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QUANTUM ENGINEERING OF STRONGLY CORRELATED MATTER WITH ULTRACOLD FERMI GASES

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14. ABSTRACT

This is the final report on the Presidential Early Career Award for Science and Education (PECASE). In this program, we aim at realizing model systems of strongly correlated electrons using ultracold fermionic atoms. The general theme is to study high-temperature superfluids, Fermi liquids ('metals') and insulators in the presence of impurities whose influence on the fermions can be controlled.

During the course of the PECASE, we have created and studied fermionic superfluids in two and three dimensions, realized topological states of fermions via spin-orbit coupling, built the first Fermi gas microscope (among the Institute of Physics top ten breakthroughs of the year in physics 2015), observed charge and spin correlations in the Fermi-Hubbard model, created the first Fermi gas of chemically stable dipolar molecules and established coherent control of these molecules. The following summarizes our main results:

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Quantum Engineering of Strongly Correlated Matter with Ultracold Fermi Gases

AFOSR PECASE

Final Progress Report
July 2011 – July 2016

PI: Martin W. Zwierlein
Program Manager: Dr. Tatjana Curcic

Abstract

This is the final report on the Presidential Early Career Award for Science and Education (PECASE). In this program, we aim at realizing model systems of strongly correlated electrons using ultracold fermionic atoms. The general theme is to study high-temperature superfluids, Fermi liquids ("metals") and insulators in the presence of impurities whose influence on the fermions can be controlled.

During the course of the PECASE, we have created and studied fermionic superfluids in two and three dimensions, realized topological states of fermions via spin-orbit coupling, built the first Fermi gas microscope (among the Institute of Physics top ten breakthroughs of the year in physics 2015), observed charge and spin correlations in the Fermi-Hubbard model, created the first Fermi gas of chemically stable dipolar molecules and established coherent control of these molecules. The following summarizes our main results:

1. Evolution of Fermion Pairing from Three to Two Dimensions

Ariel T. Sommer, Lawrence W. Cheuk, Mark Jen-Hao Ku, Waseem S. Bakr, Martin W. Zwierlein

Phys. Rev. Lett. 108, 045302 (2012)

Highlighted as a Viewpoint in Physics 5, 10 (2012) by Mohit Randeria

Interacting fermions in coupled two-dimensional (2D) layers present unique physical phenomena and are central to the description of unconventional superconductivity in high-transition-temperature cuprates and layered organic conductors. Reduced dimensionality enhances the effect of fluctuations, while interlayer coupling can stabilize superconductivity and even amplify the transition temperature. A fermionic superfluid loaded into a periodic potential should form stacks of two-dimensional superfluids with tunable interlayer coupling, a key ingredient of the model proposed by Anderson to explain high transition temperatures observed in the cuprates. For deep potentials in the regime of uncoupled 2D layers, increasing the temperature of the gas is expected to destroy superfluidity through the Berezinskii-Kosterlitz-Thouless mechanism, while more exotic multi-plane vortex loop excitations are predicted for a 3D-anisotropic BCS superfluid near the critical point.

In this work, we studied fermion pairing across the crossover from 3D to 2D in a periodic potential of increasing depth. We follow the evolution of fermion pairing in the dimensional crossover from 3D to 2D as a strongly interacting Fermi gas of ^{6}Li 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 radiofrequency spectra, even on the BCS-side of a Feshbach resonance. With increasing lattice depth, the measured binding energy E_B of fermion pairs increases in surprising agreement with mean-field theory for the BEC-BCS crossover in two dimensions.

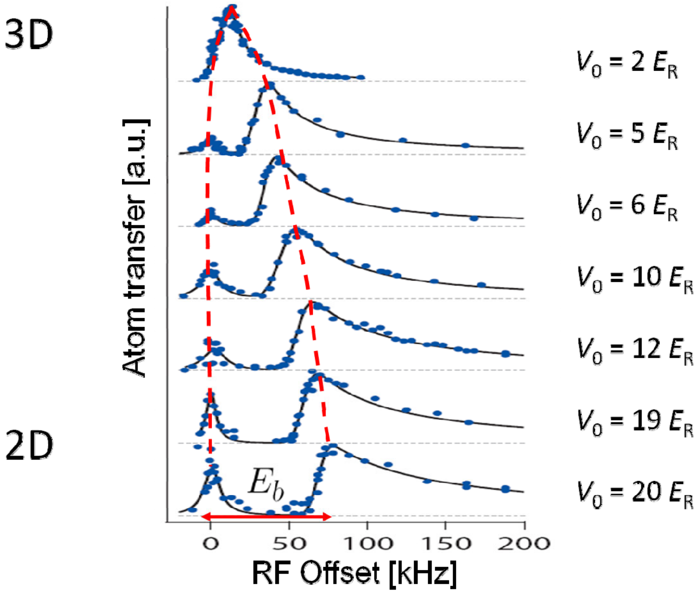


Figure 1 Figure 1 Evolution of Fermion Pairing from Three to Two Dimensions. Radio-Frequency Spectra show the opening of a pairing gap as the Fermi Gas is more and more confined to two dimensions. V0 denotes the strength of the optical lattice used to confine the gas, in units of the recoil energy ER of a 6Li atom in the lattice.

2. Revealing the Superfluid Lambda Transition in the Universal Thermodynamics of a Unitary Fermi Gas

Mark J. H. Ku, Ariel T. Sommer, Lawrence W. Cheuk, Martin W. Zwierlein
Science **335**, 563 (2012)
Highlighted in a Science Perspective by Wilhelm Zwerger

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 directly observed the superfluid phase transition in a strongly interacting Fermi gas via 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 of 16.7% of the Fermi temperature. Scaled to the density of electrons in a metal, this form of superfluidity would occur far above room temperature. Our measurements provide a benchmark for many-body theories on strongly interacting fermions, relevant for problems ranging from high-temperature superconductivity to the equation of state of neutron stars.

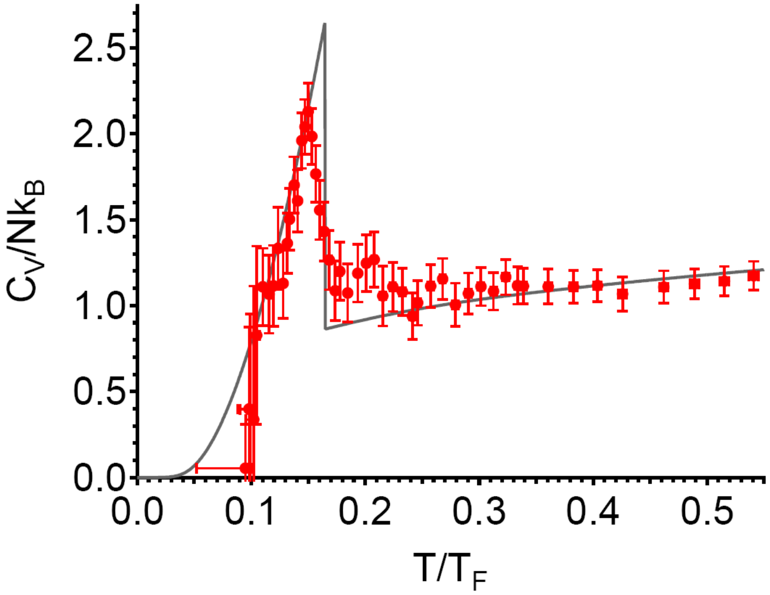


Figure 2 Observation of the Superfluid Lambda Transition in a trongly interacting Fermi Gas. Shown is the specific heat of the gas, directly obtained from the density profiles of a trapped gas.

3. Feynman diagrams versus Feynman quantum emulator

K. Van Houcke, F. Werner, E. Kozik, N. Prokofev, B. Svistunov, M. Ku, A. Sommer, L. W. Cheuk, A. Schirotzek, M. W. Zwierlein

Feynman diagrams versus Fermi-gas Feynman emulator

Nature Physics **8**, 366 (2012)

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 (BDMC), and precision experiments on ultra-cold atoms. Specifically, we compute and measure with unprecedented accuracy the normal-state equation of state of the unitary gas, a prototypical example of a strongly correlated fermionic system. Excellent agreement demonstrates that a series of Feynman diagrams can be controllably resummed in a non-perturbative regime using BDMC. This opens the door to the solution of some of the most challenging problems across many areas of physics.

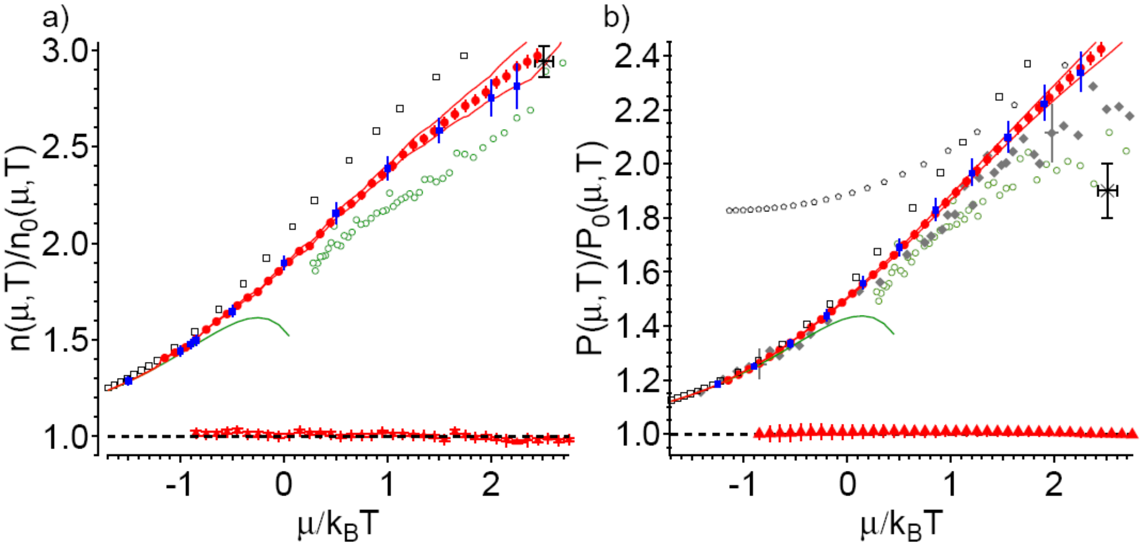


Figure 3 Equation of State of a Unitary Fermi Gas. a) Density and b) pressure as a function of the ratio of the chemical potential to the temperature. Density and pressure are normalized by the respective quantities of a non-interacting Fermi gas at the same ratio μ/k_BT.

4. Quantum degenerate Bose-Fermi mixture of chemically different atomic species with widely tunable interactions

Jee Woo Park, Cheng-Hsun Wu, Ibon Santiago, Tobias G. Tiecke, Peyman Ahmadi, Martin W. Zwierlein

Phys. Rev. A 85, 051602(R) (2012)

We have created a quantum degenerate Bose-Fermi mixture of ^{23}Na and ^{40}K with widely tunable interactions via broad interspecies Feshbach resonances. Twenty Feshbach resonances between ^{23}Na and ^{40}K were identified. 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 (ABM), this strong background scattering leads to a series of 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 will set the dominant energy scale.

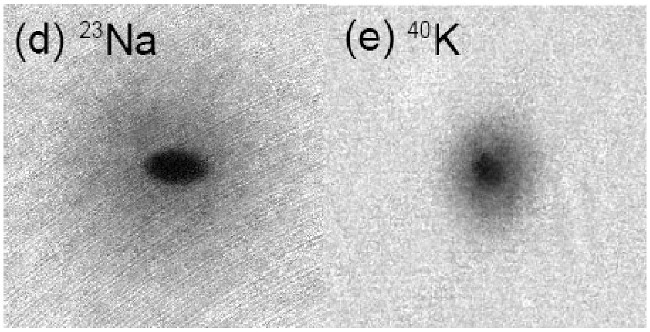


Figure 4 Strongly interacting degenerate Bose-Fermi mixture of ^{23}Na and ^{40}K. The fermion cloud (to the right) displays an untypical “bimodality” due to the strong interactions with the sodium condensate.

5. Spin-Injection Spectroscopy of a Spin-Orbit Coupled Fermi Gas

Lawrence W. Cheuk, Ariel T. Sommer, Zoran Hadzibabic, Tarik Yefsah, Waseem S. Bakr, Martin W. Zwierlein

Phys. Rev. Lett., in print, preprint arXiv: 1205.3483 (2012)

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 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. To fully inhibit transport, we open an additional spin gap, thereby creating a spin-orbit coupled lattice whose spinful band structure we probe. In the presence of s-wave interactions, such systems should display induced p-wave pairing, topological superfluidity, and Majorana edge states.

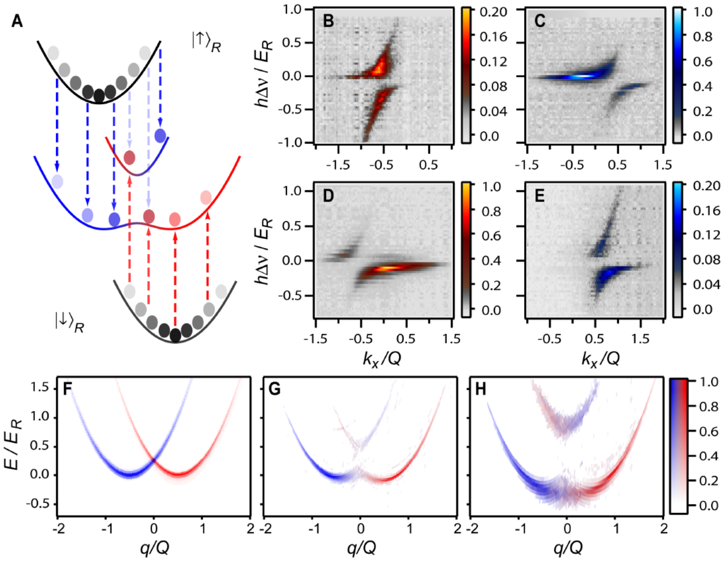


Figure 5 Spin-Injection Spectroscopy of a Spin-Orbit Coupled Fermi Gas. (A) A radiofrequency pulse transfers atoms from the reservoir states $|\uparrow>_R$ and $|\downarrow>_R$ (shown in black) into the spin-orbit coupled system (shown in red and blue). Transfer occurs when the RF photon energy equals the energy difference between

the reservoir state and the spin-orbit coupled state at quasi-momentum q. (B,C,D and E) Transfer as a function of RF frequency and detuning hΔν and quasi-momentum q. (B and C) Spin-resolved |↑> and |↓> spectra, respectively, when transferring out of $|\uparrow>_R$. (D and E) Spin-resolved |↑> and |↓> spectra, respectively, when transferring out of $|\downarrow>_R$. (F, G and H) The reconstructed spinful dispersions of a spin-orbit coupled Fermi gas for various strengths of Raman coupling.

6. Ultracold Fermionic Feshbach Molecules of ^{23}Na^{40}K

Cheng-Hsun Wu, Jee Woo Park, Peyman Ahmadi, Sebastian Will, Martin W. Zwierlein. Phys. Rev. Lett. 109, 085301 (2012).

We report on the formation of ultracold fermionic Feshbach molecules of ^{23}Na^{40}K, the first fermionic molecule that is chemically stable in its ground state. The lifetime of the nearly degenerate molecular gas exceeds 100 ms in the vicinity of the Feshbach resonance. The measured dependence of the molecular binding energy on the magnetic field demonstrates the open-channel character of the molecules over a wide field range and implies significant singlet admixture. This will enable efficient transfer into the singlet vibrational ground state, resulting in a stable molecular Fermi gas with strong dipolar interactions.

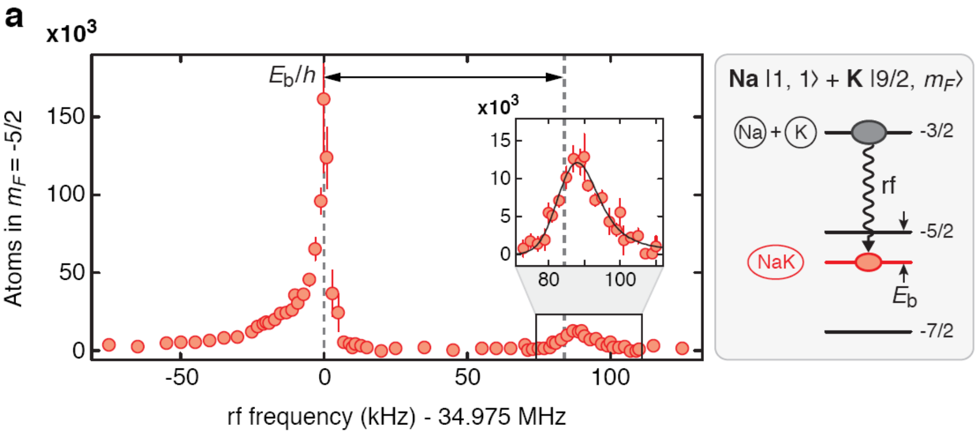


Figure 6 Radiofrequency association of ultracold Feshbach molecules of NaK. Starting with a mixture of sodium atoms in hyperfine state $|1,1>_{Na}$ and potassium atoms in hyperfine state $|9/2,-3/2>_K$, rf spectroscopy near the $|9/2,-3/2>_K$ to $|9/2,-5/2>_K$ hyperfine transition reveals free ^{40}K atoms repulsively interacting with the ^{23}Na bath (near zero rf offset), as well as associated molecules (near 85 kHz rf offset). A fit to the molecular association spectrum yields a binding energy of E_b = h x 84(6) kHz. The magnetic field corresponding to the atomic transition at 34.975 MHz was 129.4 G.

7. Heavy Solitons in a Fermionic Superfluid

Tarik Yefsah, Ariel T. Sommer, Mark J.H. Ku, Lawrence W. Cheuk, Wenjie Ji, Waseem S. Bakr, and Martin W. Zwierlein

Nature 499, 426-430 (2013), arXiv:1302.4736 (2013)

Topological excitations are found throughout nature, in proteins and DNA, as dislocations in crystals, as vortices and solitons in superfluids and superconductors, and generally in the wake of symmetry-breaking phase transitions. In fermionic systems, topological defects may provide bound states for fermions that often play a crucial role for the system's transport properties. Famous examples are Andreev bound states inside vortex cores, fractionally charged solitons in relativistic quantum field theory, and the spinless charged solitons responsible for the high conductivity of polymers. However, the free motion of topological defects in electronic systems is hindered by pinning at impurities. Here we create long-lived solitary waves in a strongly interacting fermionic superfluid by imprinting a phase step into the superfluid wavefunction, and directly observe their oscillatory motion in the trapped superfluid.

From the measured oscillation period we were able to deduce the ratio M*/M of the effective (inertial) mass M* of the solitary wave and its bare mass, M. It turned out that the inertial mass was over 200 times heavier than the bare mass. This result went against the prediction of the effective mass of planar solitons in fermionic superfluids. In on-going work (published after the current reporting period as arXiv:1402.7052 (2014)), we solved the riddle by showing that the solitary wave we had created was indeed a solitonic vortex, i.e. a nodal line of the superfluid order parameter, not a planar soliton.

Our experiments inform current theories on the dynamics and hydrodynamics of strongly interacting Fermi gases, for which there is no un-biased approach. It will be relevant for other types of strongly interacting Fermionic matter, such as nuclear physics, the study of the quark-gluon plasma, and the understanding of dynamics in neutron stars.

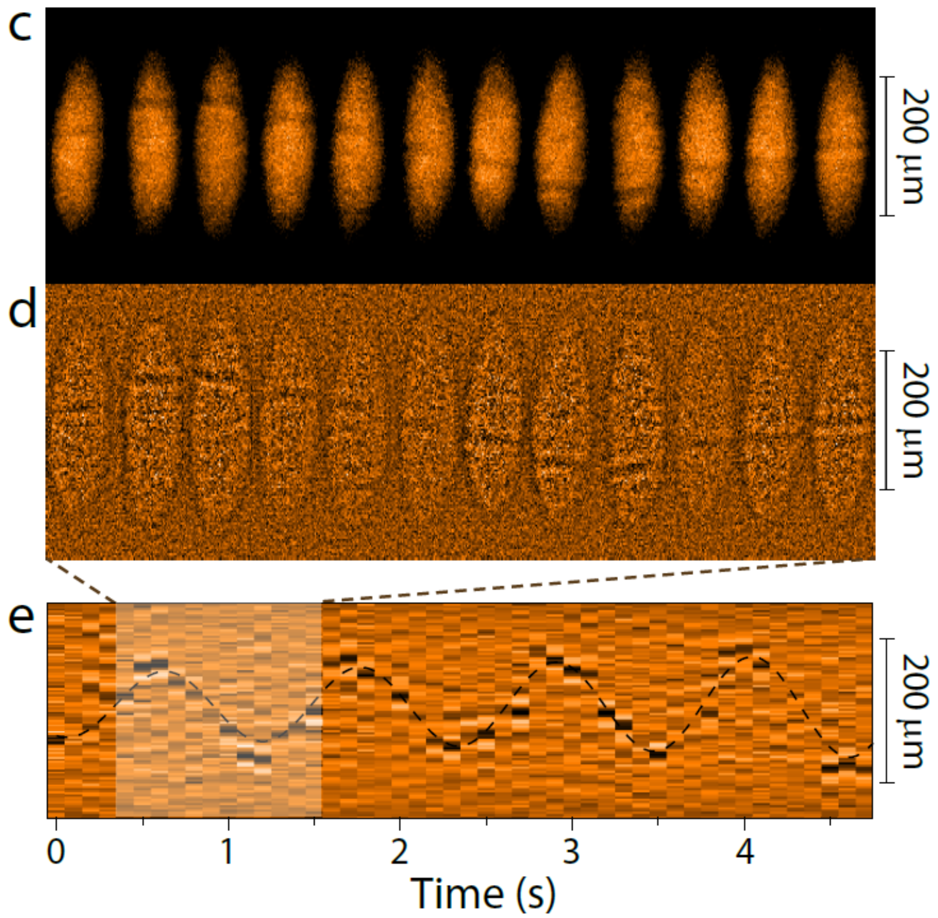


Figure 7 **Creation and Observation of solitary waves in a fermionic superfluid.** (c) Optical Density and (d) residuals of atom clouds showing solitary waves at varous hold times after creation. One period of solitary wave oscillation is shown. (e) Radially integrated residuals as a function of time revealing long-lived oscillations of the solitary wave. The period is over ten times longer than the trapping period for single atoms, revealing an extreme enhancement of the solitary wave's relative effective mass M*/M.

8. Collective Modes in a Unitary Fermi Gas

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); doi:10.1103/PhysRevLett.110.055303

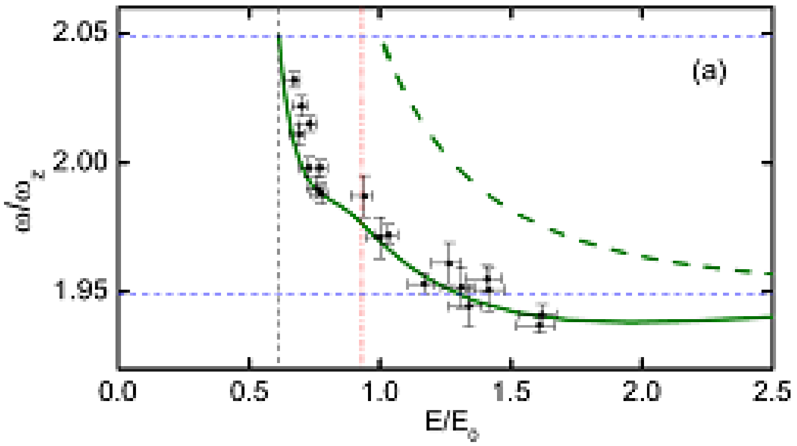


Figure 8 The frequency of a higher-order collective mode versus energy of the unitary Fermi gas. The black dots are data-points from the Innsbruck group, while the green solid curve is derived from the experimentally measured equation of state at MIT. The dashed line shows the result for a non-interacting Fermi gas.

In this joint theoretical and experimental work with Rudi Grimm's experimental group at the University of Innsbruck and the theoretical group of Sandro Stringari and Lev Pitaevskii at the University of Trento we investigate first sound in a strongly interacting Fermi gas.

The frequency of higher-order collective oscillations of first sound nature is strongly dependent on temperature and thus provides a stringent test of our previously measured equation of state. The experimental results from Innsbruck agree with high accuracy with the predictions of theory based on our experimental equation of state measurements and provide the first observation of the temperature dependence of collective frequencies near the superfluid phase transition.

9. Motion of a Solitonic Vortex in a Fermionic Superfluid

M.J.H. Ku, W. Ji, B. Mukherjee, E. Guardado-Sanchez, L.W. Cheuk, T.Yefsah, and M.W. Zwierlein.
Motion of a Solitonic Vortex in the BEC-BCS Crossover.
Phys. Rev. Lett. **113**, 065301 (2014)
Featured as a Highlight in Physics **7**, 82, 2014

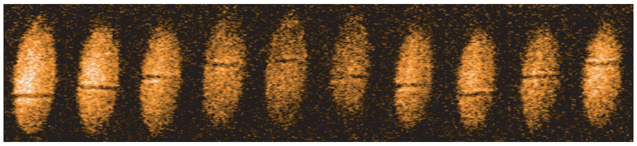


Figure 9 Motion of a Solitonic Vortex in a Fermionic Superfluid. From [2].

Topological excitations are found through-out nature, as defects in proteins and DNA, as dislocations in crystals, or as domain walls in magnets. They affect the transport properties of their host material: The high conductivity of polymers is due to charged solitons, and vortices cause residual resistivity in superconductors. In most systems in nature, the direct propagation of such excitations is not observable directly. Fermionic superfluids of ultracold atoms provide an ideal setting to study the motion of topological defects in real time. In recent experiments at MIT, a topological excitation has been created "on demand" and its free propagation was directly observed [1] (see Figure 9). The inertial mass of this localized object was found to be much larger than the total mass transported with it. In subsequent work [2], the excitation was revealed via tomographic imaging to be a solitonic vortex, a hybrid between a planar soliton and a regular vortex. Such excitations had been predicted to exist in elongated Bose-Einstein condensates, but they had not been experimentally identified before in any superfluid.

For this study, a new kind of tomographic imaging was employed, whereby only a single thin slice of the entire three-dimensional quantum gas could be imaged, thereby revealing the full 3D structure of the topological excitation. This technique allowed the direct observation of the precessional motion of the vortex.

One riddle in the previous study [1] had been the long period of the solitary wave's motion, which meant that the inertial mass of the localized wave must be much larger than the atomic mass that is transported with it, i.e. its gravitational mass. In the present work [2], this long period and the large enhancement of the inertial mass was explained via a superfluid hydrodynamic description of the vortex motion. It turned out that the period was a direct measure of the compressibility to density ratio of the gas, and thus depended strongly on the equation of gas of the system. Tuning the interaction strength of the Fermi gas allowed to vary the equation of state and therefore the compressibility, and with it the vortex period.

The solitonic vortex resembles Josephson vortices causing phase-slips in superconducting tunnel junctions. The experiments have direct implications for understanding transport in other strongly interacting Fermi systems, such as high-temperature superconductors, neutron stars as well as nuclear matter.

10. A Quantum Gas Microscope for Fermionic Atoms

Lawrence W. Cheuk, Matthew A. Nichols, Melih Okan, Thomas Gersdorf, Vinay V. Ramasesh, Waseem S. Bakr, Thomas Lompe, Martin W. Zwierlein
Phys. Rev. Lett. 114, 193001 (2015)

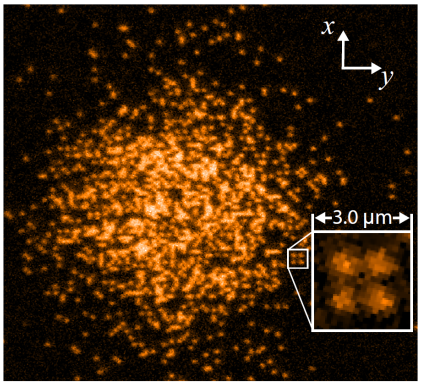


Figure 1 Potassium atoms under the Fermi Gas Microscope. The underlying optical lattice structure is apparent in the regular horizontal and vertical stripes in the cloud. An inset demonstrates the high resolution on four atoms arranged on the corners of a 3x3 square.

Our understanding of modern materials, such as high-temperature superconductors or colossal magneto-resistance materials, is still limited. The reasons for the difficulty of theoretical description are the fact that electrons are fermions, i.e. they cannot share the same quantum state, and that they are strongly interacting with each other. A prominent theoretical model that many believe might hold the key to high-temperature superconductivity is the Fermi Hubbard model, whereby electrons move on a periodic lattice and interact strongly with one another. Despite its importance, this model cannot be solved at present. Ultracold fermionic atoms in optical lattices have long been recognized as an ideal platform to study the Fermi Hubbard model, in analogy with the success of their bosonic counterparts in realizing the Bose Hubbard model. In the boson case, a milestone breakthrough was the creation of the Quantum gas microscope by Markus Greiner's group at Harvard, and later by Immanuel Bloch's group at MPQ Munich. It allows the study and manipulation of bosonic atoms in optical lattices at the single-atom level, with single-site resolution. The creation of a similar microscope for fermionic microscopes has since been a long-standing goal in the field.

In this work, we have realized such a quantum gas microscope for fermionic potassium atoms, in an optical lattice that allows the study of Fermi Hubbard physics. Around the same time, two other Fermi gas microscopes, one with lithium in Markus Greiner's group (see Phys. Rev. Lett. 114, 213002 (2015)), and one with potassium atoms in Stefan Kuhr's group at Strathclyde, saw "first light". The difficulty in these microscopes is to image atoms, in other words collect light from atoms, without having atoms leave their respective lattice site due to the photon recoil. In our case, we employ Raman sideband cooling to keep each atom in its lattice site. This technique removes a vibrational excitation in the lattice via two laser beams, whose frequency difference is tuned to exactly the energy difference between subsequent vibrational modes in the lattice, thereby removing any motional excitations that the atom might receive due to light scattering.

High-resolution optics collects the light from each atom and forms an image that allows distinguishing the position of atoms in adjacent lattice sites (about 540 nm). The imaging fidelity of a given atom is above 95%. Moreover, cooling works so well that even after imaging, each atom is with 75% probability still in the motional ground state of each lattice site, so that one may try in future experiments to first determine the atoms' position and then rearrange the atoms in a new, desired configuration. It would be like playing Maxwell's demon.

This new tool should allow the observation of magnetic phases in the Fermi Hubbard model, but also the time-dependent study of the spread of correlations, or the detection of many-fermion entanglement.

The paper received an Editor's Suggestion in PRL and was featured in *Physics*.

11. Two-photon pathway to ultracold ground state molecules of 23Na40K

Jee Woo Park, Sebastian A. Will, Martin W. Zwierlein
New Journal of Physics **17**, 075016 (2015)

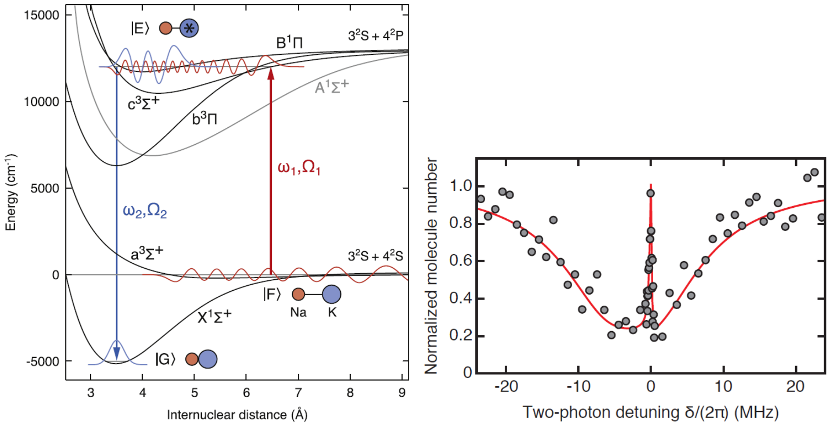


Figure 2 Left: Two-photon pathway to create ultracold molecules in their rovibrational ground state |G>, starting from Feshbach molecules |F>. Right: Observation of dark state resonance in two-photon coupling of the rovibrational ground state to the initial Feshbach molecular state.

The creation of ultracold, chemically stable molecules holds great promise for quantum information, quantum simulation, precision measurements of fundamental constants and the discovery of new states of dipolar quantum matter. To form ultracold dipolar molecules, one starts with a quantum mixture of ultracold atoms, in our case sodium and potassium. These atoms are then brought to form loosely bound Feshbach molecules with the help of a Feshbach resonance. Finally, these highly vibrationally excited molecules are to be transferred into the absolute lowest vibrational and rotational state of the molecule via a two-photon transfer. This final step is of major experimental difficulty. First, one needs to identify a suitable pathway connecting the predominantly triplet Feshbach molecules to the singlet ground state. This naturally requires an excited state as a “bridge” that has mixed singlet and triplet character. This identification represents a major challenge in molecular spectroscopy, to a large part because of the strong singlet-triplet mixing, but also due to the complicated hyperfine structure of involved levels. Next, one needs to actually find the exact location of the absolute ground state, often not known to sufficient precision. And finally, the coherent two-photon process connecting the Feshbach molecules to the absolute ground state requires two lasers, of vastly different wavelength, to be “in sync” with a relative frequency fluctuation of less than one kilohertz, i.e. a frequency stability of one part in 10^{11}. In this work, we demonstrate the coherent two-photon process connecting the Feshbach molecular state to the absolute ground state. We provide extensive spectroscopic data on excited singlet-triplet mixed states of NaK and the complete theoretical analysis of their mixing, including hyperfine interactions. The absolute ground state of NaK is found and coherent two-photon coupling is demonstrated via dark state spectroscopy. This work opens up the way towards the creation of ultracold ground-state molecules of NaK. The paper is published as part of the New Journal of Physics focus issue on new frontiers of cold molecules research.

12. Ultracold Dipolar Gas of Fermionic $^{23}Na^{40}K$ Molecules in their Absolute Ground State

Jee Woo Park, Sebastian A. Will, Martin W. Zwierlein
Phys. Rev. Lett. 114, 205302 (2015)

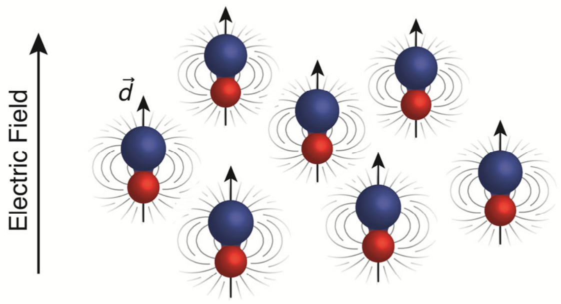


Figure 10 Molecules aligning their dipoles in an electric field. The long-range and anisotropic interaction between molecules is expected to give rise to novel states of matter at ultralow temperatures.

This year (2015) we are celebrating the twentieth anniversary of Bose-Einstein condensation in dilute gases of atoms. The various superfluid and magnetic phases of ultracold atoms have since become an extremely rich field of study. For the most part, this physics was dominated by short-range, contact interactions between atoms. Molecules possess many more degrees of freedom – they can rotate and vibrate – and consequently their interactions are more complex. Indeed, when an electric fields aligns molecules, they can possess a strong dipole moment. Dipolar interactions are long-range and anisotropic – they can be repulsive or attractive, like the interaction between magnets. A consequence of these unusual interactions are a myriad of new, exotic states of matter that have been predicted for ultracold molecules. The situation is especially rich for fermionic molecules, which cannot share one and the same quantum state. Pairing of fermionic molecules could lead to topological superfluids, for example. So far, however, the only ultracold fermionic molecules were KRb, which is chemically unstable.

In this work, we have created an ultracold gas of fermionic NaK molecules, which are chemically stable. The gas was indeed long-lived (relatively speaking), with a lifetime of 2.5s, highlighting this chemical stability. Furthermore, NaK possesses a five times larger dipole moment than KRb (2.7 Debye), and thus features 25 times larger interaction energies than KRb at the same densities. By applying an electric field, we were able to induce the largest dipole moment of any ultracold gas to date, 0.8 Debye. At this dipole strength, the typical length scale of dipolar interactions becomes on the order of the interparticle spacing. Thus, dipolar interactions completely dominate the many-body physics of the gas. It will be highly interesting to explore whether the gas can be further cooled into deep quantum degeneracy. Also, the use of microwaves to drive rotational transitions will be of high interest for future applications in quantum information and quantum simulation.

This work, published in PRL within 16 days of submission, received an Editor's Suggestion and was featured in *Physics.*

13. Cascade of Solitonic Excitations in a Superfluid Fermi Gas – From Planar Solitons to Vortex Rings and Lines

Mark J.H. Ku, Biswaroop Mukherjee, Tarik Yefsah, Martin W. Zwierlein
Phys. Rev. Lett. **116**, 045304 (2016)

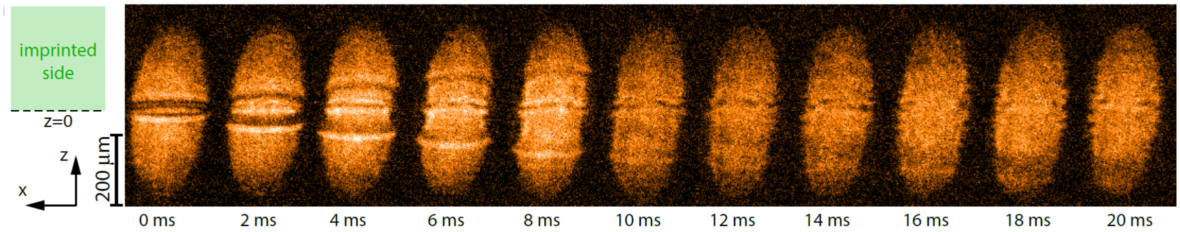


Figure 4 Cascade of solitonic excitations in a fermionic superfluid. Shown is the initial decay of a planar soliton, its undulation due to snaking, and its decay into a vortex ring (two dots in these tomographic images).

Solitonic excitations are a hallmark of non-linear systems, from the classic solitons in water to defects in polyacetylene chains to solitons and vortices in classical or quantum fluids. For a quantum system, solitonic excitations are defects in the phase of the macroscopic wave function, the complex order parameter. This leads to several non-classical effects, for example the fact that the circulation of the flow around vortices must be quantized, and that the phase change across planar solitons must be directly related to the speed of the soliton.

For weakly interacting Bose gases, forming a Bose-Einstein condensate, our understanding of solitonic excitations is far advanced, because we know the microscopic wave equation: The Gross-Pitaevskii equation (or non-linear Schrödinger equation) which has been studied in great detail. However, for strongly interacting fermionic superfluids we lack such a microscopic understanding, and theoretical studies of dynamics in strongly interacting Fermi systems are among the most difficult in modern many-body physics. Here, the microscopic length scale that sets the width of vortices and solitons is as short as it can possibly be, one interparticle spacing. Also, fermionic bound states are expected to reside inside solitons and vortices, so-called Andreev states that are naturally completely absent in the bosonic case.

We thus set out to study whether solitonic excitations can be created in strongly interacting fermionic superfluids and to investigate their subsequent fate. In this paper we successfully create a planar soliton, identified uniquely via a tomographic imaging technique, and study its subsequent cascade into vortex rings and eventually single vortex lines.
Planar solitons in this 3D setting are unstable towards „snaking“, the undulation of the soliton plane, and this snaking leads to the eventual formation of vortex rings. We were able to measure the rate of snaking of solitons in fermionic superfluids, which will provide a crucial point of comparison for future theories of strongly interacing Fermi superfluids.

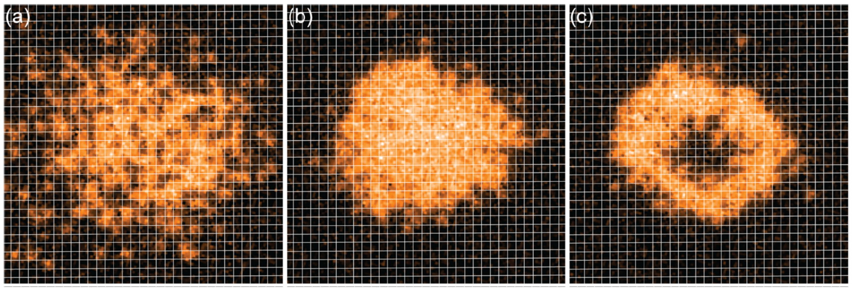
14. Coherent Microwave Control of Ultracold Molecules

Sebastian A. Will, Jee Woo Park, Zoe Z. Yan, Huanqian Loh, Martin W. Zwierlein.
Coherent Microwave Control of Ultracold ^{23}Na^{40}K Molecules.
Phys. Rev. Lett. 116, 225306 (2016)
DOI: 10.1103/PhysRevLett.116.225306

In this work we demonstrate coherent microwave control of rotational and hyperfine states of trapped, ultracold, and chemically stable 23Na40K molecules. Starting with all molecules in the absolute rovibrational and hyperfine ground state, we study rotational transitions in combined magnetic and electric fields and explain the rich hyperfine structure. Following the transfer of the entire molecular ensemble into a single hyperfine level of the first rotationally excited state, J=1, we observe collisional lifetimes of more than 3s, comparable to those in the rovibrational ground state, J=0. Long-lived ensembles and full quantum state control are prerequisites for the use of ultracold molecules in quantum simulation, precision measurements and quantum information processing.

15. Observation of 2D fermionic Mott insulators

Lawrence W. Cheuk, Matthew A. Nichols, Katherine R. Lawrence, Melih Okan, Hao Zhang, Martin W. Zwierlein.
Observation of 2D fermionic Mott insulators of ^{40}*K with single-site resolution*.
Phys. Rev. Lett. 116, 235301 (2016)
DOI: 10.1103/PhysRevLett.116.235301



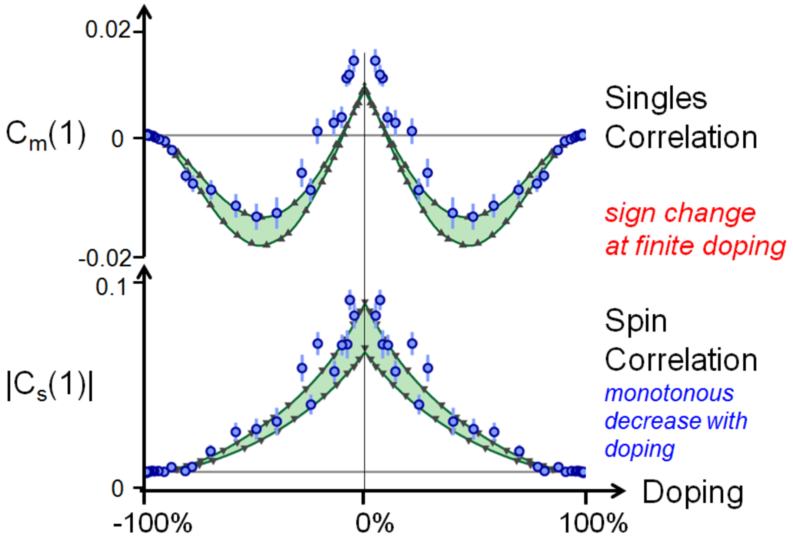
Observation of metals (a), Mott insulators (b) and band insulators (c) in an ultracold atom realization of the Fermi-Hubbard model, with single-site resolution imaging.

Under the newly built Fermi microscope, we were able to directly observe the formation of strongly correlated states of fermionic matter in optical lattices, namely metals, Mott insulators and band insulators. The system realizes the 2D Fermi-Hubbard model in pristine fashion. We directly observed the formation of local moments (singly occupied sites), which also serve us as a thermometer for all future studies. The realization of low-temperature strongly correlated states in the Fermi-Hubbard model gives strong hopes that these experiments will in the future enable precision measurements also on exotic states such as the putative superfluid phase upon doping. This is what would then relate to the high-temperature superconducting phase of cuprate superconductors.

16. Observation of Spatial Charge and Spin Correlations in the 2D Fermi-Hubbard model

Lawrence W. Cheuk, Matthew A. Nichols, Katherine R. Lawrence, Melih Okan, Hao Zhang, Ehsan Khatami, Nandini Trivedi, Thereza Paiva, Marcos Rigol, Martin W. Zwierlein.

Observation of Spatial Charge and Spin Correlations in the 2D Fermi-Hubbard Model. Science 353, 1260-1264 (2016), DOI: 10.1126/science.aag3349



Nearest-neighbor charge (top) and spin (bottom) correlations in an ultracold atom realization of the Fermi-Hubbard model. While the antiferromagnetic spin correlations decay monotonously with doping away from half-filling, the correlation between singly occupied sites displays an intriguing non-monotonous behavior: At large doping singles behave as fermions and effectively repel, while near the Mott region at half-filling, singles tend to bunch and effectively attract.

Strong electron correlations lie at the origin of transformative phenomena such as colossal magneto-resistance 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. In this work we reported 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\textemdash 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.

17. Publications

Journal Articles

1. Ariel T. Sommer, Lawrence W. Cheuk, Mark Jen-Hao Ku, Waseem S. Bakr, Martin W. Zwierlein.
   Evolution of Fermion Pairing from Three to Two Dimensions.
   Phys. Rev. Lett. **108**, 045302 (2012)

2. Mark J. H. Ku, Ariel T. Sommer, Lawrence W. Cheuk, Martin W. Zwierlein.
   Revealing the Superfluid Lambda Transition in the Universal Thermodynamics of a Unitary Fermi Gas.
   Science **335**, 563 (2012)
   Highlighted in a Science Perspective by Wilhelm Zwerger

3. K. Van Houcke, F. Werner, E. Kozik, N. Prokofev, B. Svistunov, M. Ku, A. Sommer, L. W. Cheuk, A. Schirotzek, M. W. Zwierlein.
   Feynman diagrams versus Fermi-gas Feynman emulator.
   Nature Physics **8**, 366 (2012)

4. Jee Woo Park, Cheng-Hsun Wu, Ibon Santiago, Tobias G. Tiecke, Peyman Ahmadi, Martin W. Zwierlein.
   Quantum degenerate Bose-Fermi mixture of chemically different atomic species with widely tunable interactions.
   Phys. Rev. A **85**, 051602(R) (2012)

5. 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., in print, preprint arXiv: 1205.3483 (2012)

6. 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).

7. 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 (2013), doi:10.1038/nature12338

8. 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); doi:10.1103/PhysRevLett.110.055303

9. M.J.H. Ku, W. Ji, B. Mukherjee, E. Guardado-Sanchez, L.W. Cheuk, T.Yefsah, and M.W. Zwierlein.
   Motion of a Solitonic Vortex in the BEC-BCS Crossover.
   Phys. Rev. Lett. **113**, 065301 (2014), featured as a Highlight in Physics **7**, 82, 2014

10. Jee Woo Park, Sebastian A. Will, and Martin W. Zwierlein.
    Ultracold Dipolar Gas of Fermionic 23Na40K Molecules in their Absolute Ground State.
    Phys. Rev. Lett. 114, 205302 (2015).

11. Jee Woo Park, Sebastian A. Will, and Martin W. Zwierlein.
    Two-Photon Pathway to Ultracold Ground State Molecules of 23Na40K.
    New J. Phys. 17, 075016 (2015).

12. Lawrence W. Cheuk, Matthew A. Nichols, Melih Okan, Thomas Gersdorf, Vinay V. Ramasesh, Waseem S. Bakr, Thomas Lompe, and Martin W. Zwierlein.
    A Quantum Gas Microscope for Fermionic Atoms.
    Phys. Rev. Lett. 114, 193001 (2015).

13. Mark J.H. Ku, Biswaroop Mukherjee, Tarik Yefsah, Martin W. Zwierlein.
    Cascade of Solitonic Excitations in a Superfluid Fermi Gas: From Planar Solitons to Vortex Rings and Lines.
    Phys. Rev. Lett. 116, 045304 (2016).

14. Sebastian A. Will, Jee Woo Park, Zoe Z. Yan, Huanqian Loh, Martin W. Zwierlein.
    Coherent Microwave Control of Ultracold $^{23}Na^{40}K$ *Molecules*.
    Phys. Rev. Lett. 116, 225306 (2016).

15. Lawrence W. Cheuk, Matthew A. Nichols, Katherine R. Lawrence, Melih Okan, Hao Zhang, Martin W. Zwierlein.
    Observation of 2D fermionic Mott insulators of ^{40}K *with single-site resolution*.
    Phys. Rev. Lett. 116, 235301 (2016).

16. Lawrence W. Cheuk, Matthew A. Nichols, Katherine R. Lawrence, Melih Okan, Hao Zhang, Ehsan Khatami, Nandini Trivedi, Thereza Paiva, Marcos Rigol, Martin W. Zwierlein.
    Observation of Spatial Charge and Spin Correlations in the 2D Fermi-Hubbard Model.
    Science 353, 1260-1264 (2016).

Proceedings

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)

Book chapters

17. M. Randeria, W. Zwerger, and M. Zwierlein.
    The BEC-BCS Crossover and the Unitary Fermi Gas.
    Lecture Notes in Physics, Volume 836, edited by Wilhelm Zwerger, Springer, Berlin 2012

18. Martin W. Zwierlein.
    Superfluidity in Ultracold Atomic Fermi Gases.
    long review article (200 pages), in "Novel Superfluids", Eds. K. H. Bennemann and J. B. Ketterson (Oxford University Press) (2014).

19. Zwierlein, M W
    Thermodynamics of strongly interacting Fermi gases
    In Inguscio, Massimo; Ketterle, Wolfgang; Stringari, Sandro; Roati, Giacomo (Ed.): Proceedings of the International School of Physics "Enrico Fermi", Volume 191: Quantum Matter at Ultralow Temperatures, 2016, ISSN: 18798195.

Theses:

20. Cheng Hsun Wu, *Strongly Interacting Quantum Mixtures of Ultracold Atoms,* PhD Thesis, MIT (2013)

21. Ariel Sommer, *Strongly Interacting Fermi Gases: Non-Equilibrium Dynamics and Dimensional Crossover*, PhD Thesis, MIT (2013)

22. Mark Ku, *Thermodynamics and Solitonic Excitations of a Strongly-Interacting Fermi Gas*, PhD Thesis, MIT (2015)

23. Jee Woo Park, *An Ultracold Gas of Dipolar Fermionic* $^{23}Na^{40}K$ *Molecules*, PhD Thesis, MIT (2016)

24. Lawrence W. Cheuk, *Quantum Gas Microscopy of Strongly Correlated Fermions*, PhD Thesis, MIT (2016)

Invited Talks at Conferences

1. Universal Thermodynamics and Spin Transport in Strongly Interacting Fermi Gases.
   ESF-IFRAF Fermix meeting, Paris, France, 4/14/2011

2. *Strongly Interacting Isotopic Bose-Fermi Mixture Immersed in a Fermi Sea.*
   3rd International Workshop on ultracold atoms/molecules
   Hsinchu, Taiwan, 4/30/2011 (talk by C.-H. Wu)
3. *Universal Spin Transport in a Strongly Interacting Fermi Gas.*
   INT Symposium: Fermions from Cold Atoms to Neutron Stars: Benchmarking the Many-Body Problem, Seattle, WA, 5/18/2011
4. *Universal Thermodynamics across the Superfluid Transition in a Strongly Interacting Fermi Gas.*
   INT Symposium: Fermions from Cold Atoms to Neutron Stars: Benchmarking the Many-Body Problem, Seattle, WA, 5/18/2011
5. Universal Thermodynamics across the Superfluid Transition in a Strongly Interacting Fermi Gas.
   Workshop on Frontiers in Ultracold Fermi Gases, Trieste, Italy, 6/8/2011
6. Universal Thermodynamics and Spin Transport in Strongly Interacting Fermi Gases.
   Multiflavour strongly correlated quantum gases, Hamburg, Germany, 6/24/2011
7. Universal Thermodynamics and Spin Transport in Strongly Interacting Fermi Gases.
   International Conference on Quantum Technologies, Moscow, Russia, 7/14/2011
8. Universal Thermodynamics and Spin Transport in Strongly Interacting Fermi Gases.
   Non-standard superfluids and insulators, Trieste, Italy, 7/20/2011
9. *Universal Thermodynamics and Spin Transport in Strongly Interacting Fermi Gases.*
   Quantum phenomena in graphene, other low-dimensional materials, and optical lattices, Erice, Italy, 8/4/2011
10. Universal Thermodynamics and Spin Transport in Strongly Interacting Fermi Gases.
    Strongly Correlated Electron Systems (SCES 2011), Cambridge, UK, 9/2/2011
11. Universal Thermodynamics and Spin Transport in Strongly Interacting Fermi Gases.
    Frontiers in Quantum Gases (BEC2011). San Feliu, Spain, 9/13/2011
12. *Universal Thermodynamics and Spin Transport in Strongly Interacting Fermi Gases.*
    Cecam/Pauli-Center workshop "Modeling Materials With Cold Gases Through Simulations", Zurich, Switzerland, 11/10/2011
13. *Strongly Interacting Fermi Gases: Thermodynamics, Spin Transport, Dimensional Crossover.*
    NewSpin 2 workshop "Winter school and workshop on spin physics and topological effects in cold atoms, condensed matter, and beyond", College Station, TX, 12/16/2011
14. *Strongly Interacting Fermi Gases: Thermodynamics, Spin Transport, Dimensional Crossover.*
    Aspen Winter Conference 2012 "New Directions in Ultracold Atoms", Aspen, CO, 1/9/2012
15. *Fermions in Flatland and Ultracold Fermionic Feshbach Molecules of* $^{23}Na^{40}K$.
    ITAMP workshop: Research Frontiers in Ultracold Atoms and Molecules, Cambridge, MA, 4/24/2012

16. *Universal Thermodynamics Across the Superfluid Transition in a Strongly Interacting Fermi Gas.*
    The Extreme Matter Physics of Nuclei: From Universal Properties to Neutron-Rich Extremes, Darmstadt, Germany, 4/30/2012
17. *Spin Transport in Strongly Interacting Fermi Gases & Evolution of Fermion Pairing from 3D to 2D.*
    Low-dimensional quantum gases out of Equilibrium, Minneapolis, MN, 5/11/2012
18. *Strongly Interacting Fermi Gases: Thermodynamics, Lower Dimensions and Novel Phases.*
    International Conference on Frontiers of Cold Atoms and Related Topics, Hong Kong, China, 5/16/2012
19. *Evolution of Fermion Pairing from Three to Two Dimensions.*
    DAMOP 2012, Anaheim, CA, 6/6/2012
20. *Strongly Interacting Fermi Gases: Thermodynamics, Spin Transport and Lower Dimensions.*
    Nonequilibrium phenomena in ultracold atoms and strongly interacting photons, Princeton, NJ, 6/11/2012
21. *Strongly Interacting Fermi Gases: Thermodynamics, Spin Transport, Dimensional Crossover.*
    ICAP 2012, Paris, France, 07/23/2012
22. *Ultracold Fermi Gases: Thermodynamics, Spin-Orbit Coupling, Edge States.*
    Workshop on Correlated Quantum Materials, Arlington, VA, 11/8/2012
23. *Ultracold Fermionic Feshbach Molecules of 23Na40K..*
    ESF Research Conference on Cold and Ultracold Molecules, Obergugrl, near Innsbruck, Austria, 11/19/2012
24. *Toplogical Phases in Ultracold Fermi Gases.*
    ARO Symposium on Topological Quantum Matter, Dallas, TX, 2/25/2013
25. *Heavy Solitons in a Fermionic Superfluid.*
    Kleppner Symposium, University of Sao Paolo, Sao Carlos, Brazil, 2/27/2013
26. *Ultracold Feshbach Molecules of NaK.*
    New Science with Ultracold Molecules, Santa Barbara, CA, 3/11/2013
    (Talk by S. Will)
27. *Spin-Orbit Coupled Fermi Gases.*
    APS March Meeting 2013, Baltimore, MD, 3/20/2013
28. *Thermodynamics of strongly interacting Fermi gases.*
    ITAMP workshop on "Finite temperature and low energy effects in cold atomic and molecular few-and many-body systems", Cambridge, MA, 3/25/2013
29. *Spin-Orbit Coupled Fermi Gases and Heavy Solitons in a Fermionic Superfluid.*
    NewSpin3, Mainz, Germany, 4/6/2013
    (Talk by L. Cheuk)

30. *Toplogical Phases in Ultracold Fermi Gases.*
    11th Japan-US Joint Seminar on Quantum Electronics and Laser Spectroscopy (QELS-11) "Ultimate Quantum Systems of Light and Matter- Control and Applications", Nara, Japan, 4/9/2013
31. *Spin-Orbit Coupled Fermi Gases.*
    Les Houches Workshop on "New magnetic field frontiers in atomic/molecular and solid-state physics", Les Houches, France, 5/7/2013
32. *Heavy Solitons in a Fermionic Superfluid.*
    Workshop on quantum simulations with ultracold atoms, Trieste, Italy, 5/15/2013
    (Talk by T. Yefsah)
33. *Heavy Solitons in a Fermionic Superfluid.*
    Superstripes2013: Quantum in Complex Matter, Ischia, Italy, 5/29/2013
    (Talk by T. Yefsah)
34. *Spin-Orbit Coupling and solitons in a Fermionic Superfluid.*
    DAMOP 2013, Quebec, Canada, 6/5/2013
    (Talk by L. Cheuk)
35. *Strongly interacting Fermi gases.*
    Gordon Conference on Atomic Physics, Newport, RI, 6/23/2013
36. *Heavy Solitons in a Fermionic Superfluid.*
    Synthetic Gauge Fields for Atoms and Photons, Trento, Italy, 7/8/2013
37. *Heavy Solitons in a Fermionic Superfluid.*
    Laser Physics 2013, Prague, Czech Republic, 7/17/2013
38. *Heavy Solitons in a Fermionic Superfluid.*
    International Workshop on Quantum Many Body Systems out of Equilibrium, Dresden, Germany, 8/19/2013
39. *Heavy Solitons in a Fermionic Superfluid.*
    BEC 2012, Sant Feliu, Spain, 9/9/2013
40. *Spin-Orbit Coupled Fermi Gases and Solitons in Fermionic Superfluids.*
    APS March Meeting 2014, Denver, Colorado, 3/4/2014 (talk by L. Cheuk)
41. *Strongly Interacting Fermi Gases in and out of Equilibrium.*
    Wilhelm and Else Heraeus Seminar on Discrete and Analogue Quantum Simulators, Bad Honnef, Germany, 2/10/2014
42. *Solitary Waves in a Fermionic Superfluid.*
    Strongly Coupled Systems Away From Equilibrium, Simons Center for Geometry and Physics, Stony Brook, NY, 2/24/2014
43. *Solitonic Waves in a Fermionic Superfluid.*
    Symposium "Shedding light on emergent quantum phenomena", Heidelberg, Germany, 3/10/2014
44. *Spin Diffusion and Solitary Waves in Strongly Interacting Fermi Gases.*
    ECT* workshop ``Hydrodynamics of Strongly Coupled Fluids", Trento, Italy, 5/12/2014 (talk by T. Yefsah)

45. *Solitary Waves in a Fermionic Superfluid.*
    Experimental Symposium "Precision Tests of Many-Body Physics with Ultracold Quantum Gases", Beijing, China, 6/13/2014
46. *Thermodynamics and Non-Equilibrium Dynamics of Unitary Fermi Gases.*
    Varenna School of Physics Enrico Fermi: "Quantum Matter at Ultralow Temperatures", Varenna, Italy, 7/9/2014
47. *Cascade of Solitary Waves in a Fermionic Superfluid.*
    Workshop DOQS2014 - Workshop on Many-body Dynamics and Open Quantum Systems, Glasgow, UK, 10/20/2014
48. *Cascade of Solitary Waves in a Fermionic Superfluid.*
    Probing and Understanding Exotic Superconductors and Superfluids, Trieste, Italy, 10/29/2014
49. *Strongly Interacting Fermi Gases of Atoms and Molecules.*
    Gordon Conference on Atomic Physics, Newport, RI, 6/17/2015
50. *Cascade of Solitonic Excitations in a Unitary Fermionic Superfluid.*
    ECT* workshop "Cold Atoms meets High-Energy Physics", Trento, Italy, 6/23/2015
51. *Strongly Interacting Fermi Gases of Atoms and Molecules.*
    APS March Meeting 2015, San Antonio, TX, 3/2/2015
52. *Strongly Interacting Fermi Gases of Atoms and Molecules.*
    DPG Spring Meeting 2015, Heidelberg, Germany, 3/24/2015
53. *Strongly Interacting Fermi Gases of Atoms and Molecules.*
    BEC 2015, Sant Feliu, Spain, 9/8/2015
54. *Strongly Interacting Fermi Gases of Atoms and Molecules.*
    International workshop on "Synthetic Quantum Magnetism", Dresden, Germany, 9/2/2015
55. *Cascade of Solitonic Excitations in a Unitary Fermionic Superfluid.*
    Workshop on "Cold Atoms meet Quantum Field Theory", Bad Honnef, Germany, 7/7/2015
56. *Cascade of Solitonic Excitations in a Unitary Fermionic Superfluid.*
    Interacting Fermi Gases - Precision Theory and Experiment, Trieste, Italy, 7/9/2015
57. *Strongly Interacting Fermi Gases of Atoms and Molecules.*
    UQUAM International Workshop on Ultracold Quantum Matter, Innsbruck, Austria, 9/22/2015
58. *Fermionic Mott Insulators, Band Insulators and Metals under the Quantum Gas Microscope.*
    DAMOP 2016, Providence, RI, 5/25/2016
59. *Fermionic Mott Insulators under the Microscope.*
    ICAP 2016, Seoul, South-Korea, 7/28/2016

Invited Talks at Colloquia and Seminars

1. From High-Temperature Superconductors to Neutron Stars: Ultracold Fermi Gases as Modell Matter.
   Physics Colloquium, Colby College, Colby College, ME, 10/27/2011
2. Universal Thermodynamics and Spin Transport in Strongly Interacting Fermi Gases.
   Nuclear and Particle Theory Seminar, MIT Center for Theoretical Physics, Cambridge, MA, 2/14/2011
3. Universal Spin Transport in Strongly Interacting Fermi Gases.
   Atomic Physics Seminar, Cambridge, UK, 10/22/2010
4. Von Hochtemperatur-Supraleitern zu Neutronensternen: Ultrakalte Fermi-Gase als Modell-Materie.
   Physics Colloquium, University of Darmstadt, Darmstadt, Germany, 6/18/2010

Physics Colloquium: *A Little Big Bang: Strong Interactions in Ultracold Fermi Gases.*
Given at:

5. Physics Colloquium, Colby College, Colby College, ME, 10/27/2011
6. Physics Colloquium, University of Massachusetts, Boston, Boston, MA, 10/29/2011
7. Physics Colloquium, Boston College, Boston, MA, 11/2/2011
8. Physics Colloquium, Yale University, New Haven, CT, 12/5/2011
9. Physics Colloquium, Georgetown University, Washington, D.C., 3/20/2012
10. Physics Colloquium, JILA and University of Colorado, Boulder, CO, 4/11/2012
11. Los Alamos National Laboratory Physics Colloquium, Los Alamos, NM, 7/9/2012
12. Princeton University, Princeton, NJ, 10/4/2012
13. University of Heidelberg, Heidelberg, Germany, 11/9/2012
14. Max-Planck Institute for Quantum Optics, Munich, Germany, 1/8/2013
15. Ohio State University, Columbus, OH, 2/5/2013
16. University of Toronto, Toronto, Canada, 2/7/2013
17. Penn State University, State College, PA, 3/28/2013
18. *Dipolar molecules – A new player in the world of ultracold quantum matter.*
    Physics Colloquium, Williams College, Williamstown, MA, 4/26/2013
    (Talk by S. Will)
19. *Heavy Solitons in a Fermionic Superfluid.*
    Condensed Matter Seminar, University of Massachusetts, Amherst, MA, 11/6/2013
    (talk by T. Yefsah)
20. *Ultracold Feshbach Molecules of NaK.*
    Atomic Physics Seminar, Chicago, IL, 11/7/2013 (talk by S. Will)
21. *Solitary Waves in a Fermionic Superfluid.*
    Atomic Physics Seminar, University of Bonn, Bonn, Germany, 1/7/2014
22. *A Little Big Bang: Strong Interactions in Ultracold Fermi Gases.*
    Physics Colloquium, California Institute of Technology, Pasadena, CA, 1/23/2014
23. *A Little Big Bang: Strong Interactions in Ultracold Fermi Gases.*
    Physics Colloquium, NorthEastern University, Boston, MA, 1/30/2014

24. *Solitary Waves in a Fermionic Superfluid.*
Atomic Physics Seminar, Cambridge, UK, 1/31/2014
25. *Solitary Waves in a Fermionic Superfluid.*
Joint Quantum Institute Seminar, College Park, MD, 2/3/2014
26. *A Little Big Bang: Strong Interactions in Ultracold Fermi Gases.*
Physics Colloquium, Lausanne, Switzerland, 11/17/2014

Honors and Awards

Martin Zwierlein:

- Promotion to Associate Professor with Tenure, 07/01/2012
- Silverman Family Career Development Chair, 2011 – 2013
- Promotion to Full Professor, 07/01/2013
- William W. Buechner Teaching Prize, MIT, 2012

Ariel Sommer received the Martin Deutsch Prize for Excellence in Experimental Physics from the MIT Physics Department.

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

Vinay Ramasesh wins Malcolm Cotton Brown Award from MIT physics (06/2012)

Mark Ku wins Harvey Fellowship (03/2012) and DARPA OLE best paper award (12/2011)

Postdoctoral Fellow Waseem Bakr

- Winner, DAMOP APS Thesis Prize 2013
- Infinite Kilometer (K) Award, MIT School of Science 2013

Jennifer Schloss (Graduate Student) receives Hertz Fellowship

Matthew Nichols (Graduate Student) receives NDSEG Fellowship

Postdoc Sebastian Will receives MIT's Infinite Kilometer Award for his strong community building efforts.
Ariel Sommer (PhD 2013) was selected as finalist for the APS DAMOP thesis prize 2015.
Lawrence Cheuk (PhD 2016) was selected as finalist for the APS DAMOP thesis prize 2018.

Formber group members in Faculty positions:

Postdocs:

Waseem Bakr, Professor at Princeton University

Sebastian Will, Assistant Professor at Columbia University

Tarik Yefsah, CNRS permanent researcher at Ecole Normale Supérieure, Paris

Huanqian Loh, Assistant Professor, National University of Singapore

Graduate students:

Ariel Sommer, Assistant Professor at Lehigh University

Lawrence Cheuk, Assistant Professor at Princeton University