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Quantum Simulation of Optical Conductivity

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Final Technical Report

Air Force Research Laboratory
Air Force Office of Scientific Research
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Annual Report for FA9550-19-1-0365
Support period: 15 Sept 2019 - 14 Sept 2023
"Quantum Simulation of Optical Conductivity"

PI: Joseph H. Thywissen, University of Toronto
Program Officer: Dr. Grace Metcalfe, AFOSR

Abstract:

In this project, we investigated fundamental properties of quantum degenerate fermions. Competed work includes the first observation of unitary p-wave interactions, and the benchmarking of theoretical models relevant to strong orbital interactions. Technical development of an optical lattice quantum simulator resulted in colder atoms, higher fidelity in-situ imaging, and more robust operation. Theoretical development included a non-perturbative treatment of strong scattering in a lattice. The impact of the project is an expansion of models accessible to quantum simulation by neutral atoms.

Accomplishments

The **research objective** given in the proposal for this project is *"We will investigate fundamental transport properties of quantum degenerate fermions in crystalline environments. In particular, we will use ultracold neutral atoms as a quantum simulator of technologically relevant models that encapsulate the essence of electronic properties of crystalline materials. By tuning the parameters of our simulator, we will test our ability to understand strongly correlated physics relevant to quantum materials of technological interest."*

The details of accomplishments are as follows. Our **major activities** included spectroscopy of p-wave interacting fermions in an optical lattice; technical development of our quantum simulator; and theoretical advances in understanding of conductivity for strongly interacting fermions. The **significant outcomes** included the first observation of unitary elastic p-wave interactions between fermions, and the discovery of an emergent s-wave interaction in low-dimensional systems with underlying p-wave interactions. Both of these are communicated in refereed international journals (see deliverables, below, for full citations). Plans in our original proposal that were not complete include new measurements of conductivity for strongly interacting fermions. Data acquisition was underway on this objective by the end of the funded project period.

Impacts:

This project resulted in three types of impacts:

1. **Development of the principal discipline of the project.** The principle discipline of the project is atomic, molecular, and optical (AMO) physics. Within this umbrella, the project platform is ultracold neutral atoms. Experimental and theoretical investigations within this discipline normally only consider interactions with spherical symmetry, akin to head-on collisions in the classical limit. Our published works investigate and measure interactions with rotational momentum, called 'p-wave'. They are akin to spinning or twirling motion in the classical world. At the quantum level, the

impact of this new type of interaction is to extend quantum simulations to include the intricate orbital patterns found in some materials.

2. **Development of human resources.** The human resources developed during this project are training of highly qualified personnel at the graduate, undergraduate, and postdoctoral level. Across four years, six graduate degrees in physics were earned by AFOSR-supported students. Overall, ten students developed their skills in research. Names and degree status of all personnel are listed in 'Deliverables', below.

3. **Physical resources that form infrastructure.** Intense technical development of a quantum simulator was a major outcome of this project. The simulator is now better positioned for cutting-edge investigations of iconic models of materials.

Technical report narrative for final year of support: (Sept 2022 - Sept 2023; for 2019-2022, see prior annual reports)

In September 2022, several laser systems were upgraded. A cavity lock was implemented for the far-detuned Raman beams and for photo-association (PA). Wide frequency-detuning ranges were accessed using a Vortex seed laser, while a Moglabs laser was sent to the manufacturer for repair. The optical-lattice source optics were overhauled, enabling the highest potential depths yet achieved in the lab.

From August 2022 to January 2023, we explored photo-association of fermionic potassium in an optical lattice. PA was a "bug" found when developing spin-flip Raman transitions in the lattice; in that case, we chose the excited-state detunings of the Raman beams to avoid excited-state PA resonances. In a new round of data, we intentionally tuned to these PA resonances, in order to understand the spectrum and explore their use as a correlation detector.

Eight PA lines were found in a detuning range of -40GHz to -53GHz from resonance. Surprisingly, the observed linewidths varied from 25MHz to 250MHz. Spectra taken at variable power confirmed that these widths were not due to power broadening. The explanation of these spectra remains unclear; discussion with molecular-physics theorists is ongoing. No prior high-field PA data of $^{40}K_2$ has been reported.

Earlier PA work with fermionic lithium was interpreted as a probe of the s-wave contact parameter. For fermionc potassium, near its 202G s-wave Feshbach resonance, we compared the PA rate to the known variation of contact in our gas. The scaling we found was not universal: i.e., the PA rate was not simply proportional to the closed-channel fraction of the interacting gas. The intermediate conclusion of this investigation is that the conditions of universality for PA as probe of the contact have yet to be clarified. Our measurements motivation theoretical investigation of this question, through multi-channel analysis.

From January to February 2023, we improved evaporative cooling of our ultracold Fermi gas. A spurious magnetic-field gradient associated with the Feshbach coil was eliminated, enabling evaporation of a spin mixture at high field. By tuning the interaction strength between spin states, we were able to optimize cooling, and achieve a temperature of 0.05 times the fermi energy, which was an in-lab record, and comparable to the state of the art. The reliability of thermometry was improved by higher image quality.

A key technical advance (April - July 2023) was systematic improvement of in-situ imaging. Recent published work has not required in-situ imaging, and its performance had declined. A new generation of students rebuilt the imaging stack to motorize & optimize dichroic filtering. Improved alignment eliminated an astigmatism that had plagued images in recent years. Analysis code was improved.

From July through September 2023, we returned to a central goal of this AFOSR project: measuring conductivity in an optical lattice. We tried a new method of step response, which allowed for a faster probe of particular conditions. Data acquisition has continued beyond the end of the nominal support period.

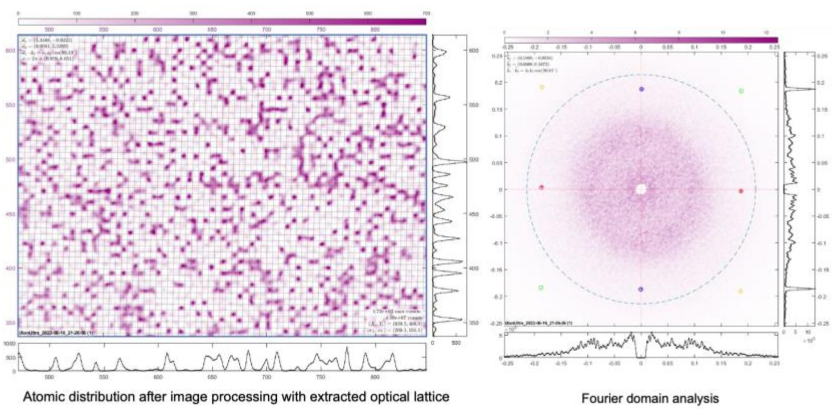

Figure 1: (Left:) Fluoresce image of fermions in an optical lattice. Each dot is a single atom; the grid is determined by an algorithm in post processing. (Right:) The Fourier transform of the image revels clear peaks at the lattice periodicity. This guides the selection of the grid seen in the real-space image.

<u>**Changes**</u>:

Problems or delays: Experimental progress on this project was affected by public health measures taken against the spread of COVID-19. The University of Toronto shut down all laboratory work in late March 2020. A staged re-opening occurred, with operations at 60% personnel level being the norm for roughly one year. Adaptations are as follows: first, we have re-analyzed previously existing data; second, we have used this pause to design and implement a series of technical improvements designed to enhance autonomy of the experimental apparatus.

Changes in approach: Discovery of near-unitary p-wave interactions presented an unexpected (but welcome) opportunity during the support period. This provoked a change in scientific agenda during our recovery from COVID and resulted in a high-profile scientific result. Concurrent theoretical and technical development also made significant progress towards the original objectives of the project.

Deliverables:

Directly Supported Students:
R. Anderson (PhD 2020)
D. Bates (MSc 2021)
F. Corapi (PhD candidate)
B. Driesen (PhD candidate)
R. Learn (MSc; PhD candidate)
K. Jackson, PhD (expected Dec 2023)
V. Venu (PhD 2022)
P. Xu (PhD 2022)
C. Fujiwara (Postdoctoral fellow)
K. Li (undergraduate summer student)

Degrees granted:
Rhys Anderson (PhD Dec 2020)
Darby Bates (MSc Jan 2021)
Vijin Venu, PhD (Sept 2022)
Peihang Xu, PhD (Dec 2022)
Robyn Learn, MSc (Aug 2022)
Sukhman Singh, MSc (Sept 2023)

Publications (all with acknowledgement of support from AFOSR):

D. J. M. Ahmed-Braun, K. G. Jackson, S. Smale, C. J. Dale, B. A. Olsen, S. J. J. M. F. Kokkelmans, P. S. Julienne, and J. H. Thywissen
Probing open- and closed-channel p-wave resonances
Physical Review Research **3**, 033269 (2021)
[doi: 10.1103/PhysRevResearch.3.033269]

M. Mamaev, P. He, T. Bilitewski, V. Venu, J. H. Thywissen, and A. M. Rey
Collective p-wave orbital dynamics of ultracold fermions
Physical Review Letters **127**, 143401 (2021)
[doi: 10.1103/PhysRevLett.127.143401]

K. G. Jackson, C. J. Dale, J. Maki, K. G. S. Xie, B. A. Olsen, D. J. M. Ahmed-Braun, Shizhong Zhang, and J. H. Thywissen
Emergent s-wave interactions between identical fermions in quasi-one-dimensional geometries
Physical Review X **13**, 201013 (2023)
[doi:10.1103/PhysRevX.13.021013]

V. Venu, P. Xu, M. Mamaev, F. Corapi, T. Bilitewski, J. P. D'Incao, C. J. Fujiwara, A. M. Rey, and J. H. Thywissen
Unitary p-wave interactions between fermions in an optical lattice
Nature **613**, 262–267 (2023)
[doi: 10.1038/s41586-022-05405-6]

Contributions to conferences during final year of support: (others listed in prior annual reports)

5 contributions by group members to DAMOP'23 -- The 54th Meeting of the APS Division of Atomic, Molecular, and Optical Physics (Spokane, Washington, 5-9 June 2023):

- "Probing two-body interactions in a deep three-dimensional optical lattice" [poster presentation], Presenter: Robyn Learn
- "Measuring two-body correlations via photoexcitation of 40K2 in an optical lattice" [oral presentation], Presenter: Frank Corapi
- "Associating emergent s-wave dimers along strongly confined directions of a spin-polarized Fermi gas" [oral presentation]; presenter: Kevin Xie
- " Emergent s-wave interactions in low-dimensional systems of a spin-polarized Fermi gas " [poster]; presenter: C. Dale
- " Orbital interactions between strongly confined fermions " [invited oral presentation]; presenter: J. Thywissen

ICPEAC (Ottawa, Ontario, 26 July - 1 August, 2023): "Associating emergent s-wave dimers along strongly confined directions of a spin-polarized Fermi gas" [K. Xie]

BEC-2023: Frontiers in Quantum Gases (St Feliu de Guixols, Spain, 9-15 September 2023): "Orbital interactions between strongly confined fermions" [J. Thywissen, invited]

Seminars during final year of support: (others listed in prior annual reports)

Colloquium of the International Centre for Theoretical Physics (Sao Paulo, Brazil, 15 March 2023), 1 hour

Lecturer, School on Light and Cold Atoms, ICTP-SAIFR (Sao Paulo, 6-17 March 2023), 4.5 hours

Cavendish Laboratories, Cambridge University (14 October 2022), 1 hour

Honors awarded to group members:

-Kevin Xie**, NSERC CGS-M** (2021)

-Dr. Cora Fujiwara**, CQIQC Prize Postdoctoral Fellowship** (2020-2023)

-Robyn Learn, **FAST Scholarship** (May 2022)

-Kiera Augusto, **NSERC CGSM** (April 2023)

-Frank Corapi, **NSERC CGSD** (May 2023)

-Robyn Learn, **NSERC PGSD** (May 2023)

REPORT OF INVENTIONS AND SUBCONTRACTS

(Pursuant to "Patent Rights" Contract Clause) (See Instructions on back)

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SECTION I - SUBJECT INVENTIONS

5. "SUBJECT INVENTIONS" REQUIRED TO BE REPORTED BY CONTRACTOR/SUBCONTRACTOR *(If "None," so state)*

NAME(S) OF INVENTOR(S) *(Last, First, Middle Initial)* a.	TITLE OF INVENTION(S) b.	DISCLOSURE NUMBER, PATENT APPLICATION SERIAL NUMBER OR PATENT NUMBER c.	ELECTION TO FILE PATENT APPLICATIONS (X) d. (1) UNITED STATES (a) YES	(1) UNITED STATES (b) NO	(2) FOREIGN (a) YES	(2) FOREIGN (b) NO	CONFIRMATORY INSTRUMENT OR ASSIGNMENT FORWARDED TO CONTRACTING OFFICER (X) e. (a) YES	e. (b) NO
None	None	None						

f. EMPLOYER OF INVENTOR(S) NOT EMPLOYED BY CONTRACTOR/SUBCONTRACTOR

(1)	(2)
(a) NAME OF INVENTOR *(Last, First, Middle Initial)*	(a) NAME OF INVENTOR *(Last, First, Middle Initial)*
(b) NAME OF EMPLOYER	(b) NAME OF EMPLOYER
(c) ADDRESS OF EMPLOYER *(Include ZIP Code)*	(c) ADDRESS OF EMPLOYER *(Include ZIP Code)*

g. ELECTED FOREIGN COUNTRIES IN WHICH A PATENT APPLICATION WILL BE FILED

(1) TITLE OF INVENTION	(2) FOREIGN COUNTRIES OF PATENT APPLICATION

SECTION II - SUBCONTRACTS *(Containing a "Patent Rights" clause)*

6. SUBCONTRACTS AWARDED BY CONTRACTOR/SUBCONTRACTOR *(If "None," so state)*

NAME OF SUBCONTRACTOR(S) a.	ADDRESS *(Include ZIP Code)* b.	SUBCONTRACT NUMBER(S) c.	FAR "PATENT RIGHTS" d. (1) CLAUSE NUMBER	d. (2) DATE *(YYYYMM)*	DESCRIPTION OF WORK TO BE PERFORMED UNDER SUBCONTRACT(S) e.	SUBCONTRACT DATES *(YYYYMMDD)* f. (1) AWARD	f. (2) ESTIMATED COMPLETION
None							

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a. NAME OF AUTHORIZED CONTRACTOR/SUBCONTRACTOR OFFICIAL *(Last, First, Middle Initial)*: Drew Gyorke

b. TITLE: Director, Agency & Foundation Funding

c. SIGNATURE: DocuSigned by: Drew Gyorke 5AAD7FAA1C774B3...

d. DATE SIGNED: 12/12/2023

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