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2. Project Title: Fermi Gases in Bichromatic Superlattices

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4. PROGRAM SCOPE

The purpose of the program is the broad study of designer materials made of ultra-cold atoms and light, which provides new paradigms for emulating exotic layered systems. Bichromatic superlattices enable control and study of both dimensionality and dispersion in layered, strongly correlated Fermi gases, to model high-temperature superfluidity/superconductivity.

Most layered materials are quasi-two-dimensional, neither two-dimensional, like a sheet, nor three-dimensional, like a gas, but somewhere in between. In quasi-2D layers with an unequal number of spin-up and spin-down electrons, particularly strong attraction between pairs of electrons with opposite spins is predicted to achieve the highest possible superconducting transition temperatures. To understand these materials, we emulate them with a layered, ultra-cold Fermi gas of ^{6}Li atoms, magnetically tuned near a collisional (Feshbach) resonance, where precise control of the attraction, spin-composition, dimensionality and dispersion provides new tests of theory.

The primary goals are of the program are: (1) Elucidation of the effects of dimensionality and confining potential shape on the enhancement of high-temperature superfluidity in a layered, strongly correlated Fermi gases; (2) Control of dispersion and the study of tunable Dirac points in one dimension.

5. RESEARCH ACCOMPLISHMENTS

1) 2D to Quasi-2D Crossover

We published a Physical Review Rapid Communication describing the first studies of the crossover from a nearly two-dimensional (2D) Fermi gas of ^{6}Li to a quasi-2D gas, resolving a controversy in previously measured pairing spectra by our group and by the MIT group.

In the 2D regime, the measured pairing energies by both groups are consistent with confinement-induced dimers, as predicted by 2D-BCS mean-field theory. These results suggested that a mean field description might be applicable in this 2D system, despite theoretical expectations that mean field theory cannot describe 2D systems, due to enhanced fluctuations in the confined geometry. For the quasi-2D regime, the measured pairing energies are in strong disagreement with confinement-induced dimers, and can be understood using a (beyond mean field) polaron model. No previous experiment has continuously tuned between these regimes, to shed light on the connection between them.

To explore this problem, we use a 1064 nm (red) standing wave to tightly confine the atoms in periodic pancake-shaped potentials V(z). A focused CO_2 laser beam is superimposed on this lattice to provide tunable confinement in the radial r direction of the pancakes. With weak confinement, the potential is nearly 2D, with atoms residing the ground z-vibrational state. With tight confinement, the increase in the radial Fermi energy accesses higher z-vibrational states. For the first time, we measure *both* the radio-frequency pairing spectra and the radial cloud size in the same experiments, enabling a stringent test of predictions.

We find that while the dimer-2D-BCS model can predict the 2D spectra, the measured cloud radii are much smaller than 2D-BCS prediction, showing that the mean-field model is not valid in this 2D system, despite apparent agreement with the spectra. In the quasi-2D regime, explaining both the spectra and the cloud profiles requires a beyond mean field treatment.

Our results clearly confirm theoretical predictions that a beyond mean field description is required throughout the 2D to quasi-2D crossover. Further, we find that for binding small compared to the Fermi energy, the measured cloud radii approach predictions for a Fermi liquid.

2) Pairing of ^{6}Li Fermions in a Bichromatic Superlattice

We undertook a comprehensive experimental and theoretical study of atom pairing spectra in a bichromatic superlattice, comprising two standing waves with a two-to-one wavelength ratio and a controllable relative phase. Our measurements confirm our model, which showed that two types of atom pairs coexist, with different symmetries. The corresponding pair wavefunctions exhibit entanglement between the center of mass coordinate and the relative coordinate.

We measured the radio-frequency spectra of atom pair states in a 1D superlattice with radial harmonic confinement and developed a beyond Hubbard, multiband model, which explains the spectral structure. This model can be used to test the validity of analytic approximations and to characterize the states and populations of atom pairs in general optical lattices. Our measurements provide a foundation for new experiments with strongly interacting fermions, paving the way for future studies of dynamical controlled superfluids, by employing a time-dependent relative phase.

For these experiments, we superposed a 532 nm (green) lattice, onto a red 1064. With control of both the amplitudes and relative phase of the green and red lattices, we were able to create periodic double-well potentials of arbitrary shape and symmetry, leading to a rich spectral structure and new questions about the entanglement between the dimer center of mass motion and the relative motion within the dimer pair.

By varying the relative phase of the lattices for fixed green and red intensities, we observed a continuous evolution of the radio frequency spectra, which can include one or two components arising from bound to bound transitions and a third component arising from a bound to free transition. To interpret the data, we developed a comprehensive theory of atom pairing in a bichromatic superlattice, using a 9-band model and including finite harmonic confinement in the radial direction. For tight radial confinement, our model reduces to the well-known Hubbard model. Our model suggests that dimer pairing can occur for two atoms in the first band or for one atom in each of the first two bands, which become nearly degenerate when the relative phase is set to create symmetric double wells. Tuning the relative phase of the lattices varies the symmetry of the double wells and breaks the degeneracy, destroying the second pairing mechanism.

Finally, we developed a method to populate the second band for a non-interacting Fermi gas and measured the quasi-momentum distribution using a new band mapping method, based on releasing the cloud into a harmonic potential.

3) Spin-Energy Correlation in Degenerate Weakly-Interacting Fermi Gases

Our most recent experiments explored a new concept of “energy-space” lattices in a very weakly interacting two-component Fermi gas of ^{6}Li, which exhibits effective long-range coupling between the “lattice sites.” In contrast to most of our studies, which are done close to a Feshbach resonance, where the cloud is strongly interacting, here, we study the region near the “zero crossing,” where the magnetic field is tuned to make the s-wave scattering length vanish. We believe that this system offers the possibility to simulate a wide variety of lattice models and may provide new methods for creating macroscopic spin entanglement.

With the scattering length tuned to be less than five bohr, the energy changing collision rate is negligible over the 1-2 second time scale of the experiments, and the single particle energies are conserved. In a harmonic trap, the quantum numbers n_x, n_y, and n_z are conserved, producing an “energy lattice,” with sites denoted by (E_x, E_y, E_z). We create an ensemble of spins by using a radio-frequency pulse to create superpositions of two lowest hyperfine states. The curvature of the bias magnetic field produces an energy-dependent precession of the spins, which correlates the spin-vector the energy. An effective long range interaction between the sites arises from forward scattering between atoms oscillating rapidly in the confining harmonic potential. This forward scattering produces a mean field frequency, which is linear in the scattering length, in contrast to the negligible energy changing collision rate, which scales quadratically.

We observed a rich time-dependent evolution, producing spin-waves and controllable spin-currents. We demonstrated that the rich spatial structure of the resulting spin-waves can be understood using a mean-field model, where the field operators are expanded in energy representation. Our model shows that macroscopic spin-vectors in energy space obey a collective evolution arising from the competition between the mean field, which tends to align the spins, and the energy-dependent Zeeman tuning, which tends to destroy the alignment. For the comparison between data and theory, we employ a degenerate gas to minimize the effects of energy tuning of the scattering length, which we study at higher temperatures.

6. OPPORTUNITIES FOR TRAINING AND PROFESSIONAL DEVELOPMENT

Currently, two graduate students and one research scholar are involved in our Fermi gas bichromatic lattice experiments. Three additional students and two-post doctoral associates are involved in our other programs. The students are engaged in all aspects of the system design and the associated theory of the experiments and results. They design and build everything from the vacuum system to mechanical support and structural components, for both the laser and the optical system. Further, the electronic and computer interfaces used in these experiments and designed by the students are state of the art and are often very complex. For example, our current optical system uses an 32 input timing diagram for control of the various laser preparation and probe beams. The students use the latest computer systems and programming methods to handle these problems. They also design and etch circuit boards for use in interfacing, multiplexing, and servo control.

In building electronics, students acquire skills in electronics design, circuit design and layout, and mechanical design and construction. Students routinely use our circuit board layout programs and our etching system to produce nearly commercial quality electronic boards and systems. Such skills are very important in the future, when as a group leader in academia or industry, a scientist must contribute to the design of specialized equipment and communicate effectively with technical staff. In optical design, students learn both the theory and practice of optical layout and acquire skills in mechanical construction, which are needed to build a complete system. Much of the software and computer interfacing used in the experiments is developed by the students, providing a skill that is transferable to many other projects.

A substantial theoretical effort is needed to understand the results of the experiments, and the students are involved is this facet also. There are many electrodynamics, quantum mechanics, statistical mechanics and thermodynamics problems, which are investigated in exploring our ultra-cold Fermi gas system.

Since students and post-doctoral staff are broadly trained in both the experiments and the theory, they are well positioned to assume roles of leadership in solving problems of current national interest. This is evidence by the broad range of careers that my former Ph. D. students pursue. I have students who have accepted academic positions, industrial positions, as well as one student who is Senior Director of Game Design at Activision and one who is a Director of Biosensor research at Saint Jude's hospital.

I meet with my post-doctoral associates daily, to discuss physics and progress on the experiments, as well as to discuss how they are mentoring the graduate and occasional undergraduate students who work with them, both in teaching experimental skills as well as theoretical concepts. I encourage my post-doctoral associates to teach undergraduate courses and mentor undergraduates, when opportunities arise. I also encourage them to take initiative in both implementing new experimental methods and learning new theory for themselves. Finally, I have an annual review, to discuss their progress, their goals, and their needs.

My current post-doctoral associate on this project, Ilya Arakelyan, taught an undergraduate electromagnetic theory course at NCSU during a summer term. He has supervised several Ph. D. graduates, including Yingyi Zhang, who did our first work on pairing spectra in reduced dimensions and Willie Ong, who did our recent experiments on spin-imbalanced quasi-2D Fermi gases. Ilya supervised Chingyun Cheng, who built our bichromatic lattice system. She graduated in December, 2016 and currently has a position in a medical research group at the University of Pennsylvania, where she joined her husband. Jayampathi Kangari is the lead student on the bichromatic lattice experiments and is making great progress toward his Ph. D. He is helping to train Saeed Pegahan, who will continue these experiments.

8. PUBLICATIONS

A) Primary support from DOE

1) Chingyun Cheng, J. Kangara, I. Arakelyan, and J. E. Thomas, “Fermi Gases in the Two-Dimensional to Quasi-Two-Dimensional Crossover,” Phys. Rev. A **94**, 031606(R) (2016).

2) J. Kangara, Chingyun Cheng, S. Pegahan, I. Arakelyan, and J. E. Thomas, ``Atom Pairing in Optical Superlattices," *Physical Review Letters* **120**, 083203 (2018), *Editor's Suggestion*.

3) S. Pegahan, J. Kangara, I. Arakelyan and J. E. Thomas, ``Spin-Energy Correlation in Degenerate Weakly-Interacting Fermi Gases," *Physical Review A* **99**, 063620 (2019), *Editor's Suggestion*.

B) Acknowledge support from DOE

4) N. Arunkumar, A. Jagannathan, and J. E. Thomas, ``Probing Energy-Dependent Feshbach Resonances by Optical Control," *Physical Review Letters* **121**, 1630404 (2018).

5) N. Arunkumar, A. Jagannathan, and J. E. Thomas, ``Designer Spatial Control of Interactions in Ultracold Gases," *Physical Review Letters* **122**, 040405 (2019).

6) Lorin Baird, Xin Wang, Stetson Roof and J. E. Thomas, ``Measuring the Hydrodynamic Linear Response of a Unitary Fermi Gas," *Physical Review Letters* **123**, 160402 (2019), *Editor's Suggestion*.