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Optical Control of Interactions in Non-equilibrium Fermi Gases

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14. ABSTRACT
We have developed broadly applicable methods for the optical control of two-body scattering interactions in an ultra-cold atomic gas, which is magnetically tuned near a collisional
(Feshbach) resonance. Using two-optical fields, we exploit electromagnetically-induced transparency (EIT) to optimize the tradeoff between the tunability of the two-body scattering parameters and unwanted optical scattering. By exploiting the high spatial and temporal resolution of optical fields, these techniques enable broad new studies of non-equilibrium dynamics. Our experiments employ an optically-trapped mixture of the two lowest hyperfine states in a 6Li Fermi gas, using two optical fields to create a dark state in the closed molecular channel of a Feshbach resonance. We tested a new theoretical approach for the optical control model, which employs a continuum-dressed (Fano) basis. This model is valid for both the broad (832.2 G) and narrow (543.2 G) resonances in 6Li, which we verified by precise measurements of the momentum dependence of the loss spectra. We constructed a new apparatus, where the optical control beams propagate co-linearly with the axis of a 1064 nm optical dipole trap. The new system enables spatially uniform control of two-body interactions as well as velocity selective control. This method paves the way for new experiments, including optical control of the second virial coefficient and the equation of state, optical control of the effective range for simulation of neutron matter, velocity-selective control of two-body interactions and synthetic FFLO states, and optical control of long range spin-spin interactions to study information scrambling.

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Abstract (250 words)

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Accomplishments

The broad objective of this project is the experimental demonstration and theoretical study of general two-field optical methods for the control of two-body scattering interactions in trapped, ultra-cold atomic gases. The experiments employ a Fermi gas of ^{6}Li in a mixture of two hyperfine states, which is magnetically tuned near a collisional (Feshbach) resonance. The two-field methods exploit electromagnetically-induced transparency (EIT) to greatly improve the tradeoff between the tunability of the two-body scattering parameters and the suppression of unwanted optical scattering, compared to older single-field methods. With the high spatial and temporal resolution of optical fields, these techniques enable broad new studies of non-equilibrium dynamics.

Publications:

1) A. Jagannathan, N. Arunkumar, J. A. Joseph, and J. E. Thomas, ``Optical control of magnetic Feshbach resonances by closed-channel electromagnetically induced transparency," Phys. Rev. Lett. **116**, 075301 (2016), *Editor's Suggestion*.

2) 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).

3) J. Kangara, Chingyun Cheng, S. Pegahan, I. Arakelyan, and J. E. Thomas, ``Atom pairing in optical superlattices," Phys. Rev. Lett **120**, 083203 (2018), *Editor's Suggestion*.

4) N. Arunkumar, A. Jagannathan, and J. E. Thomas, ``Probing energy-dependent Feshbach resonances by optical control," Phys. Rev. Lett. **121**, 1630404 (2018).

5) N. Arunkumar, A. Jagannathan, and J. E. Thomas, ``Designer spatial control of interactions in ultracold gases," Phys. Rev. Lett. **122**, 040405 (2019).

6) S. Pegahan, J. Kangara, I. Arakelyan and J. E. Thomas, ``Spin-energy correlation in degenerate weakly-interacting Fermi gases, Phys. Rev. A **99**, 063620 (2019), *Editor's Suggestion*.

7) Lorin Baird, Xin Wang, Stetson Roof and J. E. Thomas, ``Measuring the hydrodynamic linear response of a unitary Fermi gas," Phys. Rev. Lett. **123**, 160402 (2019), *Editor's Suggestion*.

8) S. Pegahan, I. Arakelyan and J. E. Thomas, ``Energy-resolved information scrambling in an energy-space lattice," Phys. Rev. Lett., **126**, 070601 (2021).

9) Xin Wang, Xiang Li, Ilya Arakelyan, and J. E. Thomas, ``Hydrodynamic relaxation in a strongly interacting Fermi gas," Phys. Rev. Lett. **128**, 090402 (2022), *Editor's Suggestion*.

Highlights of the Publications:

1) Optical control of magnetic Feshbach resonances.

- Graduate students Arun Jaganathan and his wife Nithya (publications 1, 4, 5 above) completed both of their Ph. D. thesis in my laboratory on the optical control of magnetic Feshbach resonances. They developed the original two-field optical control apparatus. This required a three diode laser system, one master laser locked to an iodine resonance and two slave lasers locked to a common optical cavity. With a relative frequency jitter of just 10's of kHz, they were able to demonstrate suppression of optical scattering near the broad Feshbach resonance, increasing the lifetime from 0.5 ms with single laser optical tuning to 0.4 sec with the two-field EIT method. Their work verified a new theoretical model of two-field optical control, using a Fano basis. Arun's thesis showed that tuning the frequency of one of the EIT lasers near the zero loss, two-photon resonance greatly improves the trade-off between loss and tunability compared to single field methods (publication 1 above).

- Nithya's thesis demonstrated broad tuning of the scattering length near the narrow resonance in ^{6}Li and probed the momentum dependence of the scattering amplitude (publication 4 above). Further, she demonstrated spatial control, by creating an "interaction sandwich," comprising a non-interacting cloud, with a strongly interacting slice in the center (publication 5 above).

- Two new graduate students, Camen Royse and Jingjing Huang, have developed a more versatile system for optical control using EIT beams that co-propagate with the trapping laser beam. They employ our ultrastable CO_2 laser for initial trapping and evaporative cooling. Then the cold atoms are transferred to a 1064 nm fiber laser trap, which serves as the "work-horse" for all subsequent experiments. Camen and Jingjin utilize high-power optical fibers to transport two optical control beams. The beams are generated on a table containing three frequency-stabilized diode lasers and transported to the fiber laser trap in the cooling and trapping region. The optical control beams propagate collinearly with the 1064 nm trapping beam. This enables precision measurements with uniform control beam intensity across the atom cloud.

- Camen and Jingjing began new experiments on the optically induced-shifts near the broad Feshbach resonance in ^{6}Li at 832.2 G. We have observed very large light shifts in the molecular component of the spectra for magnetic fields below resonance (789 and 820 G), which we have not yet understood. However, we found that one extension of our model correctly predicted the magnetic field dependence of the light-induced shift and loss observed by the Rice group of Randy Hulet for photoassociation in a BEC of ^{7}Li near a Feshbach resonance.

2) Spin-Energy Correlation and Information Scrambling

- Saeed Pegahan (publications 6 and 8 above) measured spin-energy correlation in a weakly interacting Fermi gas and began our first experiments on the study of information scrambling in weakly interacting Fermi gases with effective long-range interactions. Saeed demonstrated the measurement of out-of-time-order correlation (OTOC) functions in an "energy-space lattice." The OTOC experiments employ phase-controlled radio-frequency (rf) pulses and reversal of the many-body Hamiltonian, which is achieved using a small bias magnetic field to reverse the sign of the scattering length and a π pulse. However, this method is limited, as the bias field tuning requires 10 ms, and the bias field, when it is on, detunes the rf transition from resonance. These two measurements comprised Saeed's Ph. D. dissertation, who defended his thesis in December of 2020. Caman and Jingjing are currently using two-field optical methods to control the scattering length, which will enable more complex protocols and larger scattering lengths, with no change in the rf transition frequency.

Related programs supported in part by AFOSR

1) Atom Pairing in Optical Lattices

- Chingyun Chen completed her Ph. D. thesis on the study of the cross over between atom dimers and polarons in two-dimensional systems (publication 2 above). She employed CO_2 laser trap to provide transverse confinement for atoms trapped in a 1064 nm standing wave. Varying the transverse confinement enabled a study of the transition between quasi-2D and 2D behavior. These experiments resolved a controversy in the spectra of atom pairing in 2D systems. In true 2D, atom pairs behave as simple bound dimers, as predicted by BCS theory in two dimensions. However, for a quasi-2D system, it is found that polaron behavior dominates. Here, loosely bound dimers are larger than the interparticle spacing, and each spin up or spin down atom is surrounded by a cloud of particle-hole pairs. The radio frequency pair-breaking spectra of the true 2D and quasi-2D systems are quite different, and explained by our 2D polaron model.

- Jayampahi Kangara (Kan) completed his Ph. D. thesis on the measurement of atom pairing spectra in a bichromatic superlattice. (publication 3 above). These experiments superposed 1064 nm and 532 nm standing waves with a controllable relative position to create a one dimensional lattice of symmetric or asymmetric double-well potentials. The 532 nm beam was generated by frequency doubling of the 1064 nm beam, to assure a perfect 2:1 frequency ratio, enabling stable control of the double-well asymmetry. Kan precisely measured radio frequency atom pairing spectra, which exhibited a rich structure. This structure was successfully explained using a 9-band lattice model that included harmonic radial confinement from a CO_2 laser trap. The model showed that the center of mass and relative coordinates are entangled. Further, the data and the model revealed that two types of atom pairs co-exist in each double well, with two different symmetries.

2) Fluid dynamics in uniform Fermi gases (NSF primary).

- We have developed a broad new approach for the study of hydrodynamic transport in quantum gases. We employ digital micro-mirror devices (DMD's) to project 6 sheets of repulsive light, creating a box potential and producing a sample of uniform density. The DMD's also enable dynamical control of optical perturbations.

- Lorin Baird completed his Ph. D. thesis on the measurement of the hydrodynamic linear response of the sample, when it is subject to a moving spatially periodic optical perturbation that is dragged through the sample (publication 7 above). By modeling the data with a linearized hydrodynamic model of the coupled changes in the density and entropy, Lorin showed that the time-dependent spatial profile of the cloud could be fit and provided the first information about the thermal conductivity of a resonantly interacting (unitary) Fermi gas.

- Xin Wang greatly extended this work and completed his Ph. D. thesis by developing the method of "hydrodynamic relaxation," which enabled the first independent measurements of the universal thermal conductivity and shear viscosity of a unitary Fermi gas in the normal fluid regime (publication 9 above). In this work, a DMD projects a static, spatially periodic optical perturbation onto a uniform Fermi gas, contained in a box potential. The trapped gas is allowed to reach thermal equilibrium at a uniform temperature, but the density exhibits a spatially periodic perturbation with a selected wavelength. Abruptly extinguishing the perturbing potential causes the spatially periodic component of the density to relax, revealing a two-mode decay comprising an exponentially decaying, thermal diffusive mode and an oscillating, decaying first sound mode. Measurement of the two decay rates independently determines the thermal conductivity and shear viscosity, directly from the time dependent evolution.

We continue to be interested in recently proposed new methods for measuring the bulk viscosity, based on spatio-temporal control of the scattering length in a box potential, which is especially well-suited for our optical control methods.

Outreach

Experiments with ultracold atomic gases are of broad appeal to a general audience.

On Saturday, November 4, 2017, I participated in a Family Day, celebrating the One Hundred Year Anniversary of the Physics Department at North Carolina State University. We had several hundred people attend, comprising families from the area and former alumni and their families. My group gave laboratory tours and I gave a general audience talk on our ultracold atom program.

In April 17, 2019, I gave a general audience talk on "Making optical traps work," for the Lecture Series of the Engineers' Council at NC State University. The broad undergraduate audience included many Freshman, Park Scholars and students with diverse backgrounds in science, engineering, and mathematics.

In the Fall of 2019, Saeed Pegahan, an Iranian Ph. D. student in my group, initiated a visit to the physics department at NCSU and to our laboratories by the staff of North Carolina Senator, Thom Tillis. The purpose of the visit was to impress on the senator the importance of providing stable support for graduate students and to encourage a fast track to citizenship for international Ph. D. students in technology and science. For his effort, Saeed was honored by APS with a Five Sigma Award.

Impacts

Within the discipline

New ideas and new directions for research in ultracold gases have emerged with the demonstration of two-field optical control of scattering interactions in ultracold gases. These new optical methods move the field beyond magnetically controlled collisional (Feshbach) resonances, which have been the workhorses for control of interactions. The new optical methods, with high resolution in space and time, enable broad new studies of nonequilibrium dynamics, on time scales faster than the “Fermi time,” the time for a particle to move a de Broglie wavelength.

Other disciplines

Our research on the optical control of interactions in Fermi gases impacts fields ranging from condensed matter and materials science to neutron matter and high energy physics, and even string theory.

The new methods allow independent control of the scattering length and effective range, enabling better models of neutron matter. Counter-propagating wave control enables momentum-selective pairing, of great interest to the condensed matter community in the context of FFLO states. Conformal field methods have been used to show that spatially uniform fast temporal control of the scattering length of a Fermi gas in a box potential is equivalent to a uniform change in the density, and provides information on the bulk viscosity.

Strongly-interacting two-component Fermi gases provide a unique testing ground for non-perturbative theories of exotic systems in nature, ranging from super-high temperature superconductors to neutron stars and nuclear matter. Condensed matter theory groups are interested in the neutral atom analogs of super high temperature superconductors that are predicted to arise from the tunable resonant interactions achievable in the trapped, neutral atom systems. In the very weakly interacting regime, we have observed spin waves and control of spin current, which is of interest in the "spintronics" community.

In July of 2016, I participated in a *Workshop on Non-Equilibrium Physics and Holography* in Oxford, England, which connects to the conformal field and string theory communities.

In June of 2018, I participated in a workshop in Trento, Italy, entitled *Exploring Nuclear Physics with Ultracold Atoms*. I reported on our recent measurements on unitary Fermi gases, including our initial studies of hydrodynamic flow in box potentials and our latest experiments on optical control of interactions, which enable simulation of neutron matter.

Human Resources

During the period of this grant, 7 graduate students, 2 of them female, completed their Ph.D. theses. In this research, students acquire theoretical background in optical and quantum physics. They are broadly trained in experimental methods, including optical, electronic, mechanical, and vacuum system design, computer control and interfacing, and data acquisition and analysis. These students are particularly well equipped to tackle quantum physics problems, which are currently of national interest.

Society

By testing theoretical models of super-high temperature superconductors, strongly interacting gases may provide a platform for developing losses power transmission systems. Students who participate in this research acquire broad training in optical and quantum physics, and are well situated to tackle problems of current national interest.