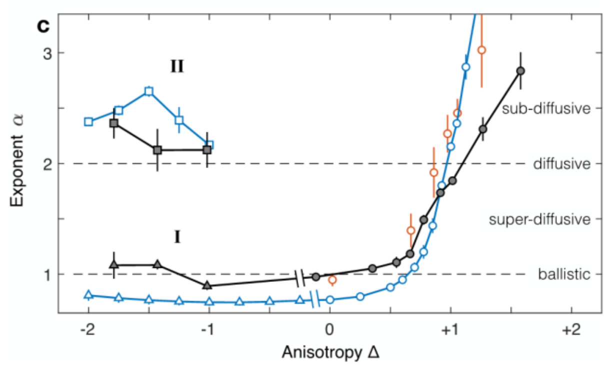
Creation of a spin helix state, realized from two hyperfine states (spin | ↑) and | ↓)). The spin S winds within the S_z S_x-plane as a function of position z in the spin chain. Deep optical lattices along x and y create an array of independent spin chains. The z-lattice is shallower and controls spin transport along each chain.

All work with ultracold atoms has addressed the isotropic Heisenberg model where $J_x=J_y=J_z$ in the spin-spin interactions between atoms on neighboring sides:

$$\mathcal{H} = \sum_{i.j} J_x S_i^x S_j^x + J_y S_i^y S_j^y + J_z S_i^z S_j^z$$

Using lithium-7 and Feshbach resonances, we were able to realize the Heisenberg model with widely tunable interaction parameters, and in particular, study spin physics over the whole range of anisotropies $\Delta=J_z/J_{x,y}$. For $\Delta=1$, we retrieve the isotropic Heisenberg model. For $\Delta=0$, we realize the so-called XX-model which is a special starting point for investigations since it is exactly solvable in one dimension by mapping the spins to non-interacting fermions.

An important question is how the relaxation time depends on the spatial period of the spin pattern. A quadratic dependence implies diffusive transport, whereas a linear dependence characterizes ballistic transport. For anisotropy $\Delta=0$, we observe ballistic transport. When the anisotropy is increased a crossover to diffusive transport occurs. For positive anisotropies, the dynamics ranges from anomalous super-diffusion to sub-diffusion depending on anisotropy, whereas for negative anisotropies, we observe a crossover in the time domain from ballistic to diffusive transport. This behavior contrasts with expectations for the linear response regime and raises new questions in understanding quantum many-body dynamics far away from equilibrium.

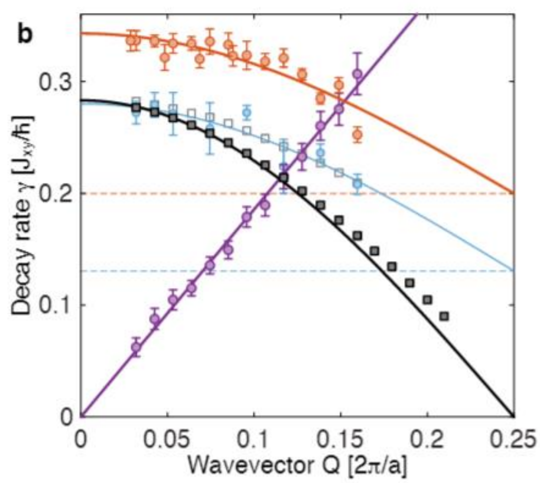


Different regimes of spin transport depending on the anisotropy Δ of the Heisenberg model. The exponent in the spin transport time increases smoothly from ballistic (red) to super-diffusive (yellow) to diffusive (blue) to sub-diffusive (green). For $\Delta < 0$ we observe behavior reminiscent of a classical gas: Transport is ballistic at (I) short times (triangles) and diffusive at (II) longer times (squares).

2. Transverse spin dynamics for anisotropic Heisenberg models

N. Jepsen, W.W. Ho, J. Amato-Grill, I .Dimitrova, E. Demler, and W. Ketterle:
Transverse spin dynamics in the anisotropic Heisenberg model realized with ultracold atoms.
Phys. Rev. X 11, 041054 (2021), https://doi.org/10.1103/PhysRevX.11.041054

In Heisenberg models with exchange anisotropy, transverse spin components are not conserved and can decay not only by transport, but also by dephasing. We utilize ultracold atoms to simulate the dynamics of 1D Heisenberg spin chains, and observe fast, local spin decay controlled by the anisotropy. However, even for isotropic interactions, we observe dephasing due to a new effect: an effective magnetic field created by superexchange processes, which is typically ignored as its effects can be transformed away if spatially uniform. However, we show through experimental studies and extensive numerical simulations how this superexchange generated field is relevant and leads to additional dephasing mechanisms over the exchange anisotropy: there is dephasing due to (i) inhomogeneity of the effective field from variations of lattice depth between chains; (ii) a twofold reduction of the field at the edges of finite chains; and (iii) fluctuations of the effective field due to the presence of mobile holes. The latter is a new coupling mechanism between holes and magnons. All these dephasing mechanisms have not been observed before with ultracold atoms and illustrate basic properties of the underlying Hubbard model.



Spin dephasing and spin transport for the Heisenberg XX model. Shown are decay rate of a spin helix states with wavevector Q. The decay rate for a transverse helix (orange) follows a cosine dependence with a constant background rate. This is in strong contrast to the longitudinal spin helix (purple) which shows linear scaling with Q (indicating ballistic transport). A spin-echo pulse reduces the background rate (dashed blue line). The black solid squares are numerical results for a single chain and the pure spin mode. The grey open squares are numerical results for the so-called tJ-model with 5\ % hole fraction.

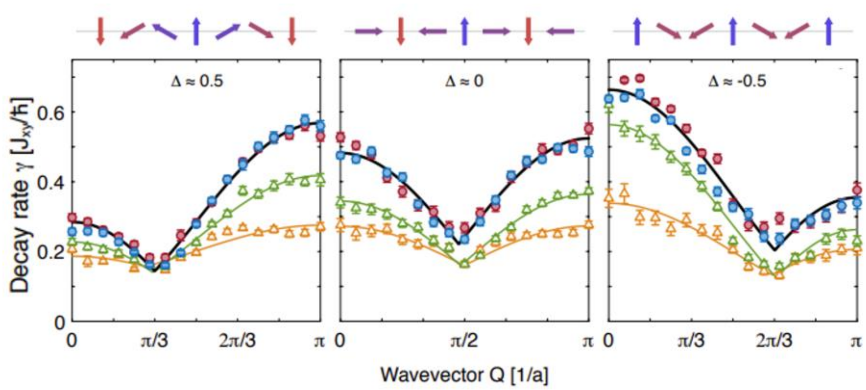
3. Observation of phantom Bethe states and their implications for quantum many-body scars

P.N. Jepsen, Y.K. Lee, H. Lin, I. Dimitrova, Y. Margalit, W.W. Ho, and W. Ketterle, *Long-lived phantom helix states in Heisenberg quantum magnets*, Nature Physics 18, 899–904 (2022), https://doi.org/10.1038/s41567-022-01651-7

Exact solutions for quantum many-body systems are rare, but provide valuable insights for the description of universal phenomena. Recently, specific solutions of the Bethe ansatz equations for 1D anisotropic Heisenberg models were found that can carry macroscopic momentum yet no energy on top of the ferromagnetically ordered "vacuum" state, dubbed phantom Bethe states. As a consequence of these phantom Bethe states, simple spin helix states at special wave-vector becomes exact eigenstates of these systems.

With ultracold Li-7 atoms on optical lattices, we can simulate the anisotropic Heisenberg model, and tune the interaction anisotropy with Feshbach resonances. Here, we show experimentally that there exist special helical spin patterns in 1D chains which are long-lived, relaxing only slowly in dynamics. The wave-vector of these special helices also shifts with the anisotropy parameter as predicted theoretically.

As the wave-vector of the spin helix is determined by the anisotropy parameter, we use these phantom spin helices to directly measure the interaction anisotropy at different magnetic fields around Feshbach resonances. The measured anisotropy agrees well with the predictions based on super-exchange and the Bose Hubbard model far from the Feshbach resonance, but we find discrepancies close to the Feshbach resonance which require an extension of the model. We find theoretically that phantom spin helices exist also in two dimensions and for certain long-range interactions which are non-integrable systems. Those systems should show non-thermalizing dynamics associated with so-called quantum many-body scars. These results have implications for the quantum simulation of spin physics, as well as many-body dynamics.

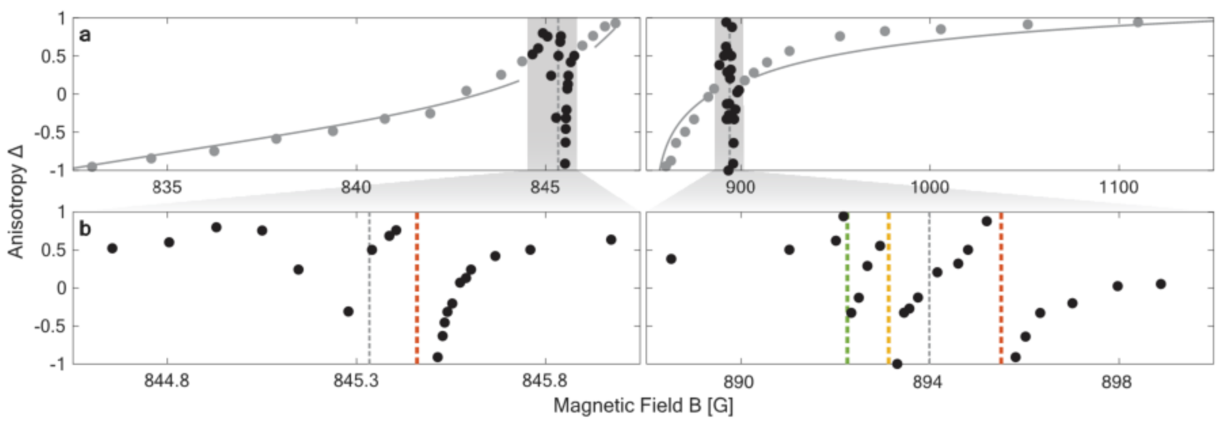


Observation of phantom helix states. Decay rate γ as a function of wavevector Q, shown for three different anisotropies Δ. The phantom helix is realized at the decay rate minimum, and its winding pattern is shown at the top. In addition to the purely transverse helices (polar angle θ = π/2, circles), the panels also show the decay of spin helices with polar angles θ = 5π/12 (green triangles) and θ = 2π/3 (orange triangles). Different anisotropies were realized by tuning the atomic interactions with an external magnetic field near a Feshbach resonance.

4. Lattice-induced Feshbach resonance

Y.K. Lee, H. Lin, and W. Ketterle: *Spin dynamics dominated by superexchange via virtual molecules.* Preprint, arXiv:2208.06054

Optical lattices and Feshbach resonances are two of the most ubiquitously-used tools in atomic physics. The presence of an optical lattice potential near a Feshbach resonance gives rise to new resonances involving excited bands of the center-of-mass motion. We report the first experimental observation of these "lattice-induced resonances" by studying the spin dynamics of Heisenberg chains of lithium-7 atoms in an optical lattice, and used them to adiabatically convert atoms into bound dimers in excited bands. We also report the first experimental evidence for off-site contact interactions in the Hubbard model. We expect these resonances to be of general importance for studying strongly-interacting quantum many-body systems in optical lattices.



Spin interaction anisotropy at different magnetic fields. The zoom-in shows the fields with large scattering lengths $\gtrsim 500\ a_0$. Far from the Feshbach resonances (dotted grey lines), the data (grey points) agree well with calculations from perturbation theory (solid grey curves). Such theory is not applicable in the regions with black data points which show resonant behavior. We see multiple dispersive features at 845.460 G, 892.250 G, 893.123 G, and 895.504 G (dashed lines). These resonances are explained by lattice-induced resonances.