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Studying emergent phenomena driven by interactions in a momentum-space lattice

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This Young Investigator Program (YIP) award focused on development of the synthetic latticebased approach to quantum simulations, in which quantum transport problems can be studied not using spatial lattices, but rather through the evolution of population in alternative degrees of freedom such as spin states or other non-spatial eigenstates. In particular, this award focused on our group's momentum-state lattice approach to Hamiltonian engineering with ultracold atoms, and even more specifically on advancing the state-of-the-art for the incorporation of interaction effects in synthetic lattice or synthetic dimensions experiments.

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Final Project Report for Award - FA9550-18-1-0082

"Studying Emergent Phenomena Driven by Interactions in a Momentum-Space Lattice"

This Young Investigator Program (YIP) award focused on development of the synthetic lattice-based approach to quantum simulations, in which quantum transport problems can be studied not using spatial lattices, but rather through the evolution of population in alternative degrees of freedom such as spin states or other non-spatial eigenstates. In particular, this award focused on our group's momentum-state lattice approach to Hamiltonian engineering with ultracold atoms, and even more specifically on advancing the state-of-the-art for the incorporation of interaction effects in synthetic lattice or synthetic dimensions experiments.

Over the past decade, several "synthetic lattice" or "synthetic dimensions" platforms based on hyperfine states and long-lived electronic states ("optical clock" states) have been developed in ultracold gases of neutral atoms. However, due to a conspiracy of sorts (nearly identical scattering lengths between different sets of internal states), there has been a dearth of evidence for interaction effects in these platforms based on internal states. In our approach based on momentum states, however, mode-dependent interactions appear naturally in bosonic systems at the level of the mean-field energy, and can be expected to give rise to nonlinear phenomena in this platform. These interactions additionally hold the potential to drive squeezing between modes of a momentum-state synthetic lattice, which would be advantageous for quantum-enhanced atom interferometry. In this YIP, we set out to harness the interactions between atoms evolving in synthetic lattices of momentum states, and to observe new kinds of resulting nonlinear phenomena. We set out to develop and enhance such capabilities along several fronts – observing their influence on dynamics in one-dimensional (1D) synthetic lattices of momentum states, expanding the scope of nonlinear phenomena by developing the capabilities for designing synthetic momentum-state lattices, and developing the ability to control interactions through a Feshbach resonance to enable the exploration of interaction-driven entanglement.

In this Final Report, we report on the progress along these various lines of advancement. In 1D momentum-state lattices, we have explored the role of interactions in driving nonlinear phenomena, both in regular lattices [1,2,3] and in quasiperiodic lattices hosting novel mobility edges [4]. We have identified a path to engineer large classes of momentum-state lattices in 2D (and 3D) based on a new laser-driving scheme [5], which will significantly expand the scope of nonlinear phenomena that may be explored in this platform. Finally, we have proceeded with a change of atomic species from rubidium-87 to potassium-39 (along with an associated renovation of our experimental apparatus), and are just now finishing the work to regain quantum degeneracy in this system. This change of species, to one with a broad and accessible Feshbach resonance, will enable the control of interactions (through tuning of the scattering length by the magnetic bias field) and pave the way towards explorations of interaction-driven entanglement.

1) Major Accomplishments

Observations of strong interaction effects in synthetic momentum state lattices

The major accomplishment under this award relates to the exploration of strong interaction effects in several types of engineered momentum state lattices. As we discussed at the outset, such experiments establishing strong interaction effects in a synthetic lattice platform are unique and important in the development of this approach. Synthetic lattices, formed by directly coupling non-traditional eigenstates (which play the role of sites) through field-driven transitions (either by lasers, microwaves, or rf) have been shown to enable new capabilities for the quantum simulation of unique model systems [6]. In particular, they allow for new capabilities in the engineering of artificial gauge fields for cold atoms, and are one of the most promising platforms for the exploration of quantum Hall physics – and eventually the realization of fractional quantum Hall matter – with cold atoms. Momentum state lattices are the only synthetic lattice platform to display significant interaction effects, and our group is leading the development of this platform, and as such these experiments play a crucial role in working towards the goals of exploring interaction-driven phenomena in novel lattices (such as disordered lattices, Hofstadter models, and various topological band structures) with cold atoms.

Under this award, we first found direct evidence for strong mode-dependent interactions in a minimal synthetic momentum state lattice with only two sites [1]. This exploration was important for establishing the understanding of these interactions and how they contribute to nonlinear phenomena in this platform. Second, we expanded from the minimal lattice system to explore the types of phenomena that would arise due to interactions in a simple multi-site array [2]. This work [2] includes experiments on macroscopic self-trapping in the array, interaction-deformed Bloch oscillations in the presence of a site-energy gradient, and studies of how interactions modify the current-phase relationship in a multi-site array. This effort has been in collaboration with the theory groups of Kaden Hazzard at Rice University and Chuanwei Zhang at UT Dallas to understand and numerically capture these experimental results in full detail. This work is nearly ready to be submitted, but has been delayed due to COVID-19 and the graduation of the primary author. The writing up of this work will be concluded in the coming weeks and months, and submitted for publication.

Beyond simple synthetic lattices with uniform properties, we have used the novel capabilities of this platform to also explore how interactions enrich the behavior and dynamics in more interesting settings. In one recent study, we have explored how our local control of hopping amplitudes and phases can be used to enable faster-than-adiabatic approaches to quantum state manipulations [3]. Additionally, we found that the nonlinear atomic interactions had a nontrivial impact on the investigated state transformations, in some cases allowing for more robust state transfer aided by interactions. More recently, we have investigated the impact of nonlinear atomic interactions on a novel type of quasiperiodic lattice system that supports localized states and a unique kind of mobility edge [4]. Specifically, it hosts an analytical mobility edge in just one dimension – a curiosity that results from the special form of the quasiperiodic site-energy modulation. Our synthetic lattice approach, which allows for the unique control of all site energies and site-to-site hopping terms in 1D, is likely the only cold-atom based architecture that could be used to study this model system. We found experimental evidence for the mobility edge in this system, and even observed and characterized how the atomic interactions shifted the localization transitions and the mobility edge itself. This work [4], in collaboration with our local condensed matter collaborator (Smitha Vishveshwara, UIUC) and the theorists who proposed the model system (Jed Pixley, Rutgers ; Sriram Ganeshan, CCNY/CUNY), was recently accepted for publication in *PRL* and chosen as an Editor's Suggestion.

Development of method for engineering momentum synthetic lattices in higher dimensions

For the exploration of nontrivial, interaction-driven phenomena in synthetic momentum state lattices, it is crucial that we can both harness the mode-dependent atomic interactions (as discussed in the preceding section) and engineer novel synthetic lattices that support intriguing nonlinear phenomena. For example, some areas of interest would be in the exploration of nonlinear modes supported in topological band structures. Along the latter direction, one major accomplishment of this award has been the discovery of a path to scaling up our momentum state synthetic lattice technique to two (and higher) dimensions, by means of driving with additional laser beams in a coordinated manner [5]. Unlike in 1D, one cannot engineer *any* lattice tight-binding model in 2D, however a wide range of lattices can be engineered, including with disorder, artificial gauge fields, flat bands due to kinetic frustration, and other various features of interest. The implementation of 2D synthetic lattices will greatly expand the scope of nonlinear, interaction-driven phenomena that may be explored in this synthetic lattice platform. Additionally, the promotion to 2D may have some impact and consequence for atom interferometry in closed spatial loops (*i.e.*, Sagnac interferometry).

Change of atomic species for the control of atomic interactions

Finally, one of the main accomplishments under this award relates to the change of atomic species to potassium-39, which has a broad Feshbach resonance allowing for the convenient control of atomic scattering properties. While we initially anticipated that this change of species – from the breaking of vacuum and swapping of source and science cells, to the redevelopment of all laser systems for cooling and imaging – would take roughly 1 year, the progress on this front has been delayed due to the COVID-19 pandemic. Specifically, the ability for the students working on this project to get into the lab and make progress on this front has been impacted since March 2020, with several months of complete shutdown followed by a decrease from the usual in-lab activities since a return to work schedule began in mid-summer 2020. Despite these setbacks, we are now in the closing stages of regaining quantum degeneracy (Bose-Einstein condensation), now with potassium-39, which would pave the way for the control of atomic interactions in our momentum state synthetic lattice platform.

2) Products and products in preparation

Peer-reviewed papers

- *Correlated dynamics in a synthetic lattice of momentum states.*
  Fangzhao Alex An*, Eric J. Meier*, Jackson Ang'ong'a, and Bryce Gadway
  Physical Review Letters **120**, 040407 (2018)

- *Counterdiabatic control of transport in a synthetic tight-binding lattice.*
  Eric J. Meier, Kinfung Ngan, Dries Sels, and Bryce Gadway
  Physical Review Research **2**, 043201 (2020) – selected as *Editor's Suggestion*

- *Interactions and mobility edges: Observing the generalized Aubry-Andre model.*
  Fangzhao Alex An, Karmela Padavic, Eric J. Meier, Suraj Hegde, Sriram Ganeshan, J. H. Pixley, Smitha Vishveshwara, and Bryce Gadway
  Physical Review Letters **126**, 040603 (2021) – selected as *Editor's Suggestion*

List of papers still in preparation for submission

- *Nonlinear dynamics in a synthetic bosonic Josephson junction array.*
  Fangzhao Alex An, Bhuvanesh Sundar, Junpeng Hou, Xiwang Luo, Eric J. Meier, Chuanwei Zhang, Kaden R.A. Hazzard, and Bryce Gadway

- *Two-dimensional synthetic momentum state lattices.*
  Shraddha Agrawal, Sai Naga Manoj Paladugu, Fangzhao Alex An, and Bryce Gadway

- *Spectroscopy of one-dimensional momentum-space lattices.*
  Sai Naga Manoj Paladugu*, Tao Chen*, Fangzhao Alex An*, Bo Yan, and Bryce Gadway

To note, finalizing these papers for submission has been hampered by the onset and continuation of the COVID-19 pandemic. One of the primary authors, Fangzhao Alex An, graduated during the pandemic in May 2020 and began employment directly thereafter. PI Gadway has taken up primary writing responsibilities for this work, but has kept somewhat busy with childcare duties during the shutdown. We expect that the first of these works will be finished and submitted in the coming weeks, and that the others will be finished and submitted by the summer of 2021.

Summary

Through this YIP award, we have pushed forward the state of the art in synthetic lattice (or synthetic dimensions) approaches to quantum simulation. In particular, using a platform of synthetic lattices based on laser-coupled atomic momentum states, we have demonstrated significant interaction effects leading to nonlinear phenomena such as self-trapping and interaction-shifted localization. We have developed a path towards exploring interacting quantum Hall matter in scalable 2D synthetic lattice architectures, through the identification of a protocol for implementing 2D synthetic momentum state lattices. Finally, we have nearly completed the achievement of Bose-Einstein condensation for a species of atom with tunable interactions, which would allow us to controllably tune interactions in this synthetic lattice platform.

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[5] – S. Agrawal, S. N. M. Paladugu, F. A. An, and B. Gadway, *in preparation*.

[6] – E. J. Meier, F. A. An, A. Dauphin, M. Maffei, P. Massignan, T. L. Hughes, and B. Gadway, *Science* **362**, 6417 (2018).