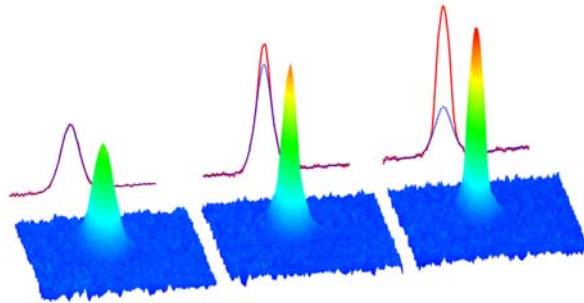


Progress in year 2004

1. Condensation of Pairs of Fermionic Atoms near a Feshbach Resonance

Ultracold atomic gases have become a medium to realize novel phenomena in condensed matter physics and test many-body theories in new regimes. Of particular interest are pairing phenomena in fermionic gases, which have direct analogies to superconductivity [1]. The interactions which drive the pairing in these gases can be controlled using a Feshbach resonance. This provides an opportunity to experimentally probe what is known as the BCS-BEC crossover; as the strength of the effective attractive interaction between particles is increased a continuous transition from condensation of delocalized Cooper pairs to condensation of tightly bound bosonic molecules is predicted.

We have observed Bose-Einstein condensation of pairs of fermionic atoms in an ultracold ${}^6\text{Li}$ gas at magnetic fields above a Feshbach resonance, where no stable ${}^6\text{Li}_2$ molecules would exist in vacuum. [2] Similar to Ref. [3], those pairs were observed after rapidly transferring them to stable molecules by sweeping the magnetic field across the Feshbach resonance, and then detecting the molecular signal. Condensate fractions as high as 80% were obtained. The large condensate fractions are interpreted in terms of preexisting molecules, which are quasi-stable even above the two-body Feshbach resonance due to the presence of the degenerate Fermi gas.

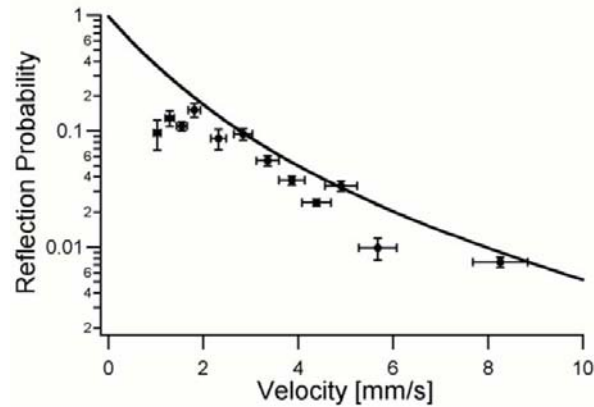


Emergence of a Bose-Einstein condensate of atom pairs as the temperature was lowered. Shown are column densities (after 6 ms of time of flight) of the fermion mixture after a rapid transfer ramp from 900 G for three different initial temperatures T/T_F 0.2, 0.1, 0.005, together with their axially integrated radial density profiles. The dashed blue line is a Gaussian fit to the thermal component. Condensate fractions are 0.0, 0.1, and 0.6. Each cloud consists of about $2 \cdot 10^6$ molecules. The field of view is 3×3 mm.

2. Quantum reflection of ultracold atoms from a solid surface

Quantum reflection is a process in which a particle reflects from a potential without reaching a classical turning point. Quantum reflection requires low incident velocity or weak attraction to the surface, conditions previously realized only using liquid helium surfaces or solid surfaces at grazing incidence [4]. In this work, we demonstrated quantum reflection of ultracold sodium atoms from a solid silicon surface at normal incidence [5].

Using Bose-Einstein condensates in a weak gravitomagnetic trap to reduce the atomic motion, atoms were incident on the surface at velocities as low as 1 mm/s, corresponding to collision energies of $k_B \times 1.5$ nanokelvin. Reflectivities of 20% are in qualitative agreement with theoretical predictions. When atoms were confined in one dimension by a silicon surface, lifetime measurements indicate reflection probabilities in excess of 50%. If higher reflectivities can be obtained with low-density of thinned surfaces, new atom-optical elements based on normal reflection will become possible.



Reflection probability vs incident velocity. The solid curve is a numerical calculation for individual atoms incident on a conducting surface.

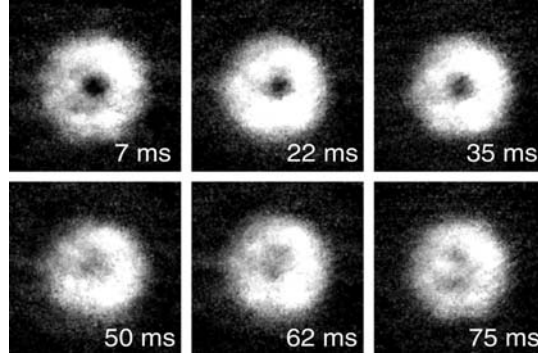
3. Observation of Feshbach resonances between two different atomic species

Feshbach resonances have made it possible to control interactions in ultracold atomic gases. By tuning the magnetic field near a value where the energy of two free atoms coincides with a molecular bound state, the sign and strength of the atomic interactions can be varied. So far, all experiments on Feshbach resonances studied collisions between two atoms of the same species. We have now observed three Feshbach resonances in collisions between ${}^6\text{Li}$ and ${}^{23}\text{Na}$ atoms [6]. The resonances were identified as narrow loss features when the magnetic field was varied. The molecular states causing these resonances have been identified, and additional ${}^6\text{Li}$ - ${}^{23}\text{Na}$ resonances are predicted. These resonances will allow the study of degenerate Bose-Fermi mixtures with adjustable interactions, and could be used to generate ultracold heteronuclear molecules. Ultracold polar molecules could be used for quantum computation, for studies of correlated many-body systems, and for searches for an electronic dipole moment.

4. Dynamical Instability of a Doubly Quantized Vortex in a Bose-Einstein condensate

The study of topological excitations and their stability is an active frontier in the field of quantum degenerate gases. Most studies focused on vortices with one quantum of circulation. In earlier work, we created doubly quantized vortices in a Bose-Einstein condensate [7], but due to technical limitation, could not observe the predicted decay. Now we have studied the time evolution of a doubly quantized vortex state [8] and

directly confirm its dynamical instability by observing that a doubly-quantized vortex core splits into two singly-quantized vortex cores [9]. The characteristic time scale of the splitting process was determined as a function of atom density and was longer at higher atomic density. The vortices were topologically imprinted into the condensate by reversing the magnetic field which created topological phases.



Decay of a doubly quantized vortex. Axial absorption images of condensates after 15 ms of ballistic expansion with a variable hold time after imprinting a doubly quantized vortex. A doubly quantized vortex decayed into two singly quantized vortices. The field of view in each image is $320 \mu\text{m} \times 320 \mu\text{m}$.

5. Feshbach Resonances in Fermionic ${}^6\text{Li}$

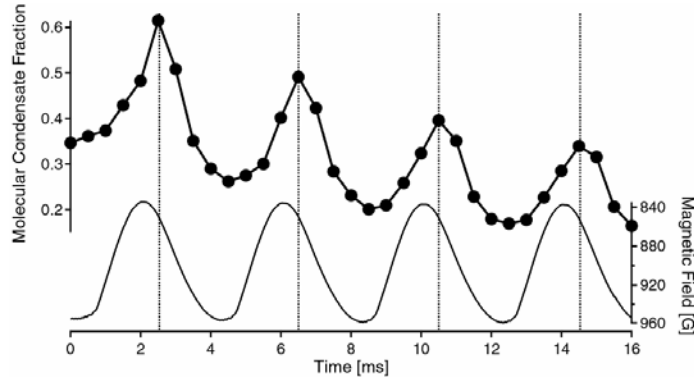
We performed a detailed study of Feshbach resonances in ${}^6\text{Li}$ with the goal of accurately characterizing the interaction potential of two ${}^6\text{Li}$ atoms. Three new resonances in the $|1\rangle$ and $|1\rangle$ states which are p-wave resonances were observed. [10] The positions of these Feshbach resonances together with the location of a narrow s-wave resonance in the $|1\rangle + |2\rangle$ mixture near 543 G were used for a precise determination of the singlet s-wave scattering length. These results, however, did not constrain the position of the broad resonance near 830 G, which also depends on the triplet scattering length. An improved measurement of its location was presented and the magnitude and the origin of possible systematic errors were discussed. This broad resonance is currently used in experiments on strongly interacting fermions.

6. Formation Time of a Fermion Pair Condensate

Atomic Fermi gases close to a Feshbach resonance can explore the entire regime from weak coupling to strong interaction between the particles. When cooled below a critical temperature, fermions form bosonic pairs which can condense into the ground state of the system. The nature of the pairs depends on the interaction strength: The particles can be either tightly bound into a small molecule or they can form long-range pairs, whose size can become comparable to or even larger than the interparticle spacing, analogous to Cooper pairs of electrons.

The control over the interactions between particles also offers a new way to study the dynamics of a strongly interacting many-body system: One may vary the interaction strength in a time-dependent fashion and observe how fast the system responds to that perturbation. Using this method, we studied the formation time of a condensate of

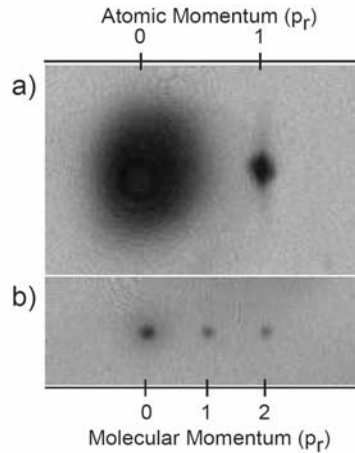
fermionic atom pairs close to a Feshbach resonance [2]. The observable was the fraction of condensed molecules in the cloud after a rapid magnetic field ramp across the Feshbach resonance. The measured response time of the system was slow compared to the rapid ramp, which provides final proof that the molecular condensates observed earlier [2, 3] reflect the presence of fermion pair condensates before the ramp.



Measurement of the formation time of fermionic pair condensates. Shown is the delayed response of the observed condensate fraction (data points and thick line to guide the eye) to a 250 Hz modulation of the interaction strength (magnetic field, thin line) on the BCS-side of the Feshbach resonance at 834 G. The vertical lines indicate the points of maximum condensate fraction, which are delayed by $500 \mu\text{s}$ with respect to the times at which the interaction is strongest (the magnetic field is closest to resonance).

7. Coherent Molecular Optics using Sodium Dimers

Coherent molecular optics was performed using two-photon Bragg scattering. [11] Molecules were produced by sweeping an atomic Bose-Einstein condensate through a Feshbach resonance [12]. Using optical standing waves of suitably chosen frequencies, sodium dimers were coherently manipulated with negligible heating or other incoherent processes. The spectral width of the molecular Bragg resonance which is Doppler sensitive corresponded to an instantaneous temperature of 20 nK, indicating that atomic coherence was transferred directly to the molecules. An autocorrelating interference technique was used to observe the quadratic spatial dependence of the phase of an expanding molecular cloud. Finally, atoms initially prepared in two momentum states were observed to crosspair with one another, forming molecules in a third momentum state. This process is analogous to sum-frequency generation in optics.

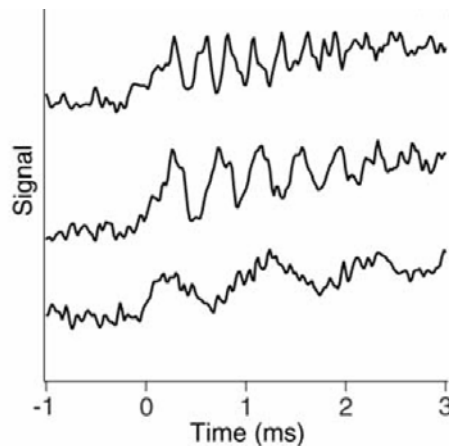


Sum frequency generation of atomic matter waves. (a) Atoms were initially prepared in momentum states 0, 1. (b) By sweeping through the Feshbach resonance, atoms combine to form molecules with momenta 0, 1, and 2. Momentum state 1 is the sum frequency of the two atomic matter waves. The “nonlinear medium” is provided by the atomic interactions. The time-of-flight in each image is 17 ms.

8. Continuous measurement of the relative phase of two Bose-Einstein condensates using light scattering

We have demonstrated an experimental technique based on stimulated light scattering to continuously sample the relative phase of two spatially separated Bose-Einstein condensates of atoms [13]. This is the first time that the phase of a condensate could be determined in a non-destructive way. The phase measurement process created a relative phase between two condensates with no initial phase relation, read out the phase, and monitored the phase evolution.

By monitoring the phase of two condensates at two separated times, interferometry between two trapped Bose-Einstein condensates without need for splitting or recombining.



Continuous optical read-out of the relative phase of two condensates. The traces show that the intensity of the light scattered from the condensates oscillates in time. Bragg scattering starts at $t=0$ when the second beam is turned on. The relative depth of the two wells was different for the three traces, generating a difference in the beat frequency between the two condensates.

1. H.T.C. Stoof and M. Houbiers, in *Bose-Einstein condensation in atomic gases*, Proceedings of the International School of Physics Enrico Fermi, Course CXL, edited by M. Inguscio, S. Stringari, and C.E. Wieman (IOS Press, Amsterdam, 1999) p. 537.
2. M.W. Zwierlein, C.A. Stan, C.H. Schunck, S.M.F. Raupach, A.J. Kerman, and W. Ketterle, *Phys. Rev. Lett.* **92**, 120403 (2004).
3. C.A. Regal, M. Greiner, and D.S. Jin, *Phys. Rev. Lett.* **92**, 040403 (2004).
4. F. Shimizu, *Phys. Rev. Lett.* **86**, 987 (2001).
5. T.A. Pasquini, Y. Shin, C. Sanner, M. Saba, A. Schirotzek, D.E. Pritchard, and W. Ketterle, *Phys. Rev. Lett.* **93**, 223201 (2004).
6. C.A. Stan, M.W. Zwierlein, C.H. Schunck, S.M.F. Raupach, and W. Ketterle, *Phys. Rev. Lett.* **93**, 143001 (2004).
7. A.E. Leanhardt, A. Görlitz, A.P. Chikkatur, D. Kielpinski, Y. Shin, D.E. Pritchard, and W. Ketterle, *Phys. Rev. Lett.* **89**, 190403 (2002).
8. Y. Shin, M. Saba, M. Vengalattore, T.A. Pasquini, C. Sanner, A.E. Leanhardt, M. Prentiss, D.E. Pritchard, and W. Ketterle, *Phys. Rev. Lett.* **93**, 160406 (2004).
9. M. Möttönen, T. Mizushima, T. Isoshima, M.M. Salomaa, and K. Machida, *Phys. Rev. A* **68**, 023611 (2003).
10. C.H. Schunck, M.W. Zwierlein, C.A. Stan, S.M.F. Raupach, W. Ketterle, A. Simoni, E. Tiesinga, C.J. Williams, and P.S. Julienne, *Phys. Rev. A* **71**, 045601 (2005).
11. J.R. Abo-Shaeer, D.E. Miller, J.K. Chin, K. Xu, T. Mukaiyama, and W. Ketterle, *Phys. Rev. Lett.* **94**, 040405 (2005).
12. K. Xu, T. Mukaiyama, J.R. Abo-Shaeer, J.K. Chin, D.E. Miller, and W. Ketterle, *Phys. Rev. Lett.* **91**, 210402 (2003).
13. M. Saba, T.A. Pasquini, C. Sanner, Y. Shin, W. Ketterle, and D.E. Pritchard, *Science* **307** (2005).