Q 26: Quantum Gases (Fermions)

Time: Wednesday 10:30–12:30 Location: Q-H10

Q 26.1 Wed 10:30 Q-H10

Observation of Cooper Pairs in a Mesoscopic 2D Fermi Gas — •Marvin Holten, Luca Bayha, Keerthan Subramanian, Sandra Brandstetter, Carl Heintze, Philipp Lunt, Philipp Preiss, and Selim Jochim — Physics Institute, University of Heidelberg, Germany

Pairing is the fundamental requirement for fermionic superfluidity and superconductivity. To understand the mechanism behind pair formation is an ongoing challenge in the study of many strongly correlated fermionic systems.

In this talk, I present the direct observation of Cooper pairs in our experiment [1]. We have implemented a fluorescence imaging technique that allows us to extract the full in-situ momentum distribution with single particle and spin resolution. We apply it to a mesoscopic Fermi gas, prepared deterministically in the ground state of a two-dimensional harmonic oscillator. Our ultracold gas allows us to tune freely between a completely non-interacting unpaired system and weak attractions where we find Cooper pair correlations at the Fermi surface. When increasing the interactions even further, the pair character is modified and the pairs gradually turn into tightly bound dimers. The collective behaviour that we discover in our mesoscopic system is closely related to observations in nuclear physics or metallic grains. Our method provides a new pathway to study many of the outstanding questions concerning fermionic pairing, for example in imbalanced systems or the normal phase.

[1] Arxiv Preprint: arXiv:2109.11511 (2021)

Q 26.2 Wed 10:45 Q-H10

Towards a New Experiment for Programmable Quantum Simulation using Li-6 Fermions — •Tobias Hammel[1], Maximilian Kaiser[1], Micha Bunjes[1], Philipp Preiss[2], Matthias Weidemüller[1], and Selim Jochim[1] — [1]Physics Institute, University of Heidelberg, Germany — [2]Max-Planck-Institute for Quantum Optics, Garching, Germany

The versatility and usability of quantum simulation using ultracold atoms is often limited by the amount of data one can collect in a given time to achieve sufficiently good statistics. This is true in particular for measurements of phase diagrams or higher order correlations where many parameters are tuned simultaneously. In this new Lithium-6 experiment built at Heidelberg University this issue is addressed with the goal to reduce cycle times to below one second to make a step towards programmable quantum simulation.

In this talk, I will give an overview of the already implemented features designed to enable high cycle rates, in particular the compact vacuum system including an octagonal, nano-texture coated glass cell, versatile magnetic field coils and a 0.66 NA objective, as well as giving an outlook on the next steps including the optical dipole trap setup at 532 and 1064nm.

A very compact setup using a 2D-MOT allows to shrink the size of the vacuum apparatus to less than 50cm. The optical setup to manipulate the system has been designed in a modular way to easily update or exchange individual parts. From this we expect an increase in stability of the setup and higher fidelities, repeatability and debuggability.

Q 26.3 Wed 11:00 Q-H10

Mesoscopic Fermion systems in rotating traps — •Philipp Lunt, Paul Hill, Diana Körner, Johannes Reiter, Selim Jochim, and Philipp Preiss — Physikalisches Institut, Im Neuenheimer Feld 226, 69120 Heidelberg

The equivalence of charged particles in external magnetic fields and neutral atoms in rapidly rotating traps opens up new avenues to study quantum hall physics with ultracold atomic gases.

In order to access the microscopic level of strongly correlated states we build on our previously established experimental methods - the deterministic preparation of ultracold ^{6}Li few Fermion systems in low dimensions [1,2], as well as local observation of their correlation and entanglement properties on the single atom level [3].

Here, we present current experimental progress towards adiabatic preparation of deterministic mesoscopic fermion systems in rapidly rotating optical potentials. We showcase the optical setup, in particular the generation of interfering a Gaussian and Laguerre-Gaussian mode to achieve rotation [4]. Moreover, we show first experimental results of the new setup.

[1] Serwane et al. Science 332 (6027), 336-338 [2] Bayha et al. Nature 587, 583-587 (2020) [3] Bergschneider et al. Nat. Phys. 15, 640-644 (2019) [4] Palm et al 2020 New J. Phys. 22 083037

Q 26.4 Wed 11:15 Q-H10

Realising the Symmetry-Protected Haldane Phase in Fermi-Hubbard Ladders — •Dominik Bourgund[1], Sarah Hirthe[1], Pimonpan Sompet[1,2], Thomas Chalopin[1], Joannis Koepsell[1], Petar Bojovic[1], Guillaume Salomon[3], Julian Bibo[4], Ruben Verresen[5], Frank Pollmann[4], Christian Gross[1,6], Immanuel Bloch[1,7], and Timon A. Hilker[1] — [1]Max-Planck-Institut für Quantenoptik, Garching, Germany — [2]Research Center for Quantum Technology, Chiang Mai, Thailand — [3]Universität Hamburg, Germany — [4]Technical University of Munich, Garching, Germany — [5]Harvard University, Cambridge, MA, USA — [6]Eberhard Karls Universität, Tübingen, Germany — [7]Ludwig-Maximilians-Universität, München, Germany

The antiferromagnetic spin-1 Haldane chain with its symmetry-protected fourfold-degenerate edge states was instrumental in understanding the impact of topological properties on quantum phases of matter. Its bulk exhibits vanishing two-point correlations, gapped excitations, and a characteristic non-local order parameter. Here we report on the realisation of such a topological Haldane phase using ultracold atoms in Fermi-Hubbard ladders. Exploiting the capabilities of our quantum gas microscope, we perform single-site and spin-resolved measurements to calculate non-local correlation functions, revealing the topological order as well as localised spin-1/2 edge states. By tuning the interactions in the system, we explore the transition from the Heisenberg limit into the Hubbard regime and thus show the robustness of the phase with respect to charge fluctuations.

Q 26.5 Wed 11:30 Q-H10

Emergence of a quantum phase transition in a few-fermion system — •Keerthan Subramanian[1], Luca Bayha[1], Marvin Holten[1], Ralf Klemt[1], Johannes Bjerlin[2], Stephanie Riemann[2], Georg Bruun[3], Philipp Preiss[1], and Selim Jochim[1] — [1]Physikaliches Insitut, Universität Heidelberg — [2]Lund University — [3]Aarhus University

Phase transitions are collective macroscopic transformations that arise in many-body systems due to competing energy scales. In this talk we try to address the minimum instance where precursors of such a phase transition can be observed for as little as 6 and 12 particles.

We deterministically prepare low entropy samples of closed-shell fermionic 6Li atoms in a 2D harmonic oscillator potential. With the ability to control interactions with a Feshbach resonance, this model system is used to explore competing energy scales. The collective modes in such a system are probed with interaction modulation spectroscopy which reveals that the lowest monopole mode(s) show a non-monotonic behavior reminiscent of the Normal-Superfluid transition in the many-body limit and the associated Higgs mode. Observation that this mode(s) consists mainly of pair excitations and features an asymptotic gap closing with increasing particle number provide evidence in favor of this association to the many-body limit. The trapping potential introduces a single particle gap in the system which leads to a long lived Higgs mode precursor which is demonstrated.

Subsequent experiments on the microscopy of such and spin-imbalanced systems are alluded to.

Q 26.6 Wed 11:45 Q-H10

Matterwave microscopy of 2D few-fermion systems — •Sandra Brandstetter, Keerthan Subramanian, Carl Heintze, Marvin Holten, Philipp Preiss, and Selim Jochim — Physics Institute, University of Heidelberg, Germany

Recent advances in deterministic preparation of ultracold few-fermion systems in combination with a spin resolved time-of-flight imaging technique with single particle resolution, have led us to the first observation of Pauli crystals [2] - demonstrating correlations in a non-interacting system due to quantum statistics - and Cooper pairing between interacting atoms in different spin states [3]. However, the exploration of correlations in real space has so far remained elusive, owing to the small system size, which we cannot resolve with our optical imaging setup.

In this talk we present the addition of a matter wave microscopy scheme [4], enabling us to access the spatial distribution of our atoms. While the initial spatial distribution is too small to resolve with our imaging setup, we can easily magnify it by a factor of 30, using a combination of two T/4 evolutions in traps with different trapping frequencies. This allows us to study the spatial correlations of few fermions in the BEC-BCS crossover, as well as the nature of the normal phase and pairing in spin-imbalanced systems.

[1] L. Bayha, et al. Nature 587.7835 (2020): 583-587.
[2] M. Holten, et al. Physical Review Letters 126.2 (2021): 020401
[3] M. Holten, et al. arXiv:2109.11511 (2021).
[4] L. Asteria et al. Nature 599, 571*575 (2021).

Q 26.7 Wed 12:00 Q-H10

Many-body quantum state diffusion for non-Markovian dynamics in strongly interacting systems — Stuart Flannigan[1], •François Damanet[2], and Andrew J. Daley[1] — [1]Department of Physics and SUPA, University of Strathclyde, G4 0NG Glasgow, United Kingdom — [2]Department of Physics and CESAM, University of Liège, B-4000 Liège, Belgium.

Capturing non-Markovian dynamics of open quantum systems is generally a challenging problem, especially for strongly-interacting many-body systems. In this work, we combine recently developed non-Markovian quantum state diffusion techniques with tensor network methods to address this challenge. As a first example, we explore a Hubbard-Holstein model with dissipative phonon modes, where this new approach allows us to quantitatively assess how correlations spread in the presence of non-Markovian dissipation in a 1D many-body system. We find regimes where correlation growth can be enhanced by these effects, offering new routes for dissipatively enhancing transport and correlation spreading, relevant for both solid state and cold atom experiments.

Reference: https://arxiv.org/abs/2108.06224

Q 26.8 Wed 12:15 Q-H10

Efficient Diagonalization Methods for Mesoscopic Fermi Systems — •Paul Hill — Physikalisches Institut, Universität Heidelberg, Deutschland

Already mesoscopic systems of interacting fermions show emergent collective phenomena such as the precursor of a quantum phase transition or cooper pairing [1,2].

These strongly correlated systems are notoriously hard to describe theoretically due to the exponential scaling of their underlying Hilbert spaces. The sparsity of typical physical Hamiltonians, however, allows us to use the Lanczos algorithm, an established numerical method in the condensed matter community. At its heart, this method seeks to identify a small sub-space of the full system on which the Hamiltonian can be efficiently diagonalized without loss of the relevant physics.

Here we use the Quanty many-body code [3] to conveniently apply the Lanczos method in the language of second quantization to the problem of few ultracold atoms interacting via s-wave scattering in a two-dimensional harmonic trap. The numerical prediction of the excitation spectrum is compared to recent experimental observations [1].

[1] Luca Bayha et al. Observing the emergence of a quantum phase transition shell by shell. Nov 2020.
[2] Marvin Holten et al. Observation of cooper pairs in a mesoscopic 2d fermi gas. Sep 2021
[3] www.quanty.org, M. W. Haverkort et al. Multiplet ligand-field theory using wannier orbitals. Apr 2012.