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14. ABSTRACT

The DARPA OLE project led to major advances of realizing and characterizing many-body systems with ultracold atoms. The phase diagrams of several paradigmatic systems was experimentally obtained and compared to state of the art theory. This includes the Fermi gas at unitarity, the imbalanced Fermi gas, and the Bose-Hubbard model. New systems were explores experimentally (fermionic Mott insulator, negative temperatures in a lattice) and theoretically, such as the fractional quantum Hall effect in optical lattices, and magnetism with SU(N) symmetry using earth alkaline atoms. The quantum microscope was invented as a new powerful technique. In addition, new

15. SUBJECT TERMS
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RPPR Final Report
as of 06-Jun-2022

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STEM Degrees: **STEM Participants:**

Major Goals:

Accomplishments:
see attachment

Training Opportunities:

Results Dissemination:

RPPR Final Report
as of 06-Jun-2022

Honors and Awards: Promotion to Full Professor of Physics, 07/01/2013 (M. Zwierlein)

William W. Buechner Teaching Prize, MIT, 2012 (M. Zwierlein)

Postdoctoral Fellow Waseem Bakr (Zwierlein group):
Winner, DAMOP APS Thesis Prize 2013, Winner, Infinite Kilometer (K) Award, MIT School of Science 2013, obtains Assistant Professorship at Princeton University, starting September 2013

Zwierlein Graduate Student Lawrence Cheuk wins MIT's Martin Deutsch award for Excellence in Experimental Physics

Jennifer Schloss (Graduate Student, Zwierlein group) receives Hertz Fellowship

Matthew Nichols (Graduate Student, Zwierlein group) receives NDSEG Fellowship

Joseph Thywissen "Fellow" of the Canadian Institute for Advanced Research

P. Zoller: David Ben Gurion Medal (2013), Wolf Prize in Physics (2013), Member of the Academy of Europe (Academia Europea) since 2013

Markus Greiner:
Junior BEC Award, Bose-Einstein Conference, 2013
I.I. Rabi Prize in Atomic, Molecular and Optical Physics (APS) DAMOP, 2013
AAAS Newcomb Cleveland Prize (2012, most outstanding research article published in Science in 2010/2011)

N. Prokofiev, Honorary degree, International Chair Professorship at USTC, Hefei, China

Aimé-Cotton prize of the French Physical Society (F. Gerbier), 2013.

Immanuel Bloch:
Senior International BEC Award 2013
Körber European Science Prize 2013
Hector Science Prize 2013
Dr. Alexander M. Cruickshank Lecturer of the Gordon Research Conference program

Protocol Activity Status:

Technology Transfer:

Partners

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I certify that the information in the report is complete and accurate:
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Signature Date:

ARO Final Report

(1) Submissions or publications under ARO sponsorship **during this reporting period**. List the title of each and give the total number for each of the following categories:

(a) Papers published in peer-reviewed journals

T.T. Wang, M.-S. Heo, T.M. Rvachov, D.A. Cotta, and W. Ketterle:
Deviation from Universality in Collisions of Ultracold 6Li2 Molecules.
Phys. Rev. Lett. 110, 173203 (2013).

Y.R. Lee, T.T. Wang, T.M. Rvachov, J.H. Choi, W. Ketterle, and M.-S. Heo:
Pauli paramagnetism of an ideal Fermi gas.
Phys. Rev. A 87, 043629 (2013).

Tarik Yefsah, Ariel T. Sommer, Mark J.H. Ku, Lawrence W. Cheuk, Wenjie Ji, Waseem S. Bakr, and Martin W. Zwierlein.
Heavy Solitons in a Fermionic Superfluid.
Nature, 499, 426–430 (2013).

Meng Khoon Tey, Leonid A. Sidorenkov, Edmundo R. Sánchez Guajardo, Rudolf Grimm, Mark J. H. Ku, Martin W. Zwierlein, Yan-Hua Hou, Lev Pitaevskii, Sandro Stringari.
Collective Modes in a Unitary Fermi Gas across the Superfluid Phase Transition.
Phys. Rev. Lett. 110, 055303 (2013).

Lawrence W. Cheuk, Ariel T. Sommer, Zoran Hadzibabic, Tarik Yefsah, Waseem S. Bakr, Martin W. Zwierlein.
Spin-Injection Spectroscopy of a Spin-Orbit Coupled Fermi Gas.
Phys. Rev. Lett. 109, 095302 (2012).

Cheng-Hsun Wu, Jee Woo Park, Peyman Ahmadi, Sebastian Will, Martin W. Zwierlein.
Ultracold Fermionic Feshbach Molecules of ^{23}Na^{40}K.
Phys. Rev. Lett. 109, 085301 (2012).

M. Gullans, T. Tiecke, S. Chang, J. Feist, J. D. Thompson, I. J. Cirac, P. Zoller, M. Lukin
Nanoplasmonic Lattices for Ultracold Atoms
Phys. Rev. Lett. 109, 235309 (2012)

N. Goldman, J. Dalibard, A. Dauphin, F. Gerbier, M. Lewenstein, P. Zoller, I. Spielman
Direct imaging of topological edges states with cold atoms
PNAS 6 (2013-04-08) (2013)

D. Banerjee, M. Bögli, M. Dalmonte, E. Rico Ortega, P. Stebler, U. Wiese, P. Zoller
Atomic Quantum Simulation of U(N) and SU(N) Non-Abelian Lattice Gauge Theories
Phys. Rev. Lett. 110, 125303 (2013)

H. Pichler, J. Schachenmayer, A. J. Daley, P. Zoller
Heating dynamics of bosonic atoms in a noisy optical lattice
Phys. Rev. A 87, 033606 (2013)

E. Dalla Torre, S. Diehl, M. Lukin, S. Sachdev, P. Strack
Keldysh approach for non-equilibrium phase transitions in quantum optics: Dicke model in optical cavities
Phys. Rev. A 87, 023831 (2013)

B. Vogell, K. Stannigel, P. Zoller, K. Hammerer, M. T. Rakher, M. Korppi, A. Jöckel, P. Treutlein
Cavity-Enhanced Long-Distance Coupling of an Atomic Ensemble to a Micromechanical Membrane
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P. Hauke, R. J. Sewell, M. W. Mitchell, M. Lewenstein
Quantum control of spin correlations in ultracold lattice gases
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Nature Communications, 4, 1585 (2013).

K. Agarwal, I. Martin, M.D. Lukin, E. Demler,
Polaronic Model of Two-level Systems in Amorphous Solids
Phys. Rev. B, 87, 144201 (2013).

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Nanoplasmonic Lattices for Ultracold Atoms
Phys. Rev. Lett., 109, 235309 (2012).

M. Knap, D. Abanin, E. Demler, Dissipative dynamics of a driven quantum spin coupled to a non-Markovian bath of ultracold fermions, Phys. Rev. Lett. 111, 265302 (2013)

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J. Bauer, C. Salomon, E. Demler, Realizing a Kondo-correlated state with ultracold atoms, Phys. Rev. Lett. 111:215304 (2013) N. Prokof'ev and B. Svistunov:
Spectral Analysis by the Method of Consistent Constraints.
JETP Lett. 97, 747 (2013).

K. Chen, Y. Huang, Y. Deng, A.B. Kuklov, N.V. Prokof'ev, and B. V. Svistunov:
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Phys. Rev. Lett. 110, 185701 (2013).

K. Chen, L. Liu, Y. Deng, L. Pollet, and N. Prokof'ev:
Universal properties of the Higgs resonance in (2+1)-dimensional U(1) critical systems.
Phys. Rev. Lett. 110, 170403 (2013).

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Bold Diagrammatic Monte Carlo Applied to Fermionized Frustrated Spins.
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S. Kulagin, N. Prokof'ev, O.A. Starykh, B.V. Svistunov, and C.N. Varney,
Bold Diagrammatic Monte Carlo technique for frustrated spin systems.
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Double transfer through Dirac points in a tunable honeycomb optical lattice.
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Jinyang Liang, Sih-Ying Wu, Rudolph N. Kohn, Jr., Michael F. Becker, and Daniel J. Heinzen, Greyscale laser image formation using a programmable binary mask, Optical Engineering 51, 108201 (2012).

J.P. Ronzheimer, M. Schreiber, S. Braun, S.S. Hodgman, S. Langer, I.P. McCulloch, F. Heidrich-Meisner, I. Bloch and U. Schneider
Expansion dynamics of interacting bosons in homogeneous lattices in one and two dimensions
Phys. Rev. Lett. 110, 205301 (2013)

M. Aidelsburger, M. Atala, S. Nascimbène, S. Trotzky, Y.-A. Chen, I. Bloch
Experimental realization of strong effective magnetic fields in optical superlattice potentials
Appl. Phys. B 113, 1 (2013)

D. Abanin, T. Kitagawa, I. Bloch, E. Demler
Interferometric approach to measuring band topology in 2D optical lattices
Phys. Rev. Lett. 110, 165304 (2013)

Bernd Schmidt, M. Reza Bakhtiari, Irakli Titvinidze, Ulrich Schneider, Michiel Snoek, and Walter Hofstetter
Dynamical arrest of ultracold lattice fermions
Phys. Rev. Lett. 110, 075302 (2013)

Simon Braun, Jens Philipp Ronzheimer, Michael Schreiber, Sean S. Hodgman, Tim Rom, Immanuel Bloch, Ulrich Schneider
Negative Absolute Temperature for Motional Degrees of Freedom
Science 339, 52 (2013)

# of papers: 49

(b) Papers published in non-peer-reviewed journals

None

(c) Presentations
i. Presentations at meetings, but not published in Conference Proceedings

about 185

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

W. Ketterle:
Ultracold fermions with repulsive interactions.

in: Proceedings of ICAP 2012, Palaiseau, France, July 23–27, EPJ Web of Conferences 57, 01001 (2013), DOI: 10.1051/epjconf/20135701001.

W. Ketterle:
From strongly interacting atomic systems to optical lattices, in: The Theory of the Quantum World, Proceedings of the 25th Solvay Conference on Physics, eds. D. Gross, M. Henneaux, and A. Sevrin (World Scientific, Singapore 2013) , pp. 104-106.

W. Bakr, L.W. Cheuk, M. J.-H. Ku, J.W. Park, A.T. Sommer, S. Will, C.-H. Wu, T. Yefsah, and M. W. Zwierlein,
Strongly Interacting Fermi Gases,
Proceedings of the International Conference on Atomic Physics (ICAP) 2012,
EPJ Web of Conferences 57, 01002 (2013)

iii. Peer-Reviewed Conference Proceeding publications (other than abstracts)

Michael F. Becker, Sih-Ying Wu, and Jinyang Liang,
Encoding Complex Values using Two DLP Spatial Light Modulators, Proc. SPIE – Emerging Micromirror Device Based Systems and Applications 8616, 86180M (2013).

(d) Manuscripts submitted, but not published

none

(e) Books

“Experimental methods of ultracold atomic physics,” D. M. Stamper-Kurn and J. H. Thywissen, Chapter 1 of Ultracold Bose and Fermi quantum gases, S. Fetter, K. Levin, D. M. Stamper-Kurn eds. Contemporary Concepts of Condensed Matter Science 5, 1–26 (Elsevier, 2012).

N. Prokof'ev,
Diagrammatic Monte Carlo and Worm Algorithm techniques.
Chapter in Strongly Correlated Systems: Numerical Methods,
Springer Series in Solid-State Sciences XXVIII, 176, Eds: A. Avella and F. Mancini (2013).

Faculty

Wolfgang Ketterle (National Academy Member) (0%)
Martin Zwierlein (4%)
Joseph Thywissen (0%)
Peter Zoller (National Academy Member) (0%)
Andrew Daley (0%)
Hanspeter Büchler (0%)
Mikhail Baranov (0%)
Sebastian Diehl (0%)
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Antoine Georges (0%)
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Markus Greiner (0%)
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Nikolay Prokof'ev (5%)
Boria Svistunov (5%)
Matthias Troyer (5%)
F. Gerbier (0 %)
J. Dalibard (0 %)
Daniel J. Heinzen (5 %)
Michael F. Becker (5%)
Immanuel Bloch (0%)

Graduate Students
PROVIDE FIRST AND LAST NAME, AND PERCENT SUPPORTED BY THE DARPA GRANT
(Include students who have participated in DARPA research, even if their salary/stipend did not come from the DARPA grant (i.e. their support is zero percent)

Ketterle group:
Hiro Miyake (50 %)
Colin Kennedy (50 %)
Edward Su (100 %)
Wujie Huang (50 %)
Timur Rvachov (0 %)
Tout Wang (0%)

Zwierlein group:
Ariel Sommer (33%)
Mark Ku (0%)
Lawrence Cheuk (15%)
Cheng-Hsun Wu (33%)
Jee Woo Park (33%)
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Jennifer Schloss (0%)
Matthew Nichols (0%)
Wenjie Ji (0%)

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Carolyn Kierans, 20%

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Camille Frapolli (0 %)

Heinzen group
Rudy Kohn, 100%
Andy Hutchison, 100%
Sih-Ying Wu, 100%

Bloch group
Jens Philipp Ronzheimer (0%)
Simon Braun (0%)
Michael Schreiber (0%)
Marcos Atala (0%)
Lucia Duca (0%)

Tracy Li (0%)
Martin Reitter (0%)
Monika Aidelsburger (0%)

Post Doctorates
PROVIDE FIRST AND LAST NAME, AND PERCENT SUPPORTED BY THE DARPA GRANT

Ketterle group:
Georgios Siviloglou (100 %)

Zwierlein group:
Waseem Bakr (0%)
Sebastian Will (0%)
Tarik Yefsah (0%)

Thywissen group:
Stefan Trotzky (0%)

Zoller group
Wolfgang Lechner (100%)

Georges group:
Jan Kunes (0 %)
Shiro Sakai (0 %)

Demler group
Vladimir Stojanovich (0 %)
Marton Kanasz-Nagi (0 %)
Richaed Schmidt (0 %)

Prokof’ev group
Lei Wang (50%)

Gerbier group
Tilman Zibold (0 %)

Bloch group
Ulrich Schneider (0%)
Monika Schleier-Smith (0%)
Sean Hodgman (0%)

Master Degrees Awarded
PROVIDE FIRST AND LAST NAME

Vinay Ramasesh (Zwierlein group)
Camille Frapolli (Gerbier group)
Sih-Ying Wu (Heinzen group)
Daniel Garbe (Bloch group)
Martin Reitter (Bloch group)

Undergraduate Students
PROVIDE FIRST AND LAST NAME, AND PERCENT SUPPORTED BY THE DARPA GRANT

Ketterle group:
Yichao Yu (0%)
Derek Kita (0%)
Dinis Cheian (0%)
Yuri Lensky (0%)

Zwierlein group:
Vinay Ramasesh (0%)
Elmer Guardado-Sanchez (0%)
Emilio Pace (0%)

Bloch group
Daniel Garbe (0%)
Martin Reitter (0%)
Robert Darius (0%)

Other staff
PROVIDE FIRST AND LAST NAME, AND PERCENT SUPPORTED BY THE DARPA GRANT

Alan Stummer, 100% (Thywissen)
Sophie Weber, 0 % (summer internship) (Gerbier)

Mark Brannan 0 % (visitor) (Gerbier)

Bodo Hecker (0%) (Bloch)
Ildiko Kecskesi (0%) (Bloch)

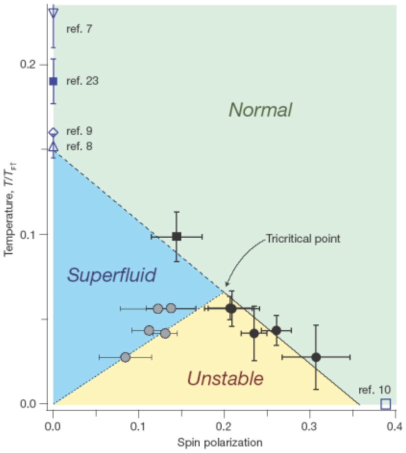
Summary of major accomplishment during the grant period:

Ketterle group (MIT)

During the grant period, we had major results in three different areas. (1) Strongly interacting Fermi gases. Since arbitrary mixtures of hyperfine states can be created using RF population transfer, we could extend our studies to imbalanced Fermi gases. A major highlight has been the exploration of the phase diagram of this system [1]. Using RF spectroscopy, we determined the pair size [2] and the gap parameter [3] of the superfluid. (2) A second area of activity was the development of a new method for thermometry [4] and for adiabatic cooling [5] using a two-component Mott insulator in a magnetic field gradient (spin gradient thermometry and spin gradient demagnetization cooling). (3) We characterized Fermi systems by observing fluctuations in the density and spin density. This method was applied to the ideal (non-interacting) Fermi gas [6], and to systems with attractive [7] and repulsive interactions [8]. For repulsive interactions, we ruled out that the simple Stoner model which predicts itinerant ferromagnetism for fermions with short range repulsion is incorrect, since the ferromagnetic phase transition is preempted by formation of fermions pairs.

1. Phase diagram of a two-component Fermi gas with resonant interactions

We have established the phase diagram of a spin-polarized Fermi gas of ^{6}Li atoms at unitarity. Using tomographic techniques, we determined the spatial structure of a trapped Fermi mixture, mapping out the superfluid phases versus temperature and density imbalance [1]. At low temperature, the sample shows spatial discontinuities in the spin polarization. This is the signature of a first-order superfluid-to-normal phase transition, which disappears at a tricritical point where the nature of the phase transition changes from first-order to second-order. We have confirmed that at zero temperature, there is a quantum phase transition from a fully paired superfluid to a partially polarized normal gas, resolving a major controversy about the Chandrasekhar-Clogston limit of superfluidity with resonant interactions. The phase diagram provides quantitative tests of theoretical calculations on the stability of fermionic superfluidity.

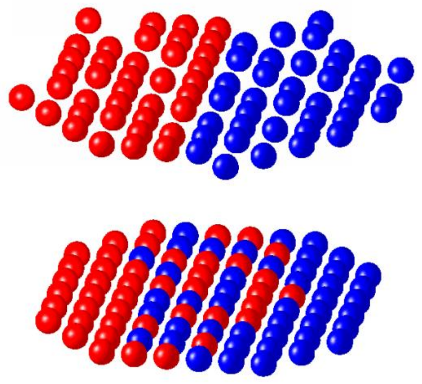


Phase diagram of a two-component Fermi gas with resonant interactions. The yellow area represents a thermodynamically unstable region, leading to phase separation between superfluid and normal. Above the tricritical point, the phase transition is continuous (second-order). The critical spin polarization at zero temperature is estimated to be ≈36%.

2. Spin gradient demagnetization cooling of ultracold atoms.

We have demonstrated a new cooling method in which a time-varying magnetic field gradient is applied to an ultracold spin mixture [5]. We prepare a two-component cloud of rubidium atoms, either in the superfluid or Mott insulator phase, in a strong field gradient separating the two components with a narrow mixed region between the pure-spin domains. In the Mott insulator, where tunneling is strongly suppressed, reduction of the magnetic field gradient leads to extremely low effective spin temperatures of less than 50 pK. Reversal of the magnetic field gradient leads to negative spin temperatures, with an absolute value smaller than 50 pK.

The spin system can also be used to cool other degrees of freedom when the magnetic field gradient is reduced while the system can tunnel and therefore reach equilibration with the spin degree of freedom (see figure). After adiabatic demagnetization in the superfluid phase and ramping up the optical lattice to the Mott insulator phase, we have observed an apparently equilibrated Mott insulator of rubidium atoms to 350 pK. These are the lowest temperatures ever measured in any system. The entropy of the spin mixture is in the regime where magnetic ordering is expected.



Illustrations of the new cooling technique. The top image is of a sample with many particle-hole excitations but no spin excitations, and the bottom image is of a sample with no particle-hole excitations but many spin excitations. These are intended to represent the sample before and after reduction of the magnetic field gradient.

3. Correlations and Pair Formation in a Repulsively Interacting Fermi Gas.

Many-body systems can often be modeled using contact interactions, greatly simplifying the analysis while maintaining the essence of the phenomenon to be studied. Such models are almost exactly realized with ultracold gases due to the large ratio of the de Broglie wavelength to the range of the interatomic forces. For itinerant fermions with strong short-range repulsion, textbook calculations predict a ferromagnetic phase transition the so-called Stoner model. Here we simulate this system using an ultracold gas of fermionic lithium atoms, and observe that the ferromagnetic phase transition does not occur. Previously, sudden changes in the loss rate, kinetic density and chemical potential of the gas were observed for strong repulsive interactions [9]. They were tentatively explained by a ferromagnetic phase transition, but not conclusively, since the smoking gun of ferromagnetism, the formation of domains, could not be observed.

In our new study, we have rapidly quenched a degenerate Fermi into the regime of strong effective repulsion near a Feshbach resonance. The spin fluctuations are monitored using speckle imaging [7]. The variance of the spin fluctuations should increase by the number of atoms per domain, and diverge at the ferromagnetic phase transition.

The absence of any major increase of spin fluctuations shows conclusively that the samples remain in the paramagnetic phase for arbitrarily large scattering length [8]. Over a wide range of interaction strengths a rapid decay into bound pairs is observed over times on the order of 10 $\hbar/E_F$ (where E_F is the Fermi energy) preventing the study of equilibrium phases of strongly repulsive fermions. Recent theoretical work predicted that the pairing instability is faster than the ferromagnetic instability [10]. Therefore, Nature does not realize a strongly repulsive Fermi gas with short range interaction, and the widely used Stoner model is unphysical since it neglects the rapid decay into pairs.

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Zwierlein group (MIT)

The Zwierlein group, joining in Phase II of OLE, worked on strongly interacting Fermi gases of atoms and molecules. One milestone was the demonstration of a novel way to perform precision thermodynamic measurements in ultracold atomic gases that do not rely on theoretical models or external thermometers. The method is general and works in 3D and 2D, as well as for atoms trapped in optical lattices. This “fit-free” thermometry was employed to directly observe the superfluid phase transition in the thermodynamics of a strongly interacting Fermi gas. The specific heat displayed the characteristic lambda-like feature at a critical temperature of 17% of the Fermi temperature. Scaled to the density of electrons in a metal, superfluidity would therefore occur far above room temperature. Furthermore, these thermodynamic measurements were accurate enough to distinguish various theoretical approaches for strongly interacting fermions. In particular, a novel theoretical method developed as part of the DARPA OLE program by Boris Svistunov and Nikolay Prokof’ev – diagrammatic Monte-Carlo – was validated by the experiment. This method can now be employed with confidence on other strongly interacting Fermi systems, such as the Fermi-Hubbard model (believed to hold the key to high-temperature superconductivity) to frustrated spin systems and the Coulomb gas, ruling all of chemistry.

The Zwierlein group also performed strongly out-of-equilibrium experiments that provide benchmarks for many-body theories. In experiments on two colliding Fermi gases of opposite spin, they observed a surprising “bouncing”, whereby the two clouds reflected off another. Interactions were therefore sufficient to reverse spin currents in these gases, despite their ultralow densities – a million times thinner than air. The subsequent remarkably slow diffusion was shown to be quantum limited – as slow as quantum mechanics allows. The spin diffusion coefficient was indeed on the order of Planck’s constant divided by the particle mass. In recent works, the group has launched solitary waves in their fermionic superfluid, waves that do not spread as they propagate. Such non-equilibrium phenomena are difficult to model theoretically – in the absence of a known wave equation for strongly interacting Fermi systems – but experiments can constrain the form of trial wave equations.

A striking feature of high-temperature superconducting materials is their highly anisotropic nature, with strong tunneling in two-dimensional CuO planes and weak interlayer tunneling. Such a situation can be mimicked by confining a free Fermi gas in a 1D optical lattice potential. The lattice structures the 3D gas into many layers, and for strong lattice depth into a series of disconnected two-dimensional gases. The Zwierlein group has studied the evolution of fermion pairing from three to two dimensions via radiofrequency spectroscopy. The pairing gap was shown to dramatically increase with increasing confinement, demonstrating the higher robustness of pairing in two dimensions as opposed to three dimensions. In two dimensions, the role of quantum fluctuations is increased compared to 3D, so it is an interesting question for future research whether there is an ideal spot in between 3D and 2D where the critical temperature for superfluidity is maximized.

The Zwierlein group has initiated a program on topological states of fermionic matter. They implemented spin-orbit coupling in a Fermi gas and introduced a new spectroscopic technique, spin-injection spectroscopy, to directly observe the resulting spinful dispersion. For energies within the spin-orbit gap, the system acted as a spin diode. They also implemented a spin-orbit coupled lattice that allowed for nearly flat bands. In the presence of s-wave interactions, such systems should display induced p-wave pairing, topological superfluidity, and Majorana edge states.

Finally, the Zwierlein group created and studied a new Bose-Fermi mixture, Na-K, and was able to create Feshbach molecules (highly vibrationally excited molecules) of NaK. In their absolute ground-state, these molecules are known to be chemically stable and to allow for a strong induced electric dipole moment of up to 2.7 Debye. Such systems open up prospects for high-speed quantum simulation of spin systems in optical lattices.

Zoller, Buechler, Demler (Innsbruck, Stuttgart and Pittsburgh groups)

The Innsbruck theory group, in collaboration with groups in Pittsburgh and Stuttgart, has made significant contributions to key areas in quantum emulation of new materials during the period of this grant. These theory contributions have particularly focused on the engineering of new models in optical lattices, preparation of important many-body states, new measurement techniques for many-body properties; and the characterization and control of heating for cold atoms in optical lattices. Here we summarize the highlights of our research in each of these directions. A recurring theme of our work is the need to verify quantum simulators, and we have devised new model systems and techniques to characterize and potentially demonstrate quantum simulation going beyond what is computable using existing classical simulations.

Engineering models and many-body states in optical lattices

Directly addressing key challenges in the experiments, we set about devising and characterizing new means to implement many-body models in experiments. Highlights in this area included a detailed study of the microscopic model describing atoms in an optical lattice in the presence of a Feshbach resonance, including strict bounds on the validity of Hubbard models in such a case [*H. P. Büchler, Phys. Rev. Lett. 104, 090402 (2010)*], and an analysis of the many-body physics arising when three-body losses combined with a continuous quantum Zeno effect give rise to models that are dominated by effective three-body interactions [*A. J. Daley et al., Phys. Rev. Lett 102, 040402 (2009); S. Diehl et al., Phys. Rev. Lett. 104, 165301 (2010)*].

A key challenge in experiments with quantum emulators is the achievement of lower temperatures and entropies, and we contributed new methods that could be used to prepare important many-body states in such regimes. In particular, we devised adiabatic ramping schemes beginning from insulating states that could be used to prepare metastable many-body states of Fermions, specifically eta-condensates in optical lattices [*A. Kantian et al., Phys. Rev. Lett. 104, 240406 (2010)*]. These state preparation techniques are generally applicable, and could also be used for production of magnetically ordered states of fermions, or generalized to systems with long-range interactions such as Rydberg excitations or polar molecules in order to produce crystalline states at long distances [*J. Schachenmayer et al., New J. Phys 12, 103044 (2010)*]. We also devised means to produce states via controlled dissipative processes, e.g., trapped atoms interacting with an untrapped reservoir in regimes that can give rise to states with topological properties [*S. Diehl et al., Nature Physics **7**, 971 (2011)*].

New Measurement techniques for many-body states

Another key challenge is the characterization of many-body properties in optical lattices. A major advance during this grant period was our proposed scheme to measure entanglement in many-body states, specifically in the form of Rényi entropies [*A. J. Daley et al., Phys. Rev. Lett. **109**, 020505 (2012)*]. This scheme can be implemented in the recently developed quantum gas microscope experiments, requiring the coupling of multiple copies of a quantum state, and measurement of local occupation numbers. Entanglement is a characteristic property of many-body quantum states that had previously been discussed in detail theoretically, and underlies the complexity of simulating many-body dynamics using current state-of-the-art techniques on a classical computer. Our proposed technique not only makes this quantity accessible in experiments, but also has key applications in verifying quantum simulators through the direct comparison of two copies of a quantum state.

Characterization and control of heating in optical lattices

In order to further address the challenge of producing low-temperature states in experiments, it is also very important to characterize and control the competing heating processes in experiments. We performed analyses of key heating processes in experiments, especially those due to spontaneous emissions [*H. Pichler et al., Phys. Rev. A **82**, 063605 (2010)*] and amplitude noise on lattice lasers. We particularly focused on the interplay between these mechanisms and many-body dynamics, identifying regimes and states that are less sensitive to heating in experiments, and devised a dressing scheme to make atoms in optical lattices more resilient to noise and disorder due to light intensity fluctuations [*H. Pichler et al., Phys. Rev. A 86, 051605(R) (2012)*].

Demler group (Harvard)

We demonstrated that alkaline-earth atoms in optical lattices can be used to implement many-body systems with the SU(N) symmetry group with N as large as 10. We showed that the interplay of the nuclear spin with the electronic degree of freedom provided by a stable optically excited state that enables the study of physics governed by the spin–orbital interaction. Such systems should provide valuable insights into the physics of strongly correlated transition-metal oxides, heavy-fermion materials and spin-liquid phases. Nat. Phys. 6: 289 (2010).

We suggested theoretically and realized experimentally a topological system in 1d using quantum walks of photons. We demonstrated the existence of bound states between systems with different bulk topological properties and verified their robustness to perturbations—a signature of topological protection. We discovered a new phenomenon: a topologically protected pair of bound states unique to periodically driven systems. Nat. Comm. 3:882 (2012).

We proposed theoretically and implemented experimentally a method for studying a Higgs mode in a two-dimensional neutral superfluid close to a quantum phase transition to a Mott insulating phase. We unambiguously identify the mode by observing the expected reduction in frequency of the onset of spectral response when approaching the transition point. Nature 487:454 (2012)

We demonstrated theoretically and then experimentally that 1d condensates after a longitudinal split exhibit prethermalization, where the observables of non-equilibrium, long-time transient states become indistinguishable from those of thermal equilibrium states. Science 337:1318 (2012).

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 showed that, by studying the dynamics of the quantum switch only, the Rényi entanglement entropy of the many-body system can be extracted. We proposed a possible design of the quantum switch, which can be realized in cold atomic systems. Phys. Rev. Lett. 109:020504 (2012) .

We propose d theoretically and implemented experimentally an interferometric method for measuring topological properties of Bloch bands in optical lattices. The key idea was to use a combination of Ramsey interference and Bloch oscillations to measure Zak phases, i.e., Berry’s phases for closed trajectories corresponding to reciprocal lattice vectors. Nature Physics 9, 795 (2013).

Gerbier group (ENS)

Magnetism with antiferromagnetic bosonic gases

We have studied the magnetic properties of spin 1 condensates with antiferromagnetic interactions. We have measured the low-temperature magnetic phase diagram [Jacob2012] by recording the change in the populations of the various Zeeman states *m=0,+1,-1* for various magnetizations and quadratic Zeeman energies (QZE). The competition between spin-exchange interactions and the QZE induce a quantum phase transition, where the spin wavefunction of the condensate changes abruptly from a superposition of *m=+1* and *m=-1* to a state where *m=0* is populated as well (and eventually dominant for large QZE). We have observed this behavior in the experiment, in excellent quantitative agreement with the theoretical predictions. More recently, we have performed a series of experiments where the magnetic order is directly measured. A gas of antiferromagnetic spin 1 bosons with zero magnetization is predicted to display a so-called spin-nematic orde : the average magnetization vanishes, but the spin-quadrupole tensor does not. This tensor characterizes the spin anisotropy of a given state independently of the average spin, a property sometimes called “alignment”. It is formally similar to the order parameter describing alignment of classical nematic liquid crystals. For a non-zero magnetization, the alignment can be quantified by a quantity A related to the average spin $\boldsymbol{S}$ by $A^2+\boldsymbol{S}^2=1$. Antiferromagnetic spinor condensates try to maximize A, or equivalently to minimize the magnitude of the transverse spin $S_x^2+S_y^2$ since the longitudinal component S_z is conserved in spinor gases. To measure this quantity directly, we induced Rabi oscillations at the Larmor frequency starting from a condensate at equilibrium. This is equivalent to a spin rotation. The variance of the magnetization after the rotation oscillates out of phase with the average, with an amplitude proportional to $S_x^2+S_y^2$ in the initial state. The experimental data show that this magnitude is minimal given the other constraints (conserved magnetization and non-zero QZE), as expected from the minimization of spin-exchange interaction energy.

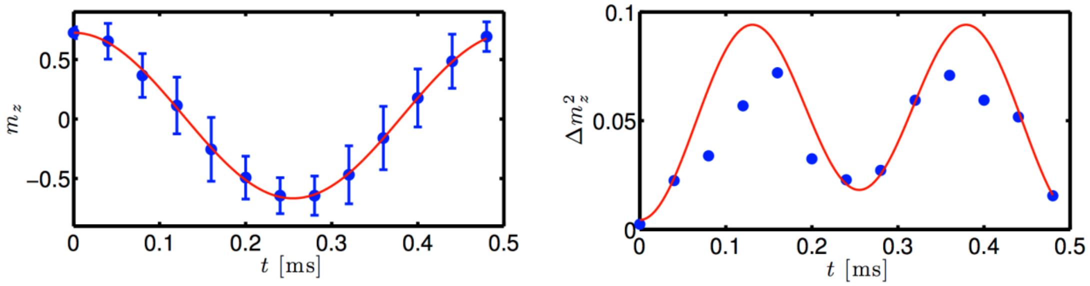

Figure 1: Average magnetization (left panel) and variance (right panel) after driving a Rabi oscillation of duration t. The Rabi oscillation is equivalent to a spin rotation along the y axis with a rotation angle proportional to the pulse duration. The variance of the magnetization after rotation (blue dots in the right panel) oscillates with an amplitude proportional to the initial transverse spin magnitude. The red curve shows the expected behavior of a T=0 condensate with initial magnetization per atom of 0.65.

When studying the low temperature phase at low magnetic field and zero magnetization, we have observed anomalously large fluctuations of the population of the Zeeman components: the variance of $N_{m=0}$ scales as $N_{m=0}{}^2$, instead of $N_{m=0}$ as usually expected. Such super-Poissonian fluctuations are characteristic of mesoscopic systems, where these collective spin fluctuations will rise and restore the broken spin rotational symmetry in a small window near zero applied field. This in fact illustrates a very general mechanism where spontaneous symmetry breaking is prevented due to collective fluctuations of the order parameter. We have studied theoretically how such fluctuations at finite temperatures as a consequence of the fragmentation of the condensate that occupies several single-particle spin states [DeSarlo2013a]. The crossover to a condensate in a single spin state with increasing QZE was studied in details. A more recent refinement of the theory based on SU(3) coherent states allowed us to analyze the experimental data accounting for various experimental effects, including in particular the conservation of magnetization. We confirmed previous results for very low fields (where the fluctuation-dissipation theorem can be used for thermometry as reported previously : The spin temperature characterizing spin fluctuations is found to be much lower than the "kinetic" temperature characterizing the thermal gas surrounding the condensate. The interpretation is that the spin fluctuations of the condensate are almost completely decoupled from other uncondensed modes in this regime. We conjecture that the former one finds its own quasi-equilibrium through spin-changing collisions involving condensed atoms only, almost independently of the surrounding thermal atoms. We will attempt to test this scenario in quench-type experiments in the future.

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[Jacob2012a] D. Jacob, L. Shao, V. Corre, T. Zibold, L. DeSarlo, E. Mimoun, J. Dalibard and F. Gerbier, Phase diagram of spin-1 antiferromagnetic Bose-Einstein condensates, Phys. Rev. A **86**, 061601(R) (2012).

Thywissen group (Toronto).

A new laboratory was built for the study of ultracold fermions in two-dimensional optical lattices. With the goal of quantum emulation, the new apparatus combined a flexible lattice geometry with excellent optical access through a microscope port. Our primary contributions were pioneering several techniques for for manipulation and high-resolution imaging of fermionic potassium (^{40}K).

Violet laser-cooling of potassium. We achieved the first addressing and manipulation of 40K using the 4S-to-5P transition at 405 nm. There are five appealing features of this line: (1) The wavelength is smaller than the standard 4S-to-4$P_{3/2}$ transition at 767nm used to image 40K, enabling a diffraction limit for imaging that is proportionally smaller. (2) Powerful solid-state sources at this wavelength are widely available, due to the commercial interest in "blue ray" optical storage technology, and in high-power violet illumination. (3) The excited-state line width is five times smaller than the conventional transition, enabling a lower Doppler limit. We built the first magneto-optical trap (MOT) at 405 nm; and demonstrated laser cooling to 65 microkelvin, which compares well to the 250 microkelvin temperatures typically achieved on the 4S-4$P_{3/2}$ transition. These techniques were also demonstrated for bosonic 39K. (4) The optical density is thirty times smaller for light at 405 nm than for 767 nm, due to the combination of the smaller line width and the branching ratio of the excited state. This makes it more amenable to manipulation of a dense quantum degenerate cloud. (5) Florescent light at 405 nm is amenable to low background imaging. Since the initial demonstration of laser-cooling with 405 nm light, we have also used this transition to take effectively zero-background images of 40K held in a far-detuned optical lattice.

Extreme optical access. We developed a new approach to quantum gas microscopy. Pioneers of quantum gas microscopes in our group (see reports by Greiner and by Bloch) use thick quartz vacuum windows; we demonstrated that a 200-micron-thick sapphire window is sufficient to hold vacuum, and retro-reflect powerful lattice beams. We could produce quantum-degenerate fermions and bosons close to this window, only one millimeter from air. The resultant optical configuration is not too different from standard microscopy, since a quartz cover slip is also a few hundred microns thick. Resolution and aberrations are insensitive to the details of the window geometry. Unlike the solid emersion technique, atoms can be imaged far from the surface, obviating the need for a super-polished surface.

Sub-micron resolution. The combined 0.6 NA and 405-nm fluorescent wavelength would give a Rayleigh diffraction limit of 0.4 µm. We tested our system using a silver nano-hole array with a period of 500 nm. We observe a contrast of approximately 15%, confirming that the diffraction limit is below 0.5 µm. Once implemented, this system would be the highest resolution quantum gas microscope yet.

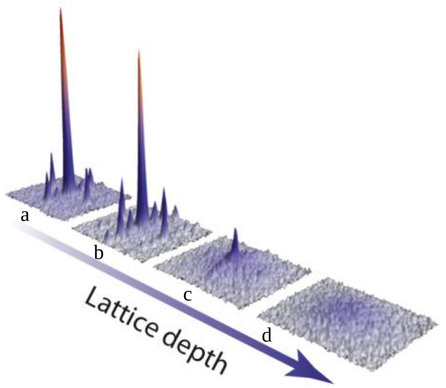
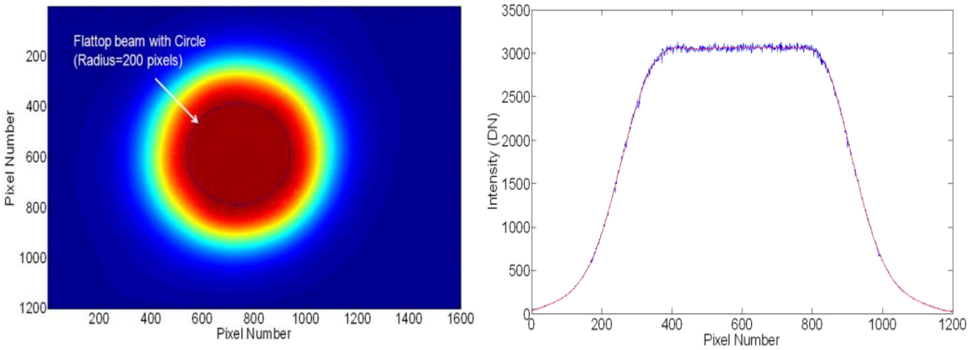


Figure 1. **Superfluid-to-Mott-insulator transition**. Bosonic 87Rb atoms are loaded into a three-dimensional optical lattice, and released at various lattice depths: (a) 12 E_R, (b) 14 E_R, (c) 18 E_R, (d) 20 E_R, where E_R is the single-photon recoil energy of 87Rb at 1054 nm. The progressive loss of contrast in the diffraction pattern indicates that phase coherence is lost across the matter wave source, which shows loss of superfluidity. Instead, atoms are localized to particular lattice sites, in an insulating phase.

Quantum phase transition. In the final six months of the report period, we loaded bosonic ^{87}Rb into optical lattices. With one- and two-dimensional lattices, we saw matter-wave diffraction from the optical crystal. Adiabatically loading into a three-dimensional lattice, we saw the Mott-insulator-to-superfluid transition (see figure). Fermionic ^{40}K loaded into the same lattice reveals a filled first Bloch band.

Heinzen/Becker group (Austin)

During this grant period, our group developed a new method for the precise shaping of a coherent laser beam. Our method is based on position-dependent attenuation of the beam by reflection from a Digital Micromirror Device (DMD), followed by an adjustable pinhole low-pass spatial filter and sampling of the resulting beam shape by a precision beam-profiling CCD camera. We developed and implemented an iterative algorithm to set the DMD pixels that minimizes the deviation of the measured beam profile from a target profile. With this method, we demonstrated the production of a flattop intensity profile beam with an accuracy of better than 0.3% RMS, significantly better than the few percent accuracy of previous methods. A false color image of one of these beams, along with its intensity profile along a line through the center of the beam, is shown in the figure below.



Flattop beam generated with the DMD-base shaper. Beam cross section on the right shows the target and experimental curves.

We analyzed and were able to quantitatively understand the energy efficiency of the shaper. We studied the performance of the shaper for more complex beam shapes, and the tradeoff between the spatial bandwidth and spatial noise of our shaper. We demonstrated beam shaping with a noise level within a factor of four of the theoretical minimum level.

We studied a number of other aspects of beam shaping, including a method to suppress the zero-order diffracted beam from the DMD, and a method to encode complex values of the light field with a DMD. We also implemented a more complex beam shaper that produced counter-propagating shaped beams for application to a cold atom-optical lattice experiment. Measurements showed that this beam shaper could produce the beams required for such an experiment.

We set up an experiment to load Bose-condensed Rb atoms into an optical trap formed by the shaped beams. This experimental set-up will allow us to study quantum degenerate gases in both shaped traps and in shaped optical lattices. Experiments to do this are ongoing.

Bloch/Schneider group (Munich)

Within the OLE program our team extensively explored the many-body physics of interacting bosonic and fermionic atoms in optical lattices. Some of the research highlights achieved during the reporting period where the first demonstration of quantum magnetism via superexchange spin-interactions with ultracold atoms (Science 319, 295 (2008)), where our team together with the Harvard group of M. Lukin and E. Demler was able to observe highly controlled superexchange interactions in optical double well potentials. We quantitatively explored the transition from weak to strong interactions and later also extended these experiments to the realization of plaquette resonating valence bond (RVB) states and the observation of their dynamical behavior (Phys. Rev. Lett. 108, 205301 (2012)). Together with the Amherst group of N. Prokofev and B. Svistunov and the ETHZ team of M. Troyer and L. Pollet, we performed the first quantitative comparison of a quantum simulator with ab-initio Quantum Monte-Carlo simulations (Nature Physics 6, 996 (2010)). The comparison established excellent agreement between the experiment and theory and allowed us to probe the critical temperature of a strongly interacting superfluid at a quantum phase transition. Next to studying static properties of quantum many-body systems across phase transitions, much of our work was also devoted on investigating non-equilibrium properties of strongly interacting quantum system. For this, we prepared a controlled high energy density initial state of a charge density wave and studied its relaxation dynamics (Nature Physics 8, 325 (2012)). By monitoring the currents, phase coherence and density evolution of the 1d quantum gas, we could observe in detail the relaxation of this state towards equilibrium. The experiment was the first quantum simulation to outperform a numerical simulation run on a state-of-the-art supercomputer and allowed to obtain new insight into the dynamical behavior of isolated quantum systems (Nature Physics 2012). Most recently, our team has been realizing topological Bloch bands and probing their geometric and topological features. Highlight results among these are the first realization of strong artificial magnetic fields in optical lattices (PRL 107, 255301 (2011), PRL 111, 185301 (2013) and the first measurement of a topological invariant in 1d - the so called Zak phase (Nature Physics 9, 795 (2013)). The latter results were based on a close collaboration with the group of E. Demler at Harvard University.

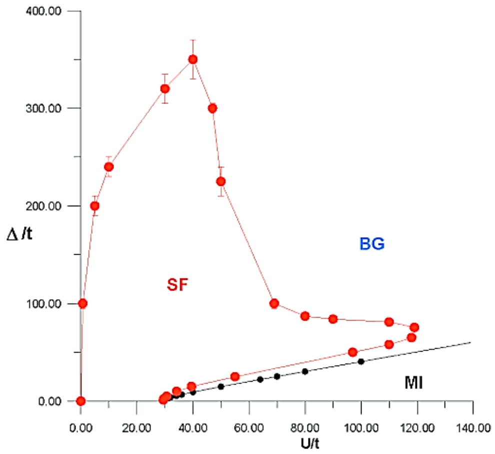
One highlight in the study of fermionic quantum gases was the realization of the fermionic Mott insulator (Science 322, 1520 (2008)) and the direct demonstration of its incompressible nature. This work, which featured potassium-40 and blue-detuned optical lattices, already showed the flexibility of our setup that was later used to analyze the physics of strongly attractive fermions (Science 327, 1621 (2010)), which was analyzed together with the team of E. Demler in Harvard. In addition, this setup was used to load Bose-Fermi mixtures of Rubidium and Potassium atoms into an optical lattice (Phys. Rev. Lett. 102, 030408 (2009)), where not only the effect of the mutual interaction on the superfluid to Mott insulating quantum phase transition was studied, but furthermore first indications of effective three particle interactions were observed. These coherent multi-body interactions were then studied in detail in bosonic systems (Nature 465, 197-201 (2010)) and Bose-Fermi mixtures (Phys. Rev. Lett. 106, 115305 (2011)).
Another focus of the experiments performed in this flexible blue-detuned lattice concerned the out-of-equilibrium dynamics of interacting many-body systems and in particular their mass flow in a homogeneous lattice: These experiments started with fermionic quantum gases in two dimensions, where we could establish that high temperature mass transport is diffusive and obeys a dynamical interaction symmetry (Nature Physics 8, 213-218 (2012)). This symmetry was again studied together with the group of E. Demler. Later we extended this type of measurement to bosonic pottasium-39, where the interaction strength can be controlled by a Feshbach resonance, similar to the fermionic case. Here we found again a diffusive dynamics in 2D, but, importantly, could show that in 1D the equivalence between hard-core bosons and free fermions gives rise to a fast ballistic expansion (Phys. Rev. Lett. 110, 205301 (2013)).

Another highlight was the creation of the first equilibrium state at negative absolute temperature in a system of mobile particles (Science 339, 52 (2013)). These states, which are characterized by inverted thermal distributions, in which high energy states are more occupied than low ones, present many at first glance counterintuitive properties, such as a negative total pressure, and offer new possibilities for quantum simulations. Furthermore, they have revived, and will probably settle, a long-standing debate about the correct Entropy definition for micro-canonical systems.

UMass-ETH group (Prokof’ev, Svistunov, Troyer)

1. Quantum Monte Carlo Simulations of interacting bosonic systems have reached an unprecedented level of accuracy and modeling. It is now possible to obtain precise data for a broad variety of physical systems (arbitrary interaction range, including dipole-dipole forces, lattice type, dimension of space, number of components, external potentials) and physical quantities (from standard thermodynamic parameters such as density, energy, entropy, condensate and superfluid densities, to time of flight images and dynamic linear response functions). Over the grant period numerical simulations were used to explore properties of key Hamiltonians in great detail to understand the interplay between solid, superfluid, and Mott-insulator phases, predict new phases of quantum matter, such as supersolids and super-counter-fluids, establish reliable thermometry for strongly correlated states, determine optimal parameter regimes for realizing interesting states experimentally and develop new measurements to study them. Simulations can now address some experimental systems “as is” by considering the same particle numbers (up to a million), temperatures, trapping and lattice potentials, and producing absorption images after finite-time of flight expansion. The hallmark achievement was validating the quantum simulator in the study of the critical temperature for superfluidity near the Mott transition [Nature Physics **6**, 998, (2010)]; it was the first *ab initio* comparison between experiments and quantum Monte Carlo simulations for strongly interacting Bose gases on a lattice for realistic systems.

2. We have achieved remarkable progress in understanding properties of disordered systems, especially the interplay between the disorder, interactions, and lattice effects. After decades of controversial results regarding the topology and nature of the superfluid-to-insulator transitions, we now have precise understanding of what transitions are allowed and under what conditions, what to expect for critical exponents, how important are finite-temperature and trapping-potential effects. The most important result was the proof of the theorem of inclusions [PRL **103**, 140402 (2009 Phys. Rev. **B** **80**, 214519 (2009)]. It states that the Bose glass phase always intervenes between the Mott insulating and superfluid phases, and that disorder-induced phase transitions between gapped (Mott insulator) and gapless phases (Bose glass) have to be of the Griffiths type when the vanishing of the gap at the critical point is due to a zero concentration of rare regions where extreme fluctuations of disorder mimic a *regular* gapless system. For the Bose-Hubbard model, simulations revealed a highly non-trivial overall shape of the phase diagram (here it is presented for the three dimensional case). The phase diagram features a long superfluid finger at strong disorder and large on-site interaction. Bosonic superfluidity is found to be extremely robust against disorder in a broad range of interaction parameters; it persists in random potentials nearly 50 (!) times larger than the particle half-bandwidth, but is readily destroyed at finite temperature.



3. We have achieved a major breakthrough in developing a new technique to deal with strongly interacting fermions, the so-called Bold Diagrammatic Monte Carlo (BDMC). In essence, BDMC solves the full quantum many-body problem by stochastically summing all the skeleton diagrams for irreducible single-particle self-energy Σ and pair self-energy Π, expressed in terms of renormalized (that is, fully dressed) single-particle and pair propagators G and Γ, which are determined self-consistently. The technique organizes the calculation of a given physical quantity as a series of diagrams representing all the possible ways particles can propagate and interact. For the many-body problem, this diagrammatic expansion is commonly used either in perturbative regimes or within uncontrolled approximations. With BDMC one goes well beyond the first few diagrams, and obtains controlled results after extrapolating to the infinite diagram order. In traditional Monte Carlo approaches, which simulate a finite volume of matter, the sign problem causes an exponential increase of the computing time with system size and inverse temperature.

In contrast, BDMC simulates a mathematical answer for the quantity of interest directly in the thermodynamic limit. This radically changes the role of the fermionic sign. Diagrammatic contributions are sign-alternating with order, topology and values of internal variables. Because the number of graphs grows factorially with diagram order, a near-cancellation between these contributions is actually necessary for the series feature a finite radius of convergence. We established that this `sign blessing' indeed takes place generically.

The most successful application of BDMC was to the equation of state of the unitary Fermi gas where the new theoretical approach was used for cross-validation of the Fermi-as Feynman emulator [Nature Physics **8**, 366 (2012)]. We are not aware of any system of strongly correlated fermions in nature where experimental and unbiased theoretical results were compared at the same level of accuracy. Even for bosons, the only analogue is liquid He-4. More recently, BDMC was developed and successfully applied to simulate properties of frustrated magnetic system, leading to the discovery of the quantum-to-classical correspondence for static response functions [PRL **110**, 070601 (2013)].

Greiner group (Harvard)

Quantum gas microscopy and magnetic quantum phase transitions

In the OLE program the Greiner group developed quantum emulation systems based on ultracold atoms in optical lattices. They started by inventing quantum gas microscopy, enabling researches to take the control of atoms in an optical lattice to the next and ultimate level of high fidelity addressing, manipulation and readout of single particles.

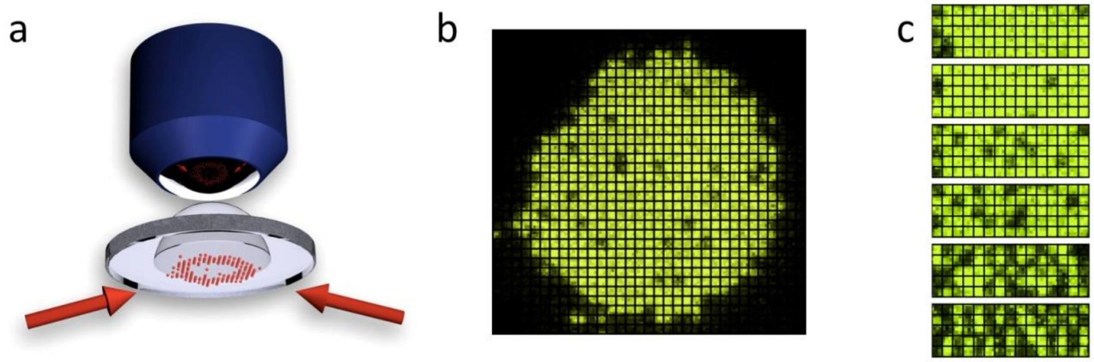


Figure caption: The Quantum gas microscope (a) developed through the OLE program now enables researchers to image and manipulate single ultracold atoms on individual lattice sites, with unprecedented fidelity. It was first used to study the quantum phase transition from a superfluid to a Mott insulator (b) on single particle level. Next it was used to realize the first quantum phase transition in a quantum magnet in optical lattices. The transition from a paramagnet to an antiferromagnet (c)(decoupled horizontal 1D chains) can be directly observed in the microscope. Each green dot in the figure is the image of a single atom.

In the quantum gas microscope researchers first prepare a many-body quantum state of interest. In the next step quantum dynamics is turned off, and all individual particles are being measured with fidelities exceeding 99%. This enables the direct measurement of populations, correlations and coherences.

Based on these advances the Greiner group was able to observe the first quantum phase transition of a quantum magnet in an optical lattice. Starting with a low entropy Mott insulator they were able to realize a one-dimensional quantum Ising spin model. They observed a reversible quantum phase transition from a paramagnet to an antiferromagnet in the Ising spin chain. The quantum gas microscope enabled them to directly detect the spin order.

Further work included the realization of photon assisted tunneling in optical lattices, the realization of an orbital excitation blockade, and the implementation of an algorithmic cooling scheme. All this work together brought quantum emulations in optical lattices to a new level.

Lukin group (Harvard)

The realization of strong interactions between individual photons is a long-standing goal of both fundamental and technological significance. Scientists have known for over half a century that light fields can interact inside nonlinear optical media, but the nonlinearity of conventional materials is negligible at the light powers associated with individual photons. Nevertheless, remarkable advances in quantum optics have recently culminated in the demonstration of several methods for generating optical nonlinearities at the level of individual photons. Systems exhibiting strong photon–photon interactions enable a number of unique applications, including quantum-by-quantum control of light fields, single-photon switches and transistors, all-optical deterministic quantum logic, and the realization of strongly correlated states of light and matter.

We considered strongly interacting systems of effective spins, subject to dissipative spin-flip processes associated with optical pumping. We predicted the existence of novel magnetic phases in the steady state of this system, which emerge due to the competition between coherent and dissipative processes. Specifically, for strongly anisotropic spin-spin interactions, we found ferromagnetic, antiferromagnetic, spin-density-wave, and staggered-*XY* steady states, which are separated by nonequilibrium phase transitions meeting at a Lifshitz point. These transitions were accompanied by quantum correlations, resulting in spin squeezing. Experimental implementations in ultracold atoms and trapped ions were discussed.

Strongly correlated quantum systems can exhibit exotic behavior controlled by topology. We predicted that the $\nu=1/2$ fractional Chern insulator arises naturally in a two-dimensional array of driven, dipolar-interacting spins. As a specific implementation, we analyzed how to prepare and detect synthetic gauge potentials for the rotational excitations of ultracold polar molecules trapped in a deep optical lattice. With the motion of the molecules pinned, under certain conditions, these rotational excitations formed a fractional Chern insulating state. We presented a detailed experimental blueprint for its realization and demonstrated that the implementation was consistent with near-term capabilities. Prospects for the realization of such phases in solid-state dipolar systems were discussed as were their possible applications.

We presented and analyzed a new approach for the generation of atomic spin-squeezed states. Our method involved the collective coupling of an atomic ensemble to a decaying mode of an open optical cavity. We demonstrated the existence of a collective atomic dark state, decoupled from the radiation field. By explicitly constructing this state we found that it can feature spin squeezing bounded only by the Heisenberg limit. We showed that such dark states can be deterministically prepared via dissipative means, thus turning dissipation into a resource for entanglement. The scaling of the phase sensitivity taking realistic imperfections into account was discussed.

We investigated nonequilibrium phase transitions for driven atomic ensembles interacting with a cavity mode and coupled to a Markovian dissipative bath. In the thermodynamic limit and at low frequencies, we showed that the distribution function of the photonic mode was thermal, with an effective temperature set by the atom-photon interaction strength. This behavior characterized the static and dynamic critical exponents of the associated superradiance transition. Motivated by these considerations, we developed a general Keldysh path-integral approach that allowed us to study physically relevant nonlinearities beyond the idealized Dicke model. Using standard diagrammatic techniques, we took into account the leading-order corrections due to the finite number N of atoms. For finite N, the photon mode behaved as a damped classical nonlinear oscillator at finite temperature. For the atoms, we proposed a Dicke action that can be solved for any N and correctly captured the atoms' depolarization due to dissipative dephasing.

Topology plays a central role in ensuring the robustness of a wide variety of physical phenomena. Notable examples range from the current-carrying edge states associated with the quantum Hall and the quantum spin Hall effects to topologically protected quantum memory and quantum logic operations. Here we proposed and analyzed a topologically protected channel for the transfer of quantum states between remote quantum nodes. In our approach, state transfer was mediated by the edge mode of a chiral spin liquid. We demonstrated that the proposed method was intrinsically robust to realistic imperfections associated with disorder and decoherence. Possible experimental implementations and applications to the detection and characterization of spin liquid phases were discussed.

While two-level systems (TLSs) are ubiqitous in solid state systems, microscopic understanding of their nature remains an outstanding problem. Conflicting phenomenological models were used to describe TLSs in seemingly similar materials when probed with different experimental techniques. Specifically, bulk measurements in amorphous solids have been interpreted using the model of a tunneling atom or group of atoms, whereas TLSs observed in the insulating barriers of Josephson junction qubits have been understood in terms of tunneling of individual electrons. Motivated by recent experiments studying TLSs in Josephson junctions, especially the effects of elastic strain on TLS properties, we analyzed the interaction of the electronic TLS with phonons. We demonstrated that strong polaronic effects leads to dramatic changes in TLS properties. Our model gave a quantitative understanding of the TLS relaxation and dephasing as probed in Josephson junction qubits, while providing an alternative interpretation of bulk experiments. We demonstrated that a model of polaron dressed electronic TLS leads to estimates for the density and distribution of parameters of TLSs consistent with bulk experiments in amorphous solids. This model explained such surprising observations of recent experiments as the existence of minima in the energy of some TLSs as a function of strain and made concrete predictions for the character of TLS dephasing near such minima. We argued that better understanding of the microscopic nature of TLSs can be used to improve properties of quantum devices, from an enhancement of relaxation time of TLSs to creating new types of strongly interacting optomechanical systems.

We investigated the quantum dynamics of systems involving small numbers of strongly interacting photons. Specifically, we developed an efficient method to investigate such systems when they are externally driven with a coherent field. Furthermore, we showed how to quantify the many-body quantum state of light via correlation functions. Finally, we applied this method to two strongly interacting cases: the Bose–Hubbard and fractional quantum Hall models, and discussed an implementation of these ideas in atom–photon system.

We proposed to use subwavelength confinement of light associated with the near field of plasmonic systems to create nanoscale optical lattices for ultracold atoms. Our approach combined the unique coherence properties of isolated atoms with the subwavelength manipulation and strong light-matter interaction associated with nanoplasmonic systems. It allowed one to considerably increase the energy scales in the realization of Hubbard models and to engineer effective long-range interactions in coherent and dissipative many-body dynamics. Realistic imperfections and potential applications were discussed.

We proposed the use of dipolar spin chains to enable long-range quantum logic between distant qubits. In our approach, an effective interaction between remote qubits was achieved by adiabatically following the ground state of the dipolar chain across the paramagnet to crystal phase transition. We demonstrated that the proposed quantum gate was particularly robust against disorder and derive scaling relations, showing that high-fidelity qubit coupling was possible in the presence of realistic imperfections. Possible experimental implementations in systems ranging from ultracold Rydberg atoms to arrays of nitrogen vacancy defect centers in diamond were discussed.

Phenomena associated with the topological properties of physical systems can be naturally robust against perturbations. This robustness is exemplified by quantized conductance and edge state transport in the quantum Hall and quantum spin Hall effects. Here we showed how exploiting topological properties of optical systems can be used to improve photonic devices. We demonstrated how quantum spin Hall Hamiltonians can be created with linear optical elements using a network of coupled resonator optical waveguides (CROW) in two dimensions. We found that key features of quantum Hall systems, including the characteristic Hofstadter butterfly and robust edge state transport, can be obtained in such systems. As a specific application, we showed that topological protection can be used to improve the performance of optical delay lines and to overcome some limitations related to disorder in photonic technologies.

We showed that dipolar interactions between ultracold polar alkali-metal dimers in optical lattices can be used to realize a highly tunable generalization of the *t-J* model, which we referred to as the *t-J-V-W* model. The model featured long-range spin-spin interactions J_z and $J_\perp$ of *XXZ* type, long-range density-density interaction *V*, and long-range density-spin interaction *W*, all of which can be controlled in both magnitude and sign independently of each other and of the tunneling *t*. The "spin" was encoded in the rotational degree of freedom of the molecules, while the interactions were controlled by applied static electric and continuous-wave microwave fields. Furthermore, we showed that nuclear spins of the molecules can be used to implement an additional (orbital) degree of freedom that was coupled to the original rotational degree of freedom in a tunable way. The presented system is expected to exhibit exotic physics and to provide insights into strongly correlated phenomena in condensed-matter systems. Realistic experimental imperfections were discussed.

We developed the theory of light propagation under the conditions of electromagnetically induced transparency in systems involving strongly interacting Rydberg states. Taking into account the quantum nature and the spatial propagation of light, we analyzed interactions involving few-photon pulses. We showed that this system can be used for the generation of nonclassical states of light including trains of single photons with an avoided volume between them, for implementing photon-photon gates, as well as for studying many-body phenomena with strongly correlated photons. By selecting two dressed rotational states of ultracold polar molecules in an optical lattice, we obtained a highly tunable generalization of the *t-J* model, which we referred to as the *t-J-V-W* model. In addition to *XXZ* spin exchange, the model featured density-density interactions and density-spin interactions; all interactions were dipolar. We show that full control of all interaction parameters in both magnitude and sign can be achieved independently of each other and of the tunneling. As a first step towards demonstrating the potential of the system, we applied the density matrix renormalization group method to obtain the 1D phase diagram of the simplest experimentally realizable case. Specifically, we showed that the tunability and the long-range nature of the interactions in the *t-J-V-W* model enable enhanced superfluidity. Finally, we showed that Bloch oscillations in a tilted lattice can be used to probe the phase diagram experimentally.

We proposed and analyzed a new approach for quantum state transfer between remote spin qubits. Specifically, we demonstrated that coherent quantum coupling between remote qubits can be achieved via certain classes of random, unpolarized (infinite temperature) spin chains. Our method was robust to coupling-strength disorder and did not require manipulation or control over individual spins. In principle, it can be used to attain perfect state transfer over an arbitrarily long range via purely Hamiltonian evolution and may be particularly applicable in a solid-state quantum information processor. As an example, we demonstrated that it can be used to attain strong coherent coupling between nitrogen-vacancy centers separated by micrometer distances at room temperature. Realistic imperfections and decoherence effects were analyzed.

We analyzed a technique for the preparation of low-entropy many-body states of atoms in optical lattices based on adiabatic passage. In particular, we showed that this method allowed preparation of strongly correlated states as stable *highest energy states* of Hamiltonians that have trivial ground states. As an example, we analyzed the generation of antiferromagnetically ordered states by adiabatic change of a staggered field acting on the spins of bosonic atoms with ferromagnetic interactions.

We proposed a method for controllable preparation and detection of interaction-induced ferromagnetism in ultracold fermionic atoms loaded in optical superlattices. First, we discussed how to probe and control Nagaoka ferromagnetism in an array of isolated plaquettes (four lattice sites arranged in a square). Then, we allowed for weak interplaquette tunneling. Since ferromagnetism is unstable in the presence of weak interplaquette couplings, we proposee to mediate long-range ferromagnetic correlations via double-exchange processes by exciting atoms to the first vibrational band. We calculated the phase diagram of the two-band plaquette array and discussed conditions for the stability and robustness of the ferromagnetic phases in this system. Experimental implementation of the proposed schemes was discussed.

Fermionic alkaline-earth atoms have unique properties that make them attractive candidates for the realization of atomic clocks and degenerate quantum gases. At the same time, they are attracting considerable theoretical attention in the context of quantum information processing. We demonstrated that when such atoms are loaded in optical lattices, they can be used as quantum simulators of unique many-body phenomena. In particular, we showed that the decoupling of the nuclear spin from the electronic angular momentum can be used to implement many-body systems with an unprecedented degree of symmetry, characterized by the $SU(N)$ group with N as large as 10. Moreover, the interplay of the nuclear spin with the electronic degree of freedom provided by a stable optically excited state should enable the study of physics governed by the spin–orbital interaction. Such systems may provide valuable insights into the physics of strongly correlated transition-metal oxides, heavy-fermion materials and spin-liquid phases.

We described a method for controlling many-body states in extended ensembles of Rydberg atoms, forming crystalline structures during laser excitation of a frozen atomic gas. Specifically, we predicted the existence of an excitation-number staircase in laser excitation of atomic ensembles into Rydberg states. It was shown that such ordered states can be selectively excited by chirped laser pulses, and, via quantum state transfer from atoms to light, be used to create crystalline photonic states.

We proposed and analyzed a scheme to interface individual neutral atoms with nanoscale solid-state systems. The interface was enabled by optically trapping the atom via the strong near-field generated by a sharp metallic nanotip. We showed that under realistic conditions, a neutral atom can be trapped with position uncertainties of just a few nanometers, and within tens of nanometers of other surfaces. Simultaneously, the guided surface plasmon modes of the nanotip allowed the atom to be optically manipulated, or for fluorescence photons to be collected, with very high efficiency. Finally, we analyzed the surface forces, heating and decoherence rates acting on the trapped atom.

Observing antiferromagnetic correlations in ultracold fermions on optical lattices is an important step towards quantum simulation of the repulsive Hubbard model. We showed that optical lattice modulation spectroscopy can be used to detect antiferromagnetic order and probe the nature of quasiparticle excitations in a fermionic Mott insulator. At high temperatures, the rate of creation of double occupancies showed a broad peak at frequency of the on-site repulsion U, reflecting the incoherent nature of the hole excitations. At low temperatures, antiferromagnetic order leads to fine structure in the response consisting of a sharp absorption edge reflecting coherent propagation of holes and oscillations as a function of modulation frequency representing spin-wave shake-off processes.

We proposed and analyzed a novel approach to quantum information processing, in which multiple qubits can be encoded and manipulated using electronic and nuclear degrees of freedom associated with individual alkaline-earth-metal atoms trapped in an optical lattice. Specifically, we described how the qubits within each register can be individually manipulated and measured with subwavelength optical resolution. We also showed how such few-qubit registers can be coupled to each other in optical superlattices via conditional tunneling to form a scalable quantum network. Finally, potential applications to quantum computation and precision measurements were discussed.

We presented a protocol to prepare decoherence-free cluster states using ultracold atoms loaded in a two dimensional superlattice. The superlattice geometry lead to an array of 2×2 plaquettes, each of them holding four spin-1⁄2 particles that can be used for encoding a single logical qubit in the twofold singlet subspace, insensitive to uniform magnetic field fluctuations in any direction. Dynamical manipulation of the supperlattice yielded distinct inter- and intraplaquette interactions and permitted us to realize one qubit and two qubit gates with high fidelity, leading to the generation of universal cluster states for measurement based quantum computation. Our proposal based on inter- and intraplaquette interactions also opened the path to study polymerized Hamiltonians which support ground states describing arbitrary quantum circuits.

We proposed and analyzed a technique that allowed one to suppress inelastic collisions and simultaneously enhance elastic interactions between cold polar molecules. The main idea was to cancel the leading dipole-dipole interaction with a suitable combination of static electric and microwave fields in such a way that the remaining van der Waals-type potential formed a three-dimensional repulsive shield. We analyzed the elastic and inelastic scattering cross sections relevant for evaporative cooling of polar molecules and discussed the prospect for the creation of stable crystalline structures.

We proposed a method for controllable generation of nonlocal entangled pairs using spinor atoms loaded in an optical superlattice. Our scheme iteratively increased the distance between entangled atoms by controlling the coupling between the double wells. When implemented in a finite linear chain of $2N$ atoms, it created a triplet valence bond state with large persistency of entanglement (of the order of N). We also studied the nonequilibrium dynamics of the one-dimensional ferromagnetic Heisenberg Hamiltonian and showed that the time evolution of a state of decoupled triplets on each double well leads to the formation of a highly entangled state where short-distance antiferromagnetic correlations coexist with longer-distance ferromagnetic ones. We presented methods for detection and characterization of the various dynamically generated states. These ideas were a step forward toward the use of atoms trapped by light as quantum-information processors and quantum simulators.

Strongly correlated quantum systems can exhibit exotic behaviour called topological order which is characterized by non-local correlations that depend on the system topology. Such systems can exhibit remarkable phenomena such as quasiparticles with anyonic statistics and have been proposed as candidates for naturally error-free quantum computation. However, anyons have never been observed in nature directly. Here, we described how to unambiguously detect and characterize such states in recently proposed spin–lattice realizations using ultracold atoms or molecules trapped in an optical lattice. We proposed an experimentally feasible technique to access non-local degrees of freedom by carrying out global operations on trapped spins mediated by an optical cavity mode. We showed how to reliably read and write topologically protected quantum memory using an atomic or photonic qubit. Furthermore, our technique can be used to probe statistics and dynamics of anyonic excitations.

We discussed a method to achieve decoherence resistant entanglement generation in strongly interacting ensembles of two-level spin systems. Our method used designed gapped Hamiltonians to create a protected manifold of multidegenerate levels which was robust against local decoherence processes. We applied the protected evolution to achieve decoherence resistant generation of many-particle Greenberger-Horne-Zeilinger (GHZ) states in two specific physical systems, trapped ions and neutral atoms in optical lattices, and discussed how to engineer the desired many-body protected manifold with them. We analyzed the fidelity of GHZ generation and showed our method can significantly increase the sensitivity in frequency spectroscopy.

Quantum mechanical superexchange interactions form the basis of quantum magnetism in strongly correlated electronic media. We reported on the direct measurement of superexchange interactions with ultracold atoms in optical lattices. After preparing a spin-mixture of ultracold atoms in an antiferromagnetically ordered state, we measured coherent superexchange-mediated spin dynamics with coupling energies from 5 hertz up to 1 kilohertz. By dynamically modifying the potential bias between neighboring lattice sites, the magnitude and sign of the superexchange interaction can be controlled, thus allowing the system to be switched between antiferromagnetic and ferromagnetic spin interactions. We compared our findings to predictions of a two-site Bose-Hubbard model and found very good agreement, but were also able to identify corrections that could be explained by the inclusion of direct nearest-neighbor interactions.

We proposed a method to perform precision measurements of the interaction parameters in systems of N ultracold spin 1⁄2 atoms. The spectroscopy was realized by first creating a coherent spin superposition of the two relevant internal states of each atom and then letting the atoms evolve under a squeezing Hamiltonian. The nonlinear nature of the Hamiltonian decreased the fundamental limit imposed by the Heisenberg uncertainty principle to $N-2$, a factor of N smaller than the fundamental limit achievable with noninteracting atoms. We studied the effect of decoherence and showed that, even with decoherence, entangled states can outperform the signal to noise limit of nonentangled states.

We presented two possible experimental implementations of the method using Bose-Einstein spinor condensates and fermionic atoms loaded in optical lattices and discussed their advantages and disadvantages.

Photons rarely interact—which makes it challenging to build all-optical devices in which one light signal controls another. Even in nonlinear optical media, in which two beams can interact because of their influence on the medium's refractive index, this interaction is weak at low light levels. Here, we proposed a novel approach to realizing strong nonlinear interactions at the single-photon level, by exploiting the strong coupling between individual optical emitters and propagating surface plasmons confined to a conducting nanowire. We showed that this system can act as a nonlinear two-photon switch for incident photons propagating along the nanowire, which can be coherently controlled using conventional quantum-optical techniques. Furthermore, we discussed how the interaction can be tailored to create a single-photon transistor, where the presence (or absence) of a single incident photon in a 'gate' field is sufficient to allow (or prevent) the propagation of subsequent 'signal' photons along the wire.

We studied the problem of rapid change of the interaction parameter (quench) in a many-body low-dimensional system. It was shown that, measuring the correlation functions after the quench, the information about a spectrum of collective excitations in a system can be obtained. This observation was supported by analysis of several integrable models and we argued that it was valid for nonintegrable models as well. Our conclusions were supplemented by performing exact numerical simulations on finite systems. We proposed that measuring the power spectrum in a dynamically split 1D Bose-Einsten condensate into two coupled condensates can be used as an experimental test of our predictions.
We described a novel approach to prepare, detect, and characterize magnetic quantum phases in ultracold spinor atoms loaded in optical superlattices. Our technique made use of singlet-triplet spin manipulations in an array of isolated double-well potentials in analogy to recently demonstrated control in quantum dots. We also discussed the many-body singlet-triplet spin dynamics arising from coherent coupling between nearest neighbor double wells and derived an effective description for such systems. We used it to study the generation of complex magnetic states by adiabatic and nonequilibrium dynamics.

We analyzed a recently proposed method to create fractional quantum Hall (FQH) states of atoms confined in optical lattices [A. Sørensen *et al.*, Phys. Rev. Lett. **94**, 086803 (2005)]. Extending the previous work, we investigated conditions under which the FQH effect can be achieved for bosons on a lattice with an effective magnetic field and finite on-site interaction. Furthermore, we characterized the ground state in such systems by calculating Chern numbers which can provide direct signatures of topological order and explored regimes where the characterization in terms of wave-function overlap fails. We also discussed various issues which are relevant for the practical realization of such FQH states with ultracold atoms in an optical lattice, including the presence of a long-range dipole interaction which can improve the energy gap and stabilize the ground state. We also investigated a detection technique based on Bragg spectroscopy to probe these systems in an experimental realization.

We reported on a study of the dynamics of decoherence of a matter-wave interferometer, consisting of a pair of low-dimensional cold atom condensates at finite temperature. We identified two distinct regimes in the time dependence of the coherence factor of the interferometer: quantum and classical. Explicit analytical results were obtained in both regimes. In particular, in the two-dimensional case in the classical (long time) regime, we found that the dynamics of decoherence is universal, exhibiting a power-law decay with an exponent, proportional to the ratio of the temperature to the Kosterlitz-Thouless temperature of a single 2D condensate. In the one-dimensional case in the classical regime we found a universal nonanalytic time dependence of decoherence, which is a consequence of the nonhydrodynamic nature of damping in 1D liquids.

École Polytechnique group (Antoine Georges)

These are the main research directions and key results over the whole period of the grant:

1) Fermions in an optical lattice: approach to the Mott state and Thermometry

During the first half of this project (2007-2010), in close connection with experimental developments in the field, we have investigated the approach to the Mott insulating state of cold fermionic atoms in optical lattices. We have also addressed the formation of antiferromagnetic correlations or long-range order. Using theoretical and numerical studies of the thermodynamic quantities, especially of entropy, of the Hubbard model, we have been able to quantify the temperature which is currently achieved in state-of-the art experiments, as well as the entropy to be achieved in future experiments in order to reach the antiferromagnetic state. Three key references on this topic are: De Leo et al. PRL 101, 210403 (2008), Jordens et al. PRL 104, 180401 (2010), De Leo et al. PRA 83, 023606 (2011).

2) Proposal of novel cooling procedures for fermionic gases

Devising new cooling procedures for cold fermionic gases is therefore crucial, with the goal of improving the current entropy per particle by roughly one order of magnitude. We have proposed several novel strategies in order to achieve these goals. The most promising one is the creation of a low-entropy state at the center of the trap using a proper shaping of the trapping potential: Bernier et al. PRB 79, 061601R, (2009). Most recently, we have proposed to use an analogue of the Peltier thermoelectric effect to achieve cooling: Grenier et al. PRL 113, 200601 (2014).

3) New methods of spectroscopy for ultra-cold fermionic gases

At the very beginning of this project, we proposed an analogue of photoemission spectroscopy in ultra-cold atomic gases, using outcoupling *rf* or Raman spectroscopy (Dao et al. PRL 98, 240402 (2007)). We have pursued the investigation of novel spectroscopies in cold gases, such as outcoupling photoemission spectroscopy (Dao et al. PRA 80, 023627 (2009)) or all-optical pump and probe methods (Dao et al. PRA 81, 043626 (2010).

4) Interplay of interactions and dissipation in open quantum systems

In the second phase of this project (2012-2013), more emphasis was put on the out of equilibrium dynamics of ultra-cold gases. The quench dynamics of closed quantum systems was studied (Bernier et al. PRL 106, 200601 (2011), Poletti et al. PRA 84, 013615 (2011)). More recently, we unraveled very intriguing physical effects resulting from the competition of interactions and a dissipative environment in open systems (the source of dissipation being e.g. spontaneous emission). These effects lead to slow dynamics of the decoherence, reminiscent of the dynamics of glassy systems (although in a context without any quenched disorder): Poletti et al., PRL 109, 045302 (2012) and PRL 111, 195301 (2013).