AFRL-AFOSR-VA-TR-2016-0132

Nonequilibrium Fermi Gases

John Thomas
North Carolina State University at Raleigh

02/02/2016
Final Report

Air Force Research Laboratory
AF Office Of Scientific Research (AFOSR)/ RTB1
Arlington, Virginia 22203
Air Force Materiel Command

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
04/01/2013	Final	3/1/2013-2/29/2016

4. TITLE AND SUBTITLE
Non-equilbrium Fermi gases

5a. CONTRACT NUMBER
FA9550-13-1-0041

5b. GRANT NUMBER
FA9550-13-1-0041

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
John E. Thomas

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Physics Department, North Carolina State University

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFOSR
875 N RANDOLPH ST
ARLINGTON VA 22203

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release

13. SUPPLEMENTARY NOTES

14. ABSTRACT
During this period, we made important breakthroughs in the optical control of two-body interactions in ultra-cold gases. We have studied magnetic Feshbach resonances in an optically-trapped mixture of the two lowest hyperfine states of a 6Li Fermi gas, using two optical fields to create a dark state in the closed molecular channel. In the experiments, the narrow Feshbach resonance is tuned by up to 3 G. For the broad resonance, the spontaneous lifetime is increased from 0.5 ms for single field tuning to 0.4 s at the dark state resonance, despite the large background scattering length.

A major breakthrough in our understanding is the experimental verification of a new model of light-induced loss spectra, employing continuum-dressed basis states, which agrees in shape and magnitude with all of our loss measurements for both broad and narrow resonances. Using this model, we show that our method substantially reduces the two-body loss rate compared to single field methods for same tuning range.

15. SUBJECT TERMS
Fermi gases, non-equilibrium, optically-controlled interactions

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
			UU		John E. Thomas
					19b. TELEPHONE NUMBER *(Include area code)* 919-515-5966

Reset

INSTRUCTIONS FOR COMPLETING SF 298

1. REPORT DATE. Full publication date, including day, month, if available. Must cite at least the year and be Year 2000 compliant, e.g. 30-06-1998; xx-06-1998; xx-xx-1998.

2. REPORT TYPE. State the type of report, such as final, technical, interim, memorandum, master's thesis, progress, quarterly, research, special, group study, etc.

3. DATES COVERED. Indicate the time during which the work was performed and the report was written, e.g., Jun 1997 - Jun 1998; 1-10 Jun 1996; May - Nov 1998; Nov 1998.

4. TITLE. Enter title and subtitle with volume number and part number, if applicable. On classified documents, enter the title classification in parentheses.

5a. CONTRACT NUMBER. Enter all contract numbers as they appear in the report, e.g. F33615-86-C-5169.

5b. GRANT NUMBER. Enter all grant numbers as they appear in the report, e.g. AFOSR-82-1234.

5c. PROGRAM ELEMENT NUMBER. Enter all program element numbers as they appear in the report, e.g. 61101A.

5d. PROJECT NUMBER. Enter all project numbers as they appear in the report, e.g. 1F665702D1257; ILIR.

5e. TASK NUMBER. Enter all task numbers as they appear in the report, e.g. 05; RF0330201; T4112.

5f. WORK UNIT NUMBER. Enter all work unit numbers as they appear in the report, e.g. 001; AFAPL30480105.

6. AUTHOR(S). Enter name(s) of person(s) responsible for writing the report, performing the research, or credited with the content of the report. The form of entry is the last name, first name, middle initial, and additional qualifiers separated by commas, e.g. Smith, Richard, J, Jr.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES). Self-explanatory.

8. PERFORMING ORGANIZATION REPORT NUMBER. Enter all unique alphanumeric report numbers assigned by the performing organization, e.g. BRL-1234; AFWL-TR-85-4017-Vol-21-PT-2.

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES). Enter the name and address of the organization(s) financially responsible for and monitoring the work.

10. SPONSOR/MONITOR'S ACRONYM(S). Enter, if available, e.g. BRL, ARDEC, NADC.

11. SPONSOR/MONITOR'S REPORT NUMBER(S). Enter report number as assigned by the sponsoring/ monitoring agency, if available, e.g. BRL-TR-829; -215.

12. DISTRIBUTION/AVAILABILITY STATEMENT. Use agency-mandated availability statements to indicate the public availability or distribution limitations of the report. If additional limitations/ restrictions or special markings are indicated, follow agency authorization procedures, e.g. RD/FRD, PROPIN, ITAR, etc. Include copyright information.

13. SUPPLEMENTARY NOTES. Enter information not included elsewhere such as: prepared in cooperation with; translation of; report supersedes; old edition number, etc.

14. ABSTRACT. A brief (approximately 200 words) factual summary of the most significant information.

15. SUBJECT TERMS. Key words or phrases identifying major concepts in the report.

16. SECURITY CLASSIFICATION. Enter security classification in accordance with security classification regulations, e.g. U, C, S, etc. If this form contains classified information, stamp classification level on the top and bottom of this page.

17. LIMITATION OF ABSTRACT. This block must be completed to assign a distribution limitation to the abstract. Enter UU (Unclassified Unlimited) or SAR (Same as Report). An entry in this block is necessary if the abstract is to be limited.

Grant Title: “Nonequilibrium Fermi Gases.”
Grant # FA9550-13-1-0041
Period: 3/1/2013-2/29/2016
Contract Officer: Tatjana Curcic

Abstract (250 words)

We study the control magnetic Feshbach resonances in an optically-trapped mixture of the two lowest hyperfine states of a ^{6}Li Fermi gas, using two optical fields to create a dark state in the closed molecular channel. In the experiments, the narrow Feshbach resonance is tuned by up to 3 G. For the broad resonance, the spontaneous lifetime is increased from 0.5 ms for single field tuning to 0.4 s at the dark state resonance, despite the large background scattering length.

A major breakthrough in our understanding is the experimental verification of a new model of light-induced loss spectra, employing continuum-dressed basis states, which agrees in shape and magnitude with all of our loss measurements for both broad and narrow resonances. Using this model, we predict the trade-off between tunability and loss for the broad resonance in ^{6}Li, showing that our two-field method substantially reduces the two-body loss rate compared to single field methods for same tuning range. We show that the EIT method creates narrow features in the scattering phase shift, enabling control by optical frequency rather than intensity, providing a general method of suppressing unwanted changes in the total trapping potential.

Publications:

1) E. Elliott, J. A. Joseph, and J. E. Thomas, “Observation of Conformal Symmetry Breaking and Scale Invariance in Expanding Fermi Gases,” Phys. Rev. Lett. **112**, 040405 (2014).

2) E. Elliott, J. A. Joseph, and J. E. Thomas, “Anomalous Minimum in the Shear Viscosity of a Fermi Gas,” Phys. Rev. Lett. **113**, 020406 (2014).

3) J. A. Joseph, E. Elliott, and J. E. Thomas, ``Shear viscosity of a unitary Fermi gas near the superfluid phase transition," Phys. Rev. Lett. **115**, 020401 (2015), selected as an *Editor's Suggestion*.

4) A. Jagannathan, N. Arunkumar, J. A. Joseph, and J. E. Thomas, "Optical control of magnetic Feshbach resonances by closed-channel EIT," submitted to Phys. Rev. Lett.

Accomplishments:

1) Optical control of magnetic Feshbach resonances.

During the period of this grant, we have made several breakthroughs in both our theoretical approach and our experimental approach to developing general methods for tuning two-body interactions in ultracold gases, using the frequencies of the optical fields as control parameters. By avoiding intensity changes in the control beams, we implement a general method of avoiding unwanted tuning of the net trapping potential, which arises from both the external trap and the optical beams. Our experiments include the following accomplishments:

- In the first experiments, we developed a diode-laser system for generating two optical fields to excite the strongest v = 38 to v' = 68 transition (control beam) and a much weaker v = 37 to v' = 68 molecular transition (EIT beam) in the closed molecular channel of the 1-2 Feshbach resonance in ^{6}Li. The molecular wavelength is 1.5 nm detuned from the atomic transition, suppressing direct optical scattering. The two fields differ in frequency by 57 GHz, with a frequency jitter < 100 kHz. This is achieved using a master diode laser, which is locked to a saturation resonance in iodine vapor. The master laser enables stabilization of an optical cavity to which two additional diode lasers are locked, generating the control and EIT fields needed to create a dark state in the closed molecular channel of a magnetic Feshbach resonance.
- We have demonstrated up to 3 G tuning of optically induced loss features in the narrow Feshbach resonance of ^{6}Li.
- We have increased the lifetime for the broad resonance from 0.5 ms with a single beam tuning method to 0.4 sec with our two-field EIT method. This is an important achievement, as the very large background scattering length in ^{6}Li, -1405 a_0, produces a very large two-body loss rate constant. A-priori, it was not obvious that this suppression could be achieved in real experiments, which are limited by relative frequency jitter.
- A major breakthrough was achieved recently in locking the diode lasers to the v = 38 to v' = 64 and v = 37 to v' = 64 transitions. As noted in Robin Cote's thesis, these transitions achieve a very good compromise in the strengths of the two coupled transitions. The v = 37 to v' = 64 transition is now so strong that we obtain the same Rabi frequency with 2 mW as we did for the v = 37 to v' = 68 transition with 100 mW, greatly increasing the EIT window.
- We have located and tuned the ^{6}Li p-wave Feshbach resonances. This is very important for studies of the effective range, which can be controlled by the two-field method at the point of minimum loss. The p-wave binding energies are large and strongly dependent on the effective range, making this system optimum for these studies. In addition, this system will enable studies of optically-controlled superfluidity in p-wave systems in reduced dimensions (pancake-shaped traps).

On the theoretical front, we have developed a new continuum-dressed state model of optically controlled magnetic Feshbach resonances. Import results include:

- We have solved a long-standing problem with the theory of optical control for broad Feshbach resonances. All previous treatments of optical control use adiabatic elimination of the excited molecular electronic state in the closed channel to obtain tractable results. Near resonance, this requires that the rate of change of the ground state amplitudes (Rabi frequencies) are smaller than the spontaneous emission rate γ_e. Unfortunately, this method is invalid in the bare basis for broad resonances, where the hyperfine coupling constant is much larger than the γ_e, causing rapid changes in the amplitudes of the bare basis states. Instead, we use the full Feshback resonance scattering states and dressed bound state as the basis. Since the hyperfine coupling is already included in this basis, the amplitudes of these states slowly vary, enabling adiabatic elimination of the excited state amplitude. As the basis is complete and includes correctly the optical couplings, it is valid for narrow resonances as well and reduces prior results valid only in the narrow resonance regime.
- We have validated our dressed-continuum state approach by comparing predictions to measured one- and two-field loss spectra. We find very good agreement in shape and absolute magnitude, using the measured Rabi frequencies.
- We are able to predict the relative momentum dependence of the two-body loss rate constant, enabling a new study of the trade-off between loss and tuning in optical control methods.
- Using the new model, we are able to show that the maximum loss rate the two-field optical control method is much smaller than that of single-field methods, for the same change in the zero energy scattering length. We find that the two-field methods enable symmetrical tuning of the scattering length about the minimum loss point, by changing the optical frequency of the control beam. In contrast, single-field methods achieve low loss only for large detunings, requiring much larger frequency changes than two-field methods for the same change in the scattering length.
- The new model shows that two-field method produces narrow features in the scattering phase shift, demonstrating that optical frequency changes can be used to tune the scattering length, rather than intensity. This provides a general method of avoiding unwanted changes in the effective atom trapping potential as the two-body parameters are tuned.
- Finally, the new model shows that the effective range can be controlled at the point of minimum loss, analogous to the EIT method of controlling dispersion in atomic vapors with suppressed absorption.

2) Thermodynamics of two-dimensional, spin-imbalanced Fermi gases.

3) Scale-invariance and viscosity measurements in strongly interacting Fermi gases.

AFOSR Deliverables Submission Survey

Response ID:5738 Data

1.

1. Report Type

Final Report

Primary Contact E-mail
Contact email if there is a problem with the report.

jethoma7@ncsu.edu

Primary Contact Phone Number
Contact phone number if there is a problem with the report

919-515-5966

Organization / Institution name

North Carolina State University

Grant/Contract Title
The full title of the funded effort.

Nonequilibrium Fermi Gases

Grant/Contract Number
AFOSR assigned control number. It must begin with "FA9550" or "F49620" or "FA2386".

FA9550-13-1-0041

Principal Investigator Name
The full name of the principal investigator on the grant or contract.

John E. Thomas

Program Manager
The AFOSR Program Manager currently assigned to the award

Tatjana Curcic

Reporting Period Start Date

03/01/2013

Reporting Period End Date

02/29/2016

Abstract

We study the control magnetic Feshbach resonances in an optically-trapped mixture of the two lowest hyperfine states of a 6Li Fermi gas, using two optical fields to create a dark state in the closed molecular channel. In the experiments, the narrow Feshbach resonance is tuned by up to 3 G. For the broad resonance, the spontaneous lifetime is increased from 0.5 ms for single field tuning to 0.4 s at the dark state resonance, despite the large background scattering length.

A major breakthrough in our understanding is the experimental verification of a new model of light-induced loss spectra, employing continuum-dressed basis states, which agrees in shape and magnitude with all of our loss measurements for both broad and narrow resonances. Using this model, we predict the trade-off between tunability and loss for the broad resonance in 6Li, showing that our two-field method substantially reduces the two-body loss rate compared to single field methods for

same tuning range. We show that the EIT method creates narrow features in the scattering phase shift, enabling control by optical frequency rather than intensity, providing a general method of suppressing unwanted changes in the total trapping potential.

Distribution Statement
This is block 12 on the SF298 form.

Distribution A - Approved for Public Release

Explanation for Distribution Statement
If this is not approved for public release, please provide a short explanation. E.g., contains proprietary information.

SF298 Form
Please attach your SF298 form. A blank SF298 can be found here. Please do not password protect or secure the PDF The maximum file size for an SF298 is 50MB.

AFD-070820-035-JET-2016.pdf

Upload the Report Document. File must be a PDF. Please do not password protect or secure the PDF . The maximum file size for the Report Document is 50MB.

AFOSRFinalReport-1-22-2016.pdf

Upload a Report Document, if any. The maximum file size for the Report Document is 50MB.

Archival Publications (published) during reporting period:

1)E. Elliott, J. A. Joseph, and J. E. Thomas, "Observation of Conformal Symmetry Breaking and Scale Invariance in Expanding Fermi Gases," Phys. Rev. Lett. 112, 040405 (2014).

2)E. Elliott, J. A. Joseph, and J. E. Thomas, "Anomalous Minimum in the Shear Viscosity of a Fermi Gas," Phys. Rev. Lett. 113, 020406 (2014).

3)J. A. Joseph, E. Elliott, and J. E. Thomas, ``Shear viscosity of a unitary Fermi gas near the superfluid phase transition," Phys. Rev. Lett. 115, 020401 (2015), selected as an Editor's Suggestion.

4)A. Jagannathan, N. Arunkumar, J. A. Joseph, and J. E. Thomas, "Optical control of magnetic Feshbach resonances by closed-channel EIT," submitted to Phys. Rev. Lett.

Changes in research objectives (if any):

Change in AFOSR Program Manager, if any:

Extensions granted or milestones slipped, if any:

AFOSR LRIR Number

LRIR Title

Reporting Period

Laboratory Task Manager

Program Officer

Research Objectives

Technical Summary

Funding Summary by Cost Category (by FY, $K)

	Starting FY	FY+1	FY+2
Salary			
Equipment/Facilities			
Supplies			
Total			

Report Document

Report Document - Text Analysis

Report Document - Text Analysis

Appendix Documents

2. Thank You

E-mail user

Jan 27, 2016 13:21:24 Success: Email Sent to: jethoma7@ncsu.edu

Response ID: 5738

Survey Submitted:	Jan 27, 2016 1:21 PM
IP Address:	152.1.52.142
Language:	English (en-US,en;q=0.5)
User Agent:	Mozilla/5.0 (Windows NT 6.1; rv:43.0) Gecko/20100101 Firefox/43.0
Http Referrer:	http://www.wpafb.af.mil/library/factsheets/factsheet.asp?id=9389
Page Path:	1 : (SKU: 1) 2 : Thank You (SKU: 2)
SessionID:	1453917858_56a906a26e52d6.05176976

Response Location

Country:	United States
Region:	NC
City:	Raleigh
Postal Code:	27606

Long & Lat:	Lat: 35.746299743652, Long:-78.723899841309