

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 this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA, 22202-4302. 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 ADDRESS.					
1. REPORT DATE (DD-MM-YYYY) 23-03-2018		2. REPORT TYPE Final Report		3. DATES COVERED (From - To) 1-Sep-2010 - 30-Apr-2017	
4. TITLE AND SUBTITLE Final Report: Atomtronics: Material and device physics of quantum gases			5a. CONTRACT NUMBER W911NF-10-1-0452		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER 611103		
6. AUTHORS			5d. PROJECT NUMBER		
			5e. TASK NUMBER		
			5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAMES AND ADDRESSES University of Maryland - College Park Office of Research Administration 3112 Lee Building 7809 Regents Drive College Park, MD 20742 -5141			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) 58156-PH-MUR.82		
12. DISTRIBUTION AVAILABILITY 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 be construed 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:			17. LIMITATION OF ABSTRACT UU	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Ian Spielman
a. REPORT UU	b. ABSTRACT UU	c. THIS PAGE UU			19b. TELEPHONE NUMBER 301-975-8664

RPPR Final Report

as of 02-Apr-2018

Agency Code:

Proposal Number: 58156PHMUR

Agreement Number: W911NF-10-1-0452

INVESTIGATOR(S):

Name: Ian B. Spielman
Email: spielman@umd.edu
Phone Number: 3019758664
Principal: Y

Organization: **University of Maryland - College Park**

Address: Office of Research Administration, College Park, MD 207425141

Country: USA

DUNS Number: 790934285

EIN: 526002033

Report Date: 31-Jul-2017

Date Received: 23-Mar-2018

Final Report for Period Beginning 01-Sep-2010 and Ending 30-Apr-2017

Title: Atomtronics: Material and device physics of quantum gases

Begin Performance Period: 01-Sep-2010

End Performance Period: 30-Apr-2017

Report Term: 0-Other

Submitted By: Ian Spielman

Email: spielman@umd.edu

Phone: (301) 975-8664

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

STEM Degrees:

STEM Participants:

Major Goals: In this project we brought together a diverse group of scientists – both experimental and theoretical – experts in fields from atomic and condensed matter physics to electrical engineering. Our project's title "Atomtronics: Material and device physics of quantum gases" illustrates the chasm we bridged, starting from the rich and fundamental physics already revealed with cold atoms systems, then leading to an understanding of the functional materials science required for practical device applications. The scope of this challenge far exceeded the capabilities of a single laboratory and successful completion required the dedicated collaborative effort of our proposed MURI team.

Our program consisted of five lines of research, each developing core ideas relevant to atomtronic devices. (1) Spinatomics: the rich and controllable spin of ultracold atoms allows devices not even conceivable in conventional electronics; (2) Cascadable spinatomics gates: we will use the interactions between atomic spins to construct cascadable "spin transistors"; (3) Systems far from equilibrium: systems of ultracold atoms can be reliably prepared in states very far from thermal equilibrium, leading to new functional behavior; (4) Cold atom closed circuits: here we studied how several atomtronic circuit elements can be interconnected into more complex integrated devices; and (5) Optoelectronic interfaces: we will also developed a platform to couple atoms to optical fields near the surface of fibers allowing effective interconnection to conventional opto-electronic devices.

Ultracold atoms had already demonstrated superior functionality relevant to important DoD missions such as navigation, timekeeping, and sensing. In such applications, the atoms are coupled immediately to external circuit elements. Future extensions of our atomtronic research may help bridge the gap between atomic sensors and external electronics more effectively than current technologies.

Accomplishments: Spin Hall effect and spin transistor

Electronic properties such as current flow are generally independent of the electron's spin angular momentum, an internal degree of freedom possessed by quantum particles. The spin Hall effect, first proposed 40 years ago, is an unusual class of phenomena in which flowing particles experience orthogonally directed, spin dependent forces—analogue to the conventional Lorentz force that gives the Hall effect, but opposite in sign for two spin states. Spin Hall effects have been observed for electrons flowing in spin-orbit-coupled materials such as GaAs and InGaAs and for laser light traversing dielectric junctions. Here we observe the spin Hall effect in a quantum-degenerate Bose gas, and use the resulting spin-dependent Lorentz forces to realize a cold-atom spin transistor. By engineering a spatially inhomogeneous spin-orbit coupling field for our quantum

RPPR Final Report

as of 02-Apr-2018

gas, we explicitly introduce and measure the requisite spin-dependent Lorentz forces, finding them to be in excellent agreement with our calculations. This 'atomtronic' transistor behaves as a type of velocity-insensitive adiabatic spin selector, with potential application in devices such as magnetic or inertial sensors. In addition, such techniques for creating and measuring the spin Hall effect are clear prerequisites for engineering topological insulators and detecting their associated quantized spin Hall effects in quantum gases. As implemented, our system realizes a laser-actuated analogue to the archetypal semiconductor spintronic device, the Datta-Das spin transistor.

We engineered a two-dimensional magnetic lattice in an elongated strip geometry, with effective per-plaquette flux $\sim 4/3$ times the flux quanta. We imaged the localized edge and bulk states of atomic Bose-Einstein condensates in this strip, with single lattice-site resolution along the narrow direction. Further, we observed both the skipping orbits of excited atoms traveling down our system's edges, analogues to edge magnetoplasmons in 2-D electron systems, and a dynamical Hall effect for bulk excitations. Our lattice's long direction consisted of the sites of an optical lattice and its narrow direction consisted of the internal atomic spin states. Our technique has minimal heating, a feature that will be important for spectroscopic measurements of the Hofstadter butterfly and realizations of Laughlin's charge pump.

Cascadable spintronics gates:

We have achieved simultaneous cooling of three different atomic species down to nanokelvin temperatures, the potassium isotopes 41K and 40K , as well as lithium (6Li). A Bose-Einstein condensate of 41K is used to cool the two fermionic species, 40K and 6Li , to degeneracy. The immediate goal of the experiment is to extend our transport studies to Fermi gases with imbalanced masses, 40K and 6Li . In later stages, we hope to use the heavy fermionic species as a "switch" for the transport properties of the light ones.

Strongly interacting Fermi systems

Strong electron correlations lie at the origin of transformative phenomena such as colossal magnetoresistance and high-temperature superconductivity. Already near room temperature, doped copper oxide materials display remarkable features such as a pseudo-gap and a "strange metal" phase with unusual transport properties. The essence of this physics is believed to be captured by the Fermi-Hubbard model of repulsively interacting, itinerant fermions on a lattice. Here we report on the site-resolved observation of charge and spin correlations in the two-dimensional (2D) Fermi-Hubbard model realized with ultracold atoms. Antiferromagnetic spin correlations are maximal at half-filling and weaken monotonically upon doping. Correlations between singly charged sites are negative at large doping, revealing the Pauli and correlation hole—a suppressed probability of finding two fermions near each other. However, as the doping is reduced below a critical value, correlations between such local magnetic moments become positive, signaling strong bunching of doublons and holes. Excellent agreement with numerical linked-cluster expansion (NLCE) and determinantal quantum Monte Carlo (DQMC) calculations is found. Positive non-local moment correlations directly imply potential energy fluctuations due to doublon-hole pairs, which should play an important role for transport in the Fermi-Hubbard model.

Ultrathin optical fibers:

We have worked to optimize our fiber pulling apparatus to be able to produce ultrathin fibers with very high transmission. This has been accomplished by paying very close attention to the algorithm that controls the pulling of the fiber, the conditions for adiabaticity, and cleaning techniques. As a result we can routinely pull fibers with a 500 nm waist with a transmission of better than 99.95%, unsurpassed in any other lab.

One of the attractive features of trapping atoms on fibers is that the very small mode volume allows high optical fields with small amounts of optical power. As a result, when probing absorption of trapped atoms, the power levels must be quite low to avoid saturation, on the order of a few picowatts. At these power levels, it is advantageous to counting single photons with an APD rather than current on a photodiode. We have constructed a gated single photon counting system to monitor this. Because the trapping laser operates at the milliwatt level, this requires rejection of trapping laser photons at the $9-10$ order of magnitude level. This was successfully accomplished using interference filters and narrow band volume Bragg gratings. In the process of developing this system, we discovered the existence of fluorescence from the fiber, at a level of a 10^4 photons per mW of trapping light. This has also been observed by the Vienna group and will be the ultimate

RPPR Final Report

as of 02-Apr-2018

background limit, although it can be avoided to a large extent with gating techniques.

We experimentally demonstrate optical trapping of ^{87}Rb atoms using a two-color evanescent field around an optical nanofiber. A model that includes scalar, vector, and tensor light shifts of the probe transition $5S_{1/2}-5P_{3/2}$ from the trapping beams, weighted by the temperature-dependent position of the atoms in the trap, qualitatively describes the observed asymmetric profile and explains differences with previous experiments that used Cs atoms. The model provides a consistent way to extract the number of atoms in the trap.

Ultracold atom closed circuits

We have created a toroidal-shaped Bose-Einstein condensate using an all-optical trap. The trap supports persistent currents with lifetimes of $>30\text{s}$ (comparable to the vacuum limited BEC lifetime). Using a blue-detuned focused laser beam, a weak link barrier has been created in the ring-shaped condensate. The barrier was aligned to intersect one side of the ring. The persistence of the current in the presence of the barrier was studied as a function of barrier height and atom number. We found that the superflow stopped abruptly when the velocity in the barrier region crossed a critical value. We have recently implemented a moving barrier and are starting to study the effects of a rotating barrier on a stationary condensate.

Using a rotating weak-link junction in a toroidal Bose-Einstein Condensate we have created an atomtronic circuit, which is analogous to an RF SQUID. In our atomtronic system rotation plays the role of magnetic field. By tuning the height of the weak link we are able to tune the critical rotation rate for phase slips, and demonstrated hysteretic behavior for the system. Recently we implemented a double-junction circuit, where two weak-link barriers are rotated around the system, this is an important step towards realizing a circuit analogous to DC-biased SQUIDS, which are used for sensitive detection of magnetic fields. In addition, theory has developed new methods for simulating effects of synthetic gauge potentials on cold atoms.

Training Opportunities: Nothing to Report

Results Dissemination: Nothing to Report

RPPR Final Report as of 02-Apr-2018

Honors and Awards: 2010 Jonathan Allen Junior Faculty Award, RLE, MIT (Zwierlein)
2010 Young Investigator Award, Air Force Office of Scientific Research (Zwierlein)
2010 Young Investigator Award, Office of Naval Research, 2010 (Zwierlein)
2010 Young Faculty Award, Defense Advanced Research Projects Agency (Zwierlein)
2010 PECASE Award: Presidential Early Career Awards for Scientists and Engineers (Zwierlein)
2010 Fellow, David and Lucile Packard Foundation (Zwierlein)
2011 IUPAP prize (Spielman)
2011 Arthur S. Flemming award (Spielman)
2010 PECASE Award: Presidential Early Career Awards for Scientists and Engineers (Spielman)
2012 Promotion to Associate Professor with Tenure, (Zwierlein)
2012 Silverman Family Career Development Chair (Zwierlein)
2012 APS Outstanding Referee (Zwierlein)
2011 Junior BEC Award (Spielman)
2011 Department of Commerce Bronze Medal (Campbell)
2012 Doctor of Science Honoris Causa, University of Oxford (Phillips)

Spielman named Fellow of APS
Karina Jimenez-Garcia (student with Spielman) named finalist for DAMOP thesis prize
Zwierlein named full professor at MIT
Waseem Bakr (postdoc with Zwierlein) wins MIT infinite kilometer award
Jennifer Schloss (student with Zwierlein) receives Hertz Fellowship
Matthew Nichols (student with Zwierlein) receives NDSEG Fellowship
Campbell receives 2012 Arthur S. Flemming award
Campbell receives 2012 Sigma Xi young scientist award

Gretchen Campbell named PECASE scholar
Ian Spielman wins 2014 NIST Stratton award
Victor Galitski wins 2013 Simons Investigator Award

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: Co-Investigator

Participant: Gretchen Campbell

Person Months Worked: 15.00

Funding Support:

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

Participant Type: Co-Investigator

Participant: Isaac Chuang

Person Months Worked: 15.00

Funding Support:

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

Participant Type: Co-Investigator

Participant: Charles Clark

Person Months Worked: 15.00

Funding Support:

Project Contribution:

RPPR Final Report
as of 02-Apr-2018

International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Co-Investigator
Participant: Sankar Das Sarma
Person Months Worked: 6.00
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Funding Support:

Participant Type: Co-Investigator
Participant: Eugene Demler
Person Months Worked: 12.00
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Funding Support:

Participant Type: Co-Investigator
Participant: Victor Galitski
Person Months Worked: 15.00
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Funding Support:

Participant Type: Co-Investigator
Participant: William Phillips
Person Months Worked: 6.00
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: Y
Other Collaborators:

Funding Support:

Participant Type: Co-Investigator
Participant: James Porto
Person Months Worked: 15.00
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Funding Support:

Participant Type: Co-Investigator
Participant: Steve Rolston
Person Months Worked: 15.00

Funding Support:

RPPR Final Report

as of 02-Apr-2018

Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Co-Investigator

Participant: Martin Zwierlein

Person Months Worked: 12.00

Funding Support:

Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: PD/PI

Participant: Ian Spielman

Person Months Worked: 15.00

Funding Support:

Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

ARTICLES:

Publication Type: Journal Article

Peer Reviewed: Y

Publication Status: 1-Published

Journal: Annals of Physics

Publication Identifier Type: DOI

Publication Identifier: 10.1016/j.aop.2011.04.001

Volume: 326

Issue: 7

First Page #: 0

Date Submitted:

Date Published:

Publication Location:

Article Title: Semiclassical solitons in strongly correlated systems of ultracold bosonic atoms in optical lattices

Authors:

Keywords: Solitons; Ultracold atoms; Optical lattice; Nonequilibrium dynamics

Abstract: We investigate theoretically soliton excitations and dynamics of their formation in strongly correlated systems of ultracold bosonic atoms in two and three dimensional optical lattices. We derive equations of nonlinear hydrodynamics in the regime of strong interactions and incommensurate fillings, when atoms can be treated as hard core bosons. When parameters change in one direction only we obtain Korteweg–de Vries type equation away from half-filling and modified KdV equation at half-filling. We apply this general analysis to a problem of the decay of the density step. We consider stability of one dimensional solutions to transverse fluctuations. Our results are also relevant for understanding nonequilibrium dynamics of lattice spin models

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

Acknowledged Federal Support:

RPPR Final Report
as of 02-Apr-2018

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review Letters
Publication Identifier Type: DOI **Publication Identifier:** 10.1103/PhysRevLett.106.220402
Volume: 106 **Issue:** 22 **First Page #:** 0
Date Submitted: **Date Published:**
Publication Location:

Article Title: Majorana Fermions in Equilibrium and in Driven Cold-Atom Quantum Wires

Authors:

Keywords: Majorana Fermions effective spin-orbit interaction

Abstract: We introduce a new approach to create and detect Majorana fermions using optically trapped 1D fermionic atoms. In our proposed setup, two internal states of the atoms couple via an optical Raman transition—simultaneously inducing an effective spin-orbit interaction and magnetic field—while a background molecular BEC cloud generates s-wave pairing for the atoms. The resulting cold-atom quantum wire supports Majorana fermions at phase boundaries between topologically trivial and nontrivial regions, as well as “Floquet Majorana fermions” when the system is periodically driven. We analyze experimental parameters, detection schemes, and various imperfections.

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

Acknowledged Federal Support:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: New Journal of Physics
Publication Identifier Type: DOI **Publication Identifier:** 10.1088/1367-2630/13/7/073018
Volume: 13 **Issue:** 7 **First Page #:** 0
Date Submitted: **Date Published:**
Publication Location:

Article Title: The dynamics and prethermalization of one-dimensional quantum systems probed through the full distributions of quantum noise

Authors:

Keywords: prethermalization Quantum noise 1D quasi-coindensates

Abstract: Quantum noise correlations have been employed in several areas of physics, including condensed matter, quantum optics and ultracold atoms, to reveal the non-classical states of the systems. To date, such analyses have mostly focused on systems in equilibrium. In this paper, we show that quantum noise is also a useful tool for characterizing and studying the non-equilibrium dynamics of a one-dimensional (1D) system. We consider the Ramsey sequence of 1D, two-component bosons, and obtain simple, analytical expressions for time evolutions of the full distribution functions for this strongly correlated, many-body system. The analysis can also be directly applied to the evolution of interference patterns between two 1D quasi-coindensates created from a single condensate through splitting. Using the tools developed in this paper, we demonstrate that 1D dynamics in these systems exhibits the phenomenon known as 'prethermalization', where the observables of non-equilibrium, long-time transient

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

Acknowledged Federal Support:

RPPR Final Report
as of 02-Apr-2018

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review A
Publication Identifier Type: DOI **Publication Identifier:** 10.1103/PhysRevA.84.011601
Volume: 84 **Issue:** 1 **First Page #:** 0
Date Submitted: **Date Published:**
Publication Location:
Article Title: Strongly interacting isotopic Bose-Fermi mixture immersed in a Fermi sea
Authors:
Keywords: Bose-Fermi mixture 41K 40K 6Li
Abstract: We have created a triply quantum-degenerate mixture of bosonic 41K and two fermionic species 40K and 6Li. The boson is shown to be an efficient coolant for the two fermions, spurring hopes for the observation of fermionic superfluids with imbalanced masses. We observe multiple heteronuclear Feshbach resonances, in particular a wide s-wave resonance for the combination 41K-40K, opening up studies of strongly interacting isotopic Bose-Fermi mixtures. For large imbalance in the local densities of different species, we enter the polaronic regime of dressed impurities immersed in a bosonic or fermionic bath.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: New Journal of Physics
Publication Identifier Type: DOI **Publication Identifier:** 10.1088/1367-2630/13/5/055009
Volume: 13 **Issue:** 5 **First Page #:** 0
Date Submitted: **Date Published:**
Publication Location:
Article Title: Spin transport in polaronic and superfluid Fermi gases
Authors:
Keywords: Polarons and electron-phonon interactions
Abstract: We present measurements of spin transport in ultracold gases of fermionic 6Li in a mixture of two spin states at a Feshbach resonance. In particular, we study the spin-dipole mode, where the two spin components are displaced from each other against a harmonic restoring force. We prepare a highly imbalanced, or polaronic, spin mixture with a spin-dipole excitation and we observe strong, unitarity-limited damping of the spin-dipole mode. In gases with small spin imbalance, below the Pauli limit for superfluidity, we observe strongly damped spin flow even in the presence of a superfluid core. This indicates strong mutual friction between superfluid and polarized normal spins, possibly involving Andreev reflection at the superfluid–normal interface.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support:

RPPR Final Report
as of 02-Apr-2018

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: Nature

Publication Identifier Type: DOI

Publication Identifier: 10.1038/nature09989

Volume: 472

Issue: 7342

First Page #: 0

Date Submitted:

Date Published:

Publication Location:

Article Title: Universal spin transport in a strongly interacting Fermi gas

Authors:

Keywords: spin transport quantum limit of diffusion

Abstract: Transport of fermions, particles with half-integer spin, is central to many fields of physics. Electron transport runs modern technology, defining states of matter such as superconductors and insulators, and electron spin is being explored as a new carrier of information¹. Neutrino transport energizes supernova explosions following the collapse of a dying star², and hydrodynamic transport of the quark–gluon plasma governed the expansion of the early Universe³. However, our understanding of non-equilibrium dynamics in such strongly interacting fermionic matter is still limited. Ultracold gases of fermionic atoms realize a pristine model for such systems and can be studied in real time with the precision of atomic physics⁴. Even above the superfluid transition, such gases flow as an almost perfect fluid with very low viscosity when interactions are tuned to a scattering resonance^{3, 5, 6, 7, 8}. In this hydrodynamic regime, collective density excitations are weakly damped^{6, 7}. Here we expe

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

Acknowledged Federal Support:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: Physical Review A

Publication Identifier Type: DOI

Publication Identifier: 10.1103/PhysRevA.83.033619

Volume: 83

Issue: 3

First Page #: 0

Date Submitted:

Date Published:

Publication Location:

Article Title: Bound states of a localized magnetic impurity in a superfluid of paired ultracold fermions

Authors:

Keywords: localized magnetic impurity Shiba

Abstract: We consider a localized impurity atom that interacts with a cloud of fermions in the paired state. We develop an effective scattering length description of the interaction between an impurity and a fermionic atom using their vacuum scattering length. Treating the pairing of fermions at the mean-field level, we show that the impurity atom acts like a magnetic impurity in the condensed matter context, and leads to the formation of a pair of Shiba bound states inside the superconducting gap. In addition, the impurity atom can lead to the formation of deeply bound states below the Fermi sea.

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

Acknowledged Federal Support:

RPPR Final Report as of 02-Apr-2018

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: Physical Review Letters

Publication Identifier Type: DOI

Publication Identifier: 10.1103/PhysRevLett.106.050402

Volume: 106

Issue: 5

First Page #: 0

Date Submitted:

Date Published:

Publication Location:

Article Title: Competition between Pairing and Ferromagnetic Instabilities in Ultracold Fermi Gases near Feshbach Resonances

Authors:

Keywords: Ferromagnetic Instabilities Feshbach resonance

Abstract: We study the quench dynamics of a two-component ultracold Fermi gas from the weak into the strong interaction regime, where the short time dynamics are governed by the exponential growth rate of unstable collective modes. We obtain an effective interaction that takes into account both Pauli blocking and the energy dependence of the scattering amplitude near a Feshbach resonance. Using this interaction we analyze the competing instabilities towards Stoner ferromagnetism and pairing.

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

Acknowledged Federal Support:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: Physical Review Letters

Publication Identifier Type: DOI

Publication Identifier: 10.1103/PhysRevLett.106.130401

Volume: 106

Issue: 13

First Page #: 0

Date Submitted:

Date Published:

Publication Location:

Article Title: Superflow in a Toroidal Bose-Einstein Condensate: An Atom Circuit with a Tunable Weak Link

Authors:

Keywords: Superflow persistent current Bose-Einstein condensate closed-loop atom circuit

Abstract: We have created a long-lived (?40??s) persistent current in a toroidal Bose-Einstein condensate held in an all-optical trap. A repulsive optical barrier across one side of the torus creates a tunable weak link in the condensate circuit, which can affect the current around the loop. Superflow stops abruptly at a barrier strength such that the local flow velocity at the barrier exceeds a critical velocity. The measured critical velocity is consistent with dissipation due to the creation of vortex-antivortex pairs. This system is the first realization of an elementary closed-loop atom circuit.

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

Acknowledged Federal Support:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: Physical Review A

Publication Identifier Type: DOI

Publication Identifier: 10.1103/PhysRevA.82.063613

Volume: 82

Issue: 6

First Page #: 0

Date Submitted:

Date Published:

Publication Location:

Article Title: Momentum-space engineering of gaseous Bose-Einstein condensates

Authors:

Keywords: diffraction standing-wave laser pulses atom-interferometry

Abstract: We show how the momentum distribution of gaseous Bose-Einstein condensates can be shaped by applying a sequence of standing-wave laser pulses. We present a theory, whose validity was demonstrated in an earlier experiment [L. Deng et al. Phys. Rev. Lett. 83 5407 (1999)], of the effect of a two-pulse sequence on the condensate wavefunction in momentum space. We generalize the previous result to the case of N pulses of arbitrary intensity separated by arbitrary intervals and show how these parameters can be engineered to produce a desired final momentum distribution. We find that several momentum distributions, important in atom-interferometry applications, can be engineered with high fidelity with two or three pulses.

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

Acknowledged Federal Support:

RPPR Final Report

as of 02-Apr-2018

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review A
Publication Identifier Type: DOI **Publication Identifier:** 10.1103/PhysRevA.82.033607
Volume: 82 **Issue:** 3 **First Page #:** 0
Date Submitted: **Date Published:**
Publication Location:

Article Title: Phase fluctuations in anisotropic Bose-Einstein condensates: From cigars to rings

Authors:

Keywords: anisotropic Bose-Einstein condensates phase-fluctuating condensate ring-shaped geometry

Abstract: We study the phase-fluctuating condensate regime of ultracold atoms trapped in a ring-shaped trap geometry, which has been realized in recent experiments. We first consider a simplified box geometry, in which we identify the conditions to create a state that is dominated by thermal phase fluctuations, and then explore the experimental ring geometry. In both cases we demonstrate that the requirement for strong phase fluctuations can be expressed in terms of the total number of atoms and the geometric length scales of the trap only. For the ring-shaped trap we discuss the zero temperature limit in which a condensate is realized where the phase is fluctuating due to interactions and quantum fluctuations. We also address possible ways of detecting the phase-fluctuating regime in ring condensates.

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

Acknowledged Federal Support:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review B
Publication Identifier Type: DOI **Publication Identifier:** 10.1103/PhysRevB.83.140510
Volume: 83 **Issue:** 14 **First Page #:** 0
Date Submitted: **Date Published:**
Publication Location:

Article Title: Chiral Rashba spin textures in ultracold Fermi gases

Authors:

Keywords: Rashba Fermi gases non-Abelian Majorana quasiparticles

Abstract: Spin-orbit (SO) coupling is an important ingredient in many recently discovered phenomena such as the spin-Hall effect and topological insulators. Of particular interest is topological superconductivity, with its potential application in topological quantum computation. The absence of disorder in ultracold atomic systems makes them ideal for quantum computation applications; however, the SO coupling schemes proposed thus far are experimentally impractical owing to large spontaneous emission rates in the alkali fermions. In this paper, we develop a scheme to generate Rashba SO coupling with a low spontaneous emission extension to a recent experiment. We show that this scheme generates a Fermi surface spin texture for 40K atoms, which is observable in time-of-flight measurements. The chiral spin texture, together with conventional s-wave interactions, leads to topological superconductivity and non-Abelian Majorana quasiparticles.

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

Acknowledged Federal Support:

RPPR Final Report

as of 02-Apr-2018

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review Letters
Publication Identifier Type: DOI **Publication Identifier:** 10.1103/PhysRevLett.108.235301
Volume: 108 **Issue:** 23 **First Page #:** 0
Date Submitted: **Date Published:**
Publication Location:
Article Title: Synthetic 3D Spin-Orbit Coupling
Authors:
Keywords: Spin orbit coupling in cold atomic gases
Abstract: We describe a method for creating a three-dimensional analogue to Rashba spin-orbit coupling in systems of ultracold atoms. This laser induced coupling uses Raman transitions to link four internal atomic states with a tetrahedral geometry, and gives rise to a Dirac point that is robust against environmental perturbations. We present an exact result showing that such a spin-orbit coupling in a fermionic system always gives rise to a molecular bound state.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review Letters
Publication Identifier Type: DOI **Publication Identifier:** 10.1103/PhysRevLett.108.225303
Volume: 108 **Issue:** 22 **First Page #:** 0
Date Submitted: **Date Published:**
Publication Location:
Article Title: Peierls Substitution in an Engineered Lattice Potential
Authors:
Keywords: Artificial gauge fields cold atoms
Abstract: Artificial gauge fields open the possibility to realize quantum many-body systems with ultracold atoms, by engineering Hamiltonians usually associated with electronic systems. In the presence of a periodic potential, artificial gauge fields may bring ultracold atoms closer to the quantum Hall regime. Here, we describe a one-dimensional lattice derived purely from effective Zeeman shifts resulting from a combination of Raman coupling and radio-frequency magnetic fields. In this lattice, the tunneling matrix element is generally complex. We control both the amplitude and the phase of this tunneling parameter, experimentally realizing the Peierls substitution for ultracold neutral atoms.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Science
Publication Identifier Type: DOI **Publication Identifier:** 10.1126/science.1212652
Volume: 335 **Issue:** 6066 **First Page #:** 0
Date Submitted: **Date Published:**
Publication Location:
Article Title: Synthetic Partial Waves in Ultracold Atomic Collisions
Authors:
Keywords: Atomic scattering artificial
Abstract: Interactions between particles can be strongly altered by their environment. We demonstrate a technique for modifying interactions between ultracold atoms by dressing the bare atomic states with light, creating an effective interaction of vastly increased range that scatters states of finite relative angular momentum at collision energies where only s-wave scattering would normally be expected. We collided two optically dressed neutral atomic Bose-Einstein condensates with equal, and opposite, momenta and observed that the usual s-wave distribution of scattered atoms was altered by the appearance of d- and g-wave contributions. This technique is expected to enable quantum simulation of exotic systems, including those predicted to support Majorana fermions.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support:

RPPR Final Report
as of 02-Apr-2018

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: EPL (Europhysics Letters)

Publication Identifier Type: DOI

Publication Identifier: 10.1209/0295-5075/97/33002

Volume: 97

Issue: 3

First Page #: 0

Date Submitted:

Date Published:

Publication Location:

Article Title: Spin-charge-density wave in a rounded-square Fermi surface for ultracold atoms

Authors:

Keywords: Interactions cold atoms hamiltonian

Abstract: We derive and discuss an experimentally realistic model describing ultracold atoms in an optical lattice including a commensurate, but staggered, spin-flip term. The resulting band structure is quite exotic; fermions in the third band have an unusual rounded picture-frame Fermi surface (essentially two concentric squircles), leading to imperfect nesting. We develop a generalized theory describing the spin and charge degrees of freedom simultaneously at the random-field-approximation level, and show that the system can develop a coupled spin-charge-density wave order. Our generic approach can be used to study spin and charge instabilities in many materials, such as high-T_c superconductors, organic compounds, graphene, and iron pnictides.

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

Acknowledged Federal Support:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: Physical Review A

Publication Identifier Type: DOI

Publication Identifier: 10.1103/PhysRevA.84.063604

Volume: 84

Issue: 6

First Page #: 0

Date Submitted:

Date Published:

Publication Location:

Article Title: Vortices in spin-orbit-coupled Bose-Einstein condensates

Authors:

Keywords: Vortices SOC BEC

Abstract: Realistic methods to create vortices in spin-orbit-coupled Bose-Einstein condensates are discussed. It is shown that, contrary to common intuition, rotation of the trap containing a spin-orbit condensate does not lead to an equilibrium state with static vortex structures but gives rise instead to nonequilibrium behavior described by an intrinsically time-dependent Hamiltonian. We propose here the following alternative methods to induce thermodynamically stable static vortex configurations: (i) to rotate both the lasers and the anisotropic trap and (ii) to impose a synthetic Abelian field on top of synthetic spin-orbit interactions. Effective Hamiltonians for spin-orbit condensates under such perturbations are derived for most currently known realistic laser schemes that induce synthetic spin-orbit couplings. The Gross-Pitaevskii equation is solved for several experimentally relevant regimes. The new interesting effects include spatial separation of left- and right-moving spin-orbit con

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

Acknowledged Federal Support:

RPPR Final Report
as of 02-Apr-2018

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review Letters
Publication Identifier Type: DOI **Publication Identifier:** 10.1103/PhysRevLett.109.085303
Volume: 109 **Issue:** 8 **First Page #:** 0
Date Submitted: **Date Published:**
Publication Location:

Article Title: Exotic Quantum Spin Models in Spin-Orbit-Coupled Mott Insulators

Authors:

Keywords: beyond mean field spin orbit coupling

Abstract: We study cold atoms in an optical lattice with synthetic spin-orbit coupling in the Mott-insulator regime. We calculate the parameters of the corresponding tight-binding model using Peierls substitution and “localized Wannier states method” and derive the low-energy spin Hamiltonian for bosons and fermions. The spin Hamiltonian is a combination of Heisenberg model, quantum compass model and Dzyaloshinskii-Moriya interactions and it has a rich classical phase diagram with collinear, spiral and vortex phases. We discuss the state of the art of experiments to realize and detect magnetic orderings in strongly correlated optical lattices.

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

Acknowledged Federal Support:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review A
Publication Identifier Type: DOI **Publication Identifier:** 10.1103/PhysRevA.85.063619
Volume: 85 **Issue:** 6 **First Page #:** 0
Date Submitted: **Date Published:**
Publication Location:

Article Title: Detecting d-wave pairing and collective modes in fermionic condensates with Bragg scattering

Authors:

Keywords: bragg scattering Fermi gas

Abstract: We show how the appearance of d-wave pairing in fermionic condensates manifests itself in inelastic light scattering. Specifically, we calculate the Bragg scattering intensity from the dynamic structure factor and the spin susceptibility, which can be inferred from spin-flip Raman transitions. This information provides a precise tool with which we can identify nontrivial correlations in the state of the system beyond the information contained in the density profile imaging alone. Due to the lack of Coulomb effects in neutral superfluids, this is also an opportunity to observe the Anderson-Bogoliubov collective mode.

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

Acknowledged Federal Support:

RPPR Final Report
as of 02-Apr-2018

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: Physical Review A

Publication Identifier Type: DOI

Publication Identifier: 10.1103/PhysRevA.83.013612

Volume: 83

Issue: 1

First Page #: 0

Date Submitted:

Date Published:

Publication Location:

Article Title: Bogoliubov theory of interacting bosons on a lattice in a synthetic magnetic field

Authors:

Keywords: artificial magnetic field bose gas

Abstract: We consider theoretically the problem of an artificial gauge potential applied to a cold atomic system of interacting neutral bosons in a tight-binding optical lattice. Using the Bose-Hubbard model, we show that an effective magnetic field leads to superfluid phases with simultaneous spatial order, which we analyze using Bogliubov theory. This gives a consistent expansion in terms of quantum and thermal fluctuations, in which the lowest order gives a Gross-Pitaevskii equation determining the condensate configuration. We apply an analysis based on the magnetic symmetry group to show how the spatial structure of this configuration depends on commensuration between the magnetic field and the lattice. Higher orders describe the quasiparticle excitations, whose spectrum combines the intricacy of the Hofstadter butterfly with the characteristic features of the superfluid phase. We use the depletion of the condensate to determine the range of validity of our approximations and also to find an

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

Acknowledged Federal Support:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: Physical Review B

Publication Identifier Type: DOI

Publication Identifier: 10.1103/PhysRevB.83.195106

Volume: 83

Issue: 19

First Page #: 0

Date Submitted:

Date Published:

Publication Location:

Article Title: Condensates induced by interband coupling in a double-well lattice

Authors:

Keywords: optical lattice Mott superfluid

Abstract: We predict novel interband physics for bosons in double-well optical lattices (OLs). An intrinsic coupling between the s and the px bands due to interaction gives rise to larger Mott regions on the phase diagram at even fillings than the ones at odd fillings. On the other hand, the ground state can form various types of condensates, including a mixture of single-particle condensates of both bands, a mixture of a single-particle condensate of one band and a pair condensate of the other band, and a pair condensate composed of one particle from one band and one hole from the other band. The predicted phenomena should be observable in current experiments on double-well OLs.

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

Acknowledged Federal Support:

RPPR Final Report

as of 02-Apr-2018

Publication Type: Journal Article

Peer Reviewed: Y

Publication Status: 1-Published

Journal: Physical Review B

Publication Identifier Type: DOI

Publication Identifier: 10.1103/PhysRevB.83.174409

Volume: 83

Issue: 17

First Page #: 0

Date Submitted:

Date Published:

Publication Location:

Article Title: Prediction of a gapless topological Haldane liquid phase in a one-dimensional cold polar molecular lattice

Authors:

Keywords: Haldane model polar molecule

Abstract: We show that ultracold two-component fermionic dipolar gases in an optical lattice with strong two-body on-site loss can be used to realize a tunable effective spin-one model. Fermion number conservation provides an unusual constraint that $\sum_i (S_i^z)^2$ is conserved, leading to a unique topological liquid phase in one dimension, which can be thought of as the gapless analog of the Haldane gapped phase of a spin-one Heisenberg chain. The properties of this phase are calculated numerically via the infinite time-evolving block decimation method and analytically via a mapping to a one-mode Luttinger liquid with hidden spin information.

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

Acknowledged Federal Support:

Publication Type: Journal Article

Peer Reviewed: Y

Publication Status: 1-Published

Journal: Nature Physics

Publication Identifier Type: DOI

Publication Identifier: 10.1038/nphys2134

Volume: 8

Issue: 1

First Page #: 0

Date Submitted:

Date Published:

Publication Location:

Article Title: Topological semimetal in a fermionic optical lattice

Authors:

Keywords: Edge states cold atoms

Abstract: Optical lattices have an important role in advancing our understanding of correlated quantum matter. The recent implementation of orbital degrees of freedom in checkerboard¹, 2 and hexagonal³ optical lattices opens up a new avenue towards discovering novel quantum states of matter that have no prior analogues in solid-state electronic materials. Here, we predict that an exotic topological semimetal emerges as a parity-protected gapless state in the orbital bands of a two-dimensional fermionic optical lattice. This new quantum state is characterized by a parabolic band-degeneracy point with Berry flux 2π , in sharp contrast to the π flux of Dirac points as in graphene. We show that the appearance of this topological liquid is universal for all lattices with D₄ point-group symmetry, as long as orbitals with opposite parities hybridize strongly with each other and the band degeneracy is protected by odd parity. Turning on inter-particle repulsive interactions, the system undergoes a phase transition

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

Acknowledged Federal Support:

RPPR Final Report
as of 02-Apr-2018

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review B
Publication Identifier Type: DOI **Publication Identifier:** 10.1103/PhysRevB.84.081101
Volume: 84 **Issue:** 8 **First Page #:** 0
Date Submitted: **Date Published:**
Publication Location:

Article Title: Momentum-resolved optical lattice modulation spectroscopy for bosons in optical lattices

Authors:

Keywords: momentum selewctive modulation

Abstract: We propose an experimental method of optical lattice modulation spectroscopy for studying the spectral function of ultracold bosons in an optical lattice. We show that different features of the single-particle spectral function in different quantum phases can be obtained by measuring the change in momentum distribution after the modulation. In the Mott phase, this gives information about the momentum-dependent gap to particle-hole excitations as well as their spectral weight. In the superfluid phase, one can obtain the spectrum of the gapless Bogoliubov quasiparticles as well as the gapped amplitude fluctuations. The distinct evolution of the response with modulation frequency in the two phases can be used to identify these phases and the quantum phase transition separating them.

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

Acknowledged Federal Support:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review A
Publication Identifier Type: DOI **Publication Identifier:** 10.1103/PhysRevA.84.031607
Volume: 84 **Issue:** 3 **First Page #:** 0
Date Submitted: **Date Published:**
Publication Location:

Article Title: Interaction-induced excited-band condensate in a double-well optical lattice

Authors:

Keywords: interaction induced BEC

Abstract: We show theoretically that interaction effects in a double-well optical lattice can induce condensates in an excited band. For a symmetric double-well lattice, bosons condense into the bottom of the excited band at the edge of the Brillouin zone if the chemical potential is above a critical value. For an asymmetric lattice, a condensate with zero momentum is automatically induced in the excited band by the condensate in the lowest band. This is due to a combined effect of interaction and lattice potential, which reduces the band gap and breaks the inversion symmetry. Our work can be generalized to a superlattice composed of multiple-well potentials at each lattice site, where condensates can be induced in even higher bands.

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

Acknowledged Federal Support:

RPPR Final Report as of 02-Apr-2018

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: Physical Review A

Publication Identifier Type: DOI

Publication Identifier: 10.1103/PhysRevA.84.061603

Volume: 84

Issue: 6

First Page #: 0

Date Submitted:

Date Published:

Publication Location:

Article Title: Mott-insulating phases and magnetism of fermions in a double-well optical lattice

Authors:

Keywords: fermions optical lattice

Abstract: We theoretically investigate, using nonperturbative strong correlation techniques, Mott-insulating phases and magnetic ordering of two-component fermions in a two-dimensional double-well optical lattice. At filling of two fermions per site, there are two types of Mott insulators, one of which is characterized by spin-1 antiferromagnetism below the Néel temperature. The superexchange interaction in this system is induced by the interplay between the interband interaction and the spin degree of freedom. A great advantage of the double-well optical lattice is that the magnetic quantum phase diagram and the Néel temperature can be easily controlled by tuning the orbital energy splitting of the two-level system. Particularly, the Néel temperature can be one order of magnitude larger than that in standard optical lattices, facilitating the experimental search for magnetic ordering in optical lattice systems.

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

Acknowledged Federal Support:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: Physical Review A

Publication Identifier Type: DOI

Publication Identifier: 10.1103/PhysRevA.84.053621

Volume: 84

Issue: 5

First Page #: 0

Date Submitted:

Date Published:

Publication Location:

Article Title: Proposed signature of Anderson localization and correlation-induced delocalization in an N-leg optical lattice

Authors:

Keywords: Anderson localization exact

Abstract: We propose a realization of the one-dimensional random dimer model and certain N-leg generalizations using cold atoms in an optical lattice. We show that these models exhibit multiple delocalization energies that depend strongly on the symmetry properties of the corresponding Hamiltonian, and we provide analytical and numerical results for the localization length as a function of energy. We demonstrate that the N-leg systems possess similarities with their one-dimensional ancestors but are demonstrably distinct. The existence of critical delocalization energies leads to dips in the momentum distribution that serve as a clear signal of the localization-delocalization transition. These momentum distributions are different for models with different group symmetries and are identical for those with the same symmetry.

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

Acknowledged Federal Support:

RPPR Final Report

as of 02-Apr-2018

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: Review of Scientific Instruments

Publication Identifier Type: DOI

Publication Identifier: 10.1063/1.4747163

Volume: 83

Issue: 8

First Page #: 0

Date Submitted:

Date Published:

Publication Location:

Article Title: Partial-transfer absorption imaging: A versatile technique for optimal imaging of ultracold gases

Authors:

Keywords: Imaging ultracold atoms

Abstract: Partial-transfer absorption imaging is a tool that enables optimal imaging of atomic clouds for a wide range of optical depths. In contrast to standard absorption imaging, the technique can be minimally destructive and can be used to obtain multiple successive images of the same sample. The technique involves transferring a small fraction of the sample from an initial internal atomic state to an auxiliary state and subsequently imaging that fraction absorptively on a cycling transition. The atoms remaining in the initial state are essentially unaffected. We demonstrate the technique, discuss its applicability, and compare its performance as a minimally destructive technique to that of phase-contrast imaging.

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

Acknowledged Federal Support:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: Physical Review Letters

Publication Identifier Type: DOI

Publication Identifier: 10.1103/PhysRevLett.109.020504

Volume: 109

Issue: 2

First Page #: 0

Date Submitted:

Date Published:

Publication Location:

Article Title: Measuring Entanglement Entropy of a Generic Many-Body System with a Quantum Switch

Authors:

Keywords: Entropy quantum gas

Abstract: Entanglement entropy has become an important theoretical concept in condensed matter physics because it provides a unique tool for characterizing quantum mechanical many-body phases and new kinds of quantum order. However, the experimental measurement of entanglement entropy in a many-body system is widely believed to be unfeasible, owing to the nonlocal character of this quantity. Here, we propose a general method to measure the entanglement entropy. The method is based on a quantum switch (a two-level system) coupled to a composite system consisting of several copies of the original many-body system. The state of the switch controls how different parts of the composite system connect to each other. We show that, by studying the dynamics of the quantum switch only, the Rényi entanglement entropy of the many-body system can be extracted. We propose a possible design of the quantum switch, which can be realized in cold atomic systems. Our work provides a route towards testing the scaling

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

Acknowledged Federal Support:

RPPR Final Report
as of 02-Apr-2018

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: Physical Review A

Publication Identifier Type: DOI

Publication Identifier: 10.1103/PhysRevA.85.021602

Volume: 85

Issue: 2

First Page #: 0

Date Submitted:

Date Published:

Publication Location:

Article Title: Fermi polarons in two dimensions

Authors:

Keywords: Polarons experiment theory

Abstract: We theoretically analyze inverse radio-frequency (rf) spectroscopy experiments in two-component Fermi gases. We consider a small number of impurity atoms interacting strongly with a bath of majority atoms. In two-dimensional geometries we find that the main features of the rf spectrum correspond to an attractive polaron and a metastable repulsive polaron. Our results suggest that the attractive polaron has been observed in a recent experiment [B. Fröhlich et al. Phys. Rev. Lett. 106 105301 (2011)].

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

Acknowledged Federal Support:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: Physical Review A

Publication Identifier Type: DOI

Publication Identifier: 10.1103/PhysRevA.85.023621

Volume: 85

Issue: 2

First Page #: 0

Date Submitted:

Date Published:

Publication Location:

Article Title: Pairing instabilities in quasi-two-dimensional Fermi gases

Authors:

Keywords: Pairing Stoner

Abstract: We study nonequilibrium dynamics of ultracold two-component Fermi gases in low-dimensional geometries after the interactions are quenched from a weakly interacting to a strongly interacting regime. We develop a T-matrix formalism that takes into account the interplay between Pauli blocking and tight confinement in low-dimensional geometries. We employ our formalism to study the formation of molecules in quasi-two-dimensional Fermi gases near Feshbach resonance and show that the rate at which molecules form depends strongly on the transverse confinement. Furthermore, Pauli blocking gives rise to a sizable correction to the binding energy of molecules.

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

Acknowledged Federal Support:

RPPR Final Report
as of 02-Apr-2018

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Nature Communications
Publication Identifier Type: DOI **Publication Identifier:** 10.1038/ncomms1872
Volume: 3 **Issue:** 0 **First Page #:** 0
Date Submitted: **Date Published:**
Publication Location:

Article Title: Observation of topologically protected bound states in photonic quantum walks

Authors:

Keywords: topology laser

Abstract: Topological phases exhibit some of the most striking phenomena in modern physics. Much of the rich behaviour of quantum Hall systems, topological insulators, and topological superconductors can be traced to the existence of robust bound states at interfaces between different topological phases. This robustness has applications in metrology and holds promise for future uses in quantum computing. Engineered quantum systems—notably in photonics, where wavefunctions can be observed directly—provide versatile platforms for creating and probing a variety of topological phases. Here we use photonic quantum walks to observe bound states between systems with different bulk topological properties and demonstrate their robustness to perturbations—a signature of topological protection. Although such bound states are usually discussed for static (time-independent) systems, here we demonstrate their existence in an explicitly time-dependent situation. Moreover, we discover a new phenomenon: a topolo

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

Acknowledged Federal Support:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review Letters
Publication Identifier Type: DOI **Publication Identifier:** 10.1103/PhysRevLett.108.045302
Volume: 108 **Issue:** 4 **First Page #:** 0
Date Submitted: **Date Published:**
Publication Location:

Article Title: Evolution of Fermion Pairing from Three to Two Dimensions

Authors:

Keywords: Fermion Pairing

Abstract: We follow the evolution of fermion pairing in the dimensional crossover from three-dimensional to two-dimensional as a strongly interacting Fermi gas of ^6Li atoms becomes confined to a stack of two-dimensional layers formed by a one-dimensional optical lattice. Decreasing the dimensionality leads to the opening of a gap in radio-frequency spectra, even on the Bardeen-Cooper-Schrieffer side of a Feshbach resonance. The measured binding energy of fermion pairs closely follows the theoretical two-body binding energy and, in the two-dimensional limit, the zero-temperature mean-field Bose-Einstein-condensation to Bardeen-Cooper-Schrieffer crossover theory.

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

Acknowledged Federal Support:

RPPR Final Report as of 02-Apr-2018

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: Science

Publication Identifier Type: DOI

Publication Identifier: 10.1126/science.1214987

Volume: 335

Issue: 6068

First Page #: 0

Date Submitted:

Date Published:

Publication Location:

Article Title: Revealing the Superfluid Lambda Transition in the Universal Thermodynamics of a Unitary Fermi Gas

Authors:

Keywords: Lambda Cold atoms transition

Abstract: Fermi gases, collections of fermions such as neutrons and electrons, are found throughout nature, from solids to neutron stars. Interacting Fermi gases can form a superfluid or, for charged fermions, a superconductor. We have observed the superfluid phase transition in a strongly interacting Fermi gas by high-precision measurements of the local compressibility, density, and pressure. Our data completely determine the universal thermodynamics of these gases without any fit or external thermometer. The onset of superfluidity is observed in the compressibility, the chemical potential, the entropy, and the heat capacity, which displays a characteristic lambda-like feature at the critical temperature $T_c/T_F = 0.167(13)$. The ground-state energy is ϵ_N EF with $\epsilon = 0.376(4)$. Our measurements provide a benchmark for many-body theories of strongly interacting fermions.

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

Acknowledged Federal Support:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: Nature Physics

Publication Identifier Type: DOI

Publication Identifier: 10.1038/nphys2273

Volume: 8

Issue: 5

First Page #: 0

Date Submitted:

Date Published:

Publication Location:

Article Title: Feynman diagrams versus Fermi-gas Feynman emulator

Authors:

Keywords: Feynman diagram quantum Monte Carlo

Abstract: Precise understanding of strongly interacting fermions, from electrons in modern materials to nuclear matter, presents a major goal in modern physics. However, the theoretical description of interacting Fermi systems is usually plagued by the intricate quantum statistics at play. Here we present a cross-validation between a new theoretical approach, bold diagrammatic Monte Carlo^{1, 2, 3}, and precision experiments on ultracold atoms. Specifically, we compute and measure, with unprecedented precision, the normal-state equation of state of the unitary gas, a prototypical example of a strongly correlated fermionic system^{4, 5, 6}. Excellent agreement demonstrates that a series of Feynman diagrams can be controllably resummed in a non-perturbative regime using bold diagrammatic Monte Carlo.

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

Acknowledged Federal Support:

RPPR Final Report as of 02-Apr-2018

Publication Type: Journal Article

Peer Reviewed: Y

Publication Status: 1-Published

Journal: Physical Review A

Publication Identifier Type: DOI

Publication Identifier: 10.1103/PhysRevA.85.051602

Volume: 85

Issue: 5

First Page #: 0

Date Submitted:

Date Published:

Publication Location:

Article Title: Quantum degenerate Bose-Fermi mixture of chemically different atomic species with widely tunable interactions

Authors:

Keywords: quantum gas mixture

Abstract: We have created a quantum degenerate Bose-Fermi mixture of ^{23}Na and ^{40}K with widely tunable interactions via broad interspecies Feshbach resonances. Over 30 Feshbach resonances between ^{23}Na and ^{40}K were identified, including p-wave multiplet resonances. The large and negative triplet background scattering length between ^{23}Na and ^{40}K causes a sharp enhancement of the fermion density in the presence of a Bose condensate. As explained via the asymptotic bound-state model, this strong background scattering leads to wide Feshbach resonances observed at low magnetic fields. Our work opens up the prospect to create chemically stable, fermionic ground-state molecules of ^{23}Na - ^{40}K , where strong, long-range dipolar interactions would set the dominant energy scale.

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

Acknowledged Federal Support:

Publication Type: Journal Article

Peer Reviewed: Y

Publication Status: 1-Published

Journal: Physical Review Letters

Publication Identifier Type: DOI

Publication Identifier: 10.1103/PhysRevLett.109.095302

Volume: 109

Issue: 9

First Page #: 0

Date Submitted:

Date Published:

Publication Location:

Article Title: Spin-Injection Spectroscopy of a Spin-Orbit Coupled Fermi Gas

Authors:

Keywords: Spin orbit coupling fermi

Abstract: The coupling of the spin of electrons to their motional state lies at the heart of recently discovered topological phases of matter. Here we create and detect spin-orbit coupling in an atomic Fermi gas, a highly controllable form of quantum degenerate matter. We directly reveal the spin-orbit gap via spin-injection spectroscopy, which characterizes the energy-momentum dispersion and spin composition of the quantum states. For energies within the spin-orbit gap, the system acts as a spin diode. We also create a spin-orbit coupled lattice and probe its spinful band structure, which features additional spin gaps and a fully gapped spectrum. In the presence of s-wave interactions, such systems should display induced p-wave pairing, topological superfluidity, and Majorana edge states.

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

Acknowledged Federal Support:

RPPR Final Report

as of 02-Apr-2018

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: Physical Review E

Publication Identifier Type: DOI

Publication Identifier: 10.1103/PhysRevE.86.056710

Volume: 86

Issue: 5

First Page #: 0

Date Submitted:

Date Published:

Publication Location:

Article Title: Approximate mean-field equations of motion for quasi-two-dimensional Bose-Einstein-condensate systems

Authors:

Keywords: mean-field Bose-Einstein-condensate systems

Abstract: We present a method for approximating the solution of the three-dimensional, time-dependent Gross-Pitaevskii equation (GPE) for Bose-Einstein-condensate systems where the confinement in one dimension is much tighter than in the other two. This method employs a hybrid Lagrangian variational technique whose trial wave function is the product of a completely unspecified function of the coordinates in the plane of weak confinement and a Gaussian in the strongly confined direction having a time-dependent width and quadratic phase. The hybrid Lagrangian variational method produces equations of motion that consist of (1) a two-dimensional (2D) effective GPE whose nonlinear coefficient contains the width of the Gaussian and (2) an equation of motion for the width that depends on the integral of the fourth power of the solution of the 2D effective GPE. We apply this method to the dynamics of Bose-Einstein condensates confined in ring-shaped potentials and compare the approximate solution to the

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

Acknowledged Federal Support:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: New Journal of Physics

Publication Identifier Type: DOI

Publication Identifier: 10.1088/1367-2630/15/4/043010

Volume: 15

Issue: 4

First Page #: 0

Date Submitted:

Date Published:

Publication Location:

Article Title: Integrated optical dipole trap for cold neutral atoms with an optical waveguide coupler

Authors:

Keywords: evanescent wave integrated optical dipole trap

Abstract: An integrated optical dipole trap uses two-color (red and blue-detuned) traveling evanescent wave fields for trapping cold neutral atoms. To achieve longitudinal confinement, we propose using an integrated optical waveguide coupler, which provides a potential gradient along the beam propagation direction sufficient to confine atoms. This integrated optical dipole trap can support an atomic ensemble with a large optical depth due to its small mode area. Its quasi-TE₀ waveguide mode has an advantage over the HE₁₁ mode of a nanofiber, with little inhomogeneous Zeeman broadening at the trapping region. The longitudinal confinement eliminates the need for a one dimensional optical lattice, reducing collisional blockaded atomic loading, potentially producing larger ensembles. The waveguide trap allows for scalability and integrability with nano-fabrication technology. We analyze the potential performance of such integrated atom traps.

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

Acknowledged Federal Support:

RPPR Final Report

as of 02-Apr-2018

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: Physical Review A

Publication Identifier Type: DOI

Publication Identifier: 10.1103/PhysRevA.87.043604

Volume: 87

Issue: 4

First Page #: 0

Date Submitted:

Date Published:

Publication Location:

Article Title: Unconventional spin-density waves in dipolar Fermi gases

Authors:

Keywords: dipolar spin-density waves

Abstract: We show that unconventional spin order arises naturally in two-component dipolar Fermi gases of atoms or molecules, which recently became accessible experimentally, in optical lattices. Using an unbiased functional renormalization-group analysis, we find that dipolar interactions lead to an instability of the gas toward an $s=1$ spin-density wave state. This phase is the particle-hole analog of spin-triplet, p-wave Cooper pairs. The order parameter for such spin-density waves of p-wave orbital symmetry is a vector in spin space and, moreover, is defined on lattice bonds rather than on lattice sites. We determine the rich quantum phase diagram of dipolar fermions at half filling on the square lattice as a function of the dipolar orientation and discuss how these exotic spin-density waves emerge amidst competition with superfluid and charge-density wave phases.

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

Acknowledged Federal Support:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: Physical Review A

Publication Identifier Type: DOI

Publication Identifier: 10.1103/PhysRevA.86.063636

Volume: 86

Issue: 6

First Page #: 0

Date Submitted:

Date Published:

Publication Location:

Article Title: Loop-structure stability of a double-well-lattice Bose-Einstein condensate

Authors:

Keywords: Bloch solutions Bravais Bose-Einstein condensate

Abstract: In this work, we consider excited many-body mean-field states of bosons in a double-well optical lattice by investigating stationary Bloch solutions to the nonlinear equations of motion. We show that, for any positive interaction strength, a loop structure emerges at the edge of the band structure whose existence is entirely due to interactions. This can be contrasted to the case of a conventional optical (Bravais) lattice where a loop appears only above a critical repulsive interaction strength. Motivated by the possibility of realizing such nonlinear Bloch states experimentally, we analyze the collective excitations about these nonlinear stationary states and thereby establish conditions for the system's energetic and dynamical stability. We find that there are regimes that are dynamically stable and thus apt to be realized experimentally.

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

Acknowledged Federal Support:

Nothing to report