Superconductivity and Superfluidity: From Condensed Matter to Ultracold Quantum Gases

Brazilian-German WE-Heraeus-Seminar

14 Oct - 18 Oct 2024
at the International Institute of Physics IIP,
Natal, Brazil

The WE-Heraeus Foundation supports research and education in science, especially in physics.
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Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de

Aims and scope of the Brazilian-German WE-Heraeus-Seminar:

The fields of superconductivity in condensed matter and superfluidity in ultracold quantum gases have made major experimental advances in the last few years. The recent discovery of multiband superconductors, that may exhibit crossovers or quantum phase transitions from the Bardeen-Cooper-Schieffer (BCS) to the Bose-Einstein-Condensation (BEC) as function of carrier density or doping, is now a major topic of research in condensed matter, encompassing materials such Iron Selenides, Magic Angle Twisted Bilayer and Trilayer Graphene as well as High-Tc Cuprates and Lithium-doped Nitrates. In ultracold quantum gases, the discovery of the crossover from BCS to BEC superfluidity as function of interactions was made several years ago. Back then, quantum gases were confined in harmonic traps. However, today, with the advent of digital mirror devices (DMDs), box trap potentials have been created and uniform systems are now experimentally available. Furthermore, time-dependent disordered potentials are being explored and the experimental discovery of supersolids, a quantum state of matter that is a superfluid with crystalline order, in dipolar gases has also stimulated new research directions.

The goal of the Binational Wilhelm and Else Heraeus Seminar Superconductivity and Superfluidity: From Condensed Matter to Ultracold Quantum Gases is to bring together scientists from Germany and Brazil working on superconductivity in condensed matter and superfluidity in ultracold quantum gases to discuss the research frontiers in these areas and to cross-polinate ideas with other scientists coming from other parts of the world. On the one hand, invited plenary talks by 25 selected leading international experts will guarantee a high scientific level for the seminar, and will provide its main backbone. On the other hand, all other participants will be given the opportunity to present their current research work within a high-class setting through shorter contributed talks or through posters, thereby generating a forum for identifying the most promising current trends and future perspectives in condensed matter or ultracold quantum gases experiments.

Scientific Organizers:

Prof. Dr. Rodrigo Pereira	Federal University of Rio Grande do Norte, Natal, Brazil E-mail: rodrigo.pereira.2@ufrn.br
PD Dr. Axel Pelster	RPTU Kaiserslautern-Landau, Germany E-mail: axel.pelster@physik.uni-kl.de
Prof. Dr. Carlos Sá de Melo	Georgia Institute of Technology, Atlanta, USA E-mail: carlos.sademelo@physics.gatech.edu

Introduction

Administrative Organization:

Dr. Stefan Jorda
Martina Albert

Wilhelm und Else Heraeus-Stiftung
Kurt-Blaum-Platz 1
63450 Hanau, Germany

Phone +49 6181 92325-14
Fax +49 6181 92325-15
E-mail albert@we-heraeus-stiftung.de
Internet : www.we-heraeus-stiftung.de

Address IIP:

Universidade Federal do Rio Grande do Norte, Anel Viário da UFRN – Lagoa Nova, RN, 59078-970, Brazil

Address Hotel:

Praiamar Natal Hotel
R. Francisco Gurgel, 33.
Ponta Negra, Natal - RN, 59090-050, Brazil

Program

Sunday, October 13, 2024
15:00 – 19:00 Arrival at Hotel
19:30 – 21:00 Dinner

Monday, October 14, 2024

8:15am – Bus leaves hotel

Opening and Welcome
08:45 – 09:00 Alvaro Ferraz (IIP, Natal)
09:00 – 09:15 Stefan Jorda (WEH foundation)

Session 1: Morning – Superconductors: Unconventional
09:15 – 10:00 Laura Greene (Florida, USA):
Unconventional Superconductivity overview and Planar Tunneling into Kondo Lattices
10:00 – 10:45 Ilya Eremin (Bochum, Germany):
Magnetic fluctuations, superconducting instability, and layer selectivity in bilayer nickelates under high pressure

10.45 – 11.15 **Coffee Break**

Session 2: Morning – Superconductors: Two dimensional systems
11:15 – 12:00 Yoshihiro Iwasa (Tokyo, Japan):
Density controlled BCS-BEC crossover in a 2D superconductor
12:00 – 12:45 Hermann Freire (Goias, Brazil):
Non-Fermi liquid, superconductivity and pair density wave in a doped Mott insulator: Lessons from a 2D exactly solvable model

12:45 – 14:15 **Lunch**

Session 3: Afternoon – Superfluids: Condensates of Light
14:15 – 15:00 Johann Kroha (Bonn, Germany):
Coherence and dephasing in driven-dissipative condensates of light

Session 4: Afternoon – Poster Flash Presentations
15:30 – 16:15 Plenary Poster Flash Presentations I

16:15 – 16:45 **Coffee Break**

16:45 – 17:30 Plenary Poster Flash Presentations II

17:30 – 18:00 Hotel Transportation

19:30 – 21:00 **Dinner**

Tuesday, October 15, 2024

8:30am – Bus leaves hotel

Session 5: Morning – Superfluids: Turbulence
9:00 – 9:45 Amilson Rogelso Fritsch (São Carlos, Brazil):
Relaxation of an out-of-equilibrium closed quantum system: Experimental observations of decay of turbulence and the stages to reach equilibrium
9:45 – 10:30 Ednilson Santos (São Carlos, Brazil):
Hydrodynamic Energy Spectrum from Wave Turbulence

10:30 – 11:00 **Coffee Break**

Session 6: Morning – Superconductors and Superfluids: Fermi surfaces and topology
11:00 – 11:45 Carsten Timm (Dresden, Germany):
Superconductors with Fermi surfaces
11:45 – 12:30 Vivian França (São Paulo, Brazil):
Topological phases in one-dimensional superfluid Hubbard chains probed by entanglement measures

12:30 – 14:00 **Lunch**

Session 7: Afternoon – Superfluids: Bosons and Fermions
14:00 – 14:45 Arnaldo Gammal (São Paulo, Brazil):
Stability of Bose-condensed mixtures in a shell trap and Faraday waves induced by a Rabi coupling
14:45 – 15:15 Marcia Frometa (Florence, Italy):
Shapiro steps in a 6Li Fermi superfluid Josephson junction

15:15 – 15:45 **Coffee Break**

Section 8: Afternoon – Posters
15:45 – 17:15 Poster Session I

17:30 – 18:00 Hotel Transportation

19:30 – 21:00 **Dinner**

Wednesday, October 16, 2024

8:30am – Bus leaves hotel

Session 9: Morning – Superconductors: Iron Selenide and Twisted Bilayers
09:00 – 09:45 Yuji Matsuda (Kyoto, Japan):
Exploring the BCS-BEC Crossover Regime in FeSe-based superconductors
09:45 – 10:30 Rafael Fernandes (Illinois, USA):
A critical nematic phase with pseudogap-like behavior in twisted bilayers

10:30 – 11:00 **Coffee Break**

Session 10: Morning – Superfluids: Vortex Dynamics and Hubbard Model
11:00 – 11:45 Kali E. Wilson (Stratchclyde, UK):
Vortex Dynamics in Binary Superfluids
11:45 – 12:30 Thereza Paiva (Rio de Janeiro, Brazil):
Attractive Hubbard model: recent advances

12:30 – 14:00 **Lunch**

14:00 – 18:00 **Excursion**

19:00 – 22:00 **Conference Dinner**

Thursday, October 17, 2024

8:30am – Bus leaves hotel

Session 11: Morning – Superconductors: New Materials and Quantum Phases
9:00 – 9:45 Rossitza Pentcheva (Duisburg-Essen, Germany):
Interface- and defect-induced quantum phases in nickelate thin films and superlattices
9:45 – 10:30 Stevan Nadj-Perge (Pasadena, USA):
Imaging strongly correlated and superconducting phases in twisted trilayer graphene

10:30 – 11:00 **Coffee Break**

Session 12: Morning – Superconductors: Chains
11:00 – 11:45 Flavia Ramos (Kaiserslautern, Germany):
Nonlinear effects on charge fractionalization in critical chains
11:45 – 12:30 Mucio Continentino (Rio de Janeiro, Brazil):
Interplay between topology and interactions in superconducting chains

12:30 – 14:00 **Lunch**

Session 13: Afternoon – Superfluids: Phase Transitions
14:00 – 14:45 Gabriele Ferrari (Trento, Italy):
False vacuum decay via bubble formation in ferromagnetic superfluids
14:45 – 15:15 Krissia Zawadzki (São Carlos, Brazil):
Optimal work storage across the fermionic superfluid-insulator transition

15:15 – 15:45 **Coffee Break**

Session 14: Afternoon – Posters
15:45 – 17:15 Poster Session II

17:30 – 18:00 Hotel Transportation

19:30 – 21:00 **Dinner**

Friday, October 18, 2024

8:30am – Bus leaves hotel

Session 15: Morning – Superconductors: Cuprates
9:00 – 9:45 Neil Harrison (Los Alamos, USA):
Small Pockets and the Origin of the Low Superfluid Density in the Underdoped Cuprates
9:45 – 10:30 Eduardo Marino (Rio de Janeiro, Brazil):
A Successful Theory for High-Tc Superconductivity in Cuprates

10:30 – 11:00 **Coffee Break**

Session 12: Morning – Superfluids: Fermions
11:00 – 11:45 Artur Widera (Kaiserslautern, Germany):
Superfluids along the BEC-BCS crossover in time-controlled disorder
11:45 – 12:30 Jacques Tempere (Antwerp, Belgium)
Collective excitations and vortices in Fermi superfluids

12:30 – 14:00 **Lunch**

Session 14: Afternoon – Superfluids: Supersolids
14:00 – 14:45 Ralf Klemt (Stuttgart, Germany):
Sound and amplitude modes in trapped dipolar supersolids
14:45 – 15:15 Tobias Grass (Bilbao, Spain):
Lattice bosons with non-local interactions: From Bose metals to
supersolids and string-ordered phases of matter

15:15 – 15:45 **Coffee Break**

15:45 – 16:15 Concluding Remarks – Poster Prizes

16:30 – 17:00 Hotel Transportation

19:30 – 21:00 **Dinner**

Abstracts of Lectures

(in alphabetical order)

Andre Lima[1], M. S. Figueira[2] and Mucio A. Continentino[1]

[1]Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil
[2]Instituto de Física, Universidade Federal Fluminense, Niteroi, Brazil

Most studies of non-trivial topological systems are carried out in models that admit an exact solution. This raises the question, to which extent the consideration of electronic correlations in real systems, modify these results. Exact results in correlated electronic systems with non-trivial topological properties are scarce but fundamental to this problem. Among the soluble models with non-trivial topology, we single out the Kitaev p-wave superconductor. It plays a crucial role in clarifying the appearance of emergent quasi-particles, the Majorana modes, associated with non-trivial topological phases. Given the relevance of this model, it would be extremely useful if it can be extended to include correlations and remain solvable. In this work we investigate a superconducting Kitaev chain that interacts through a Falicov-Kimball Hamiltonian with a background of localized electrons. For some relevant values of the parameters of this extended model solutions can be obtained, which allows for a detailed study of the interplay between electronic correlations and non-trivial topological behavior. Besides, the random occupation of the lattice by the local moments brings the new ingredient of disorder with some additional interesting effects.

Magnetic fluctuations, superconducting instability, and layer selectivity in bilayer nickelates under high pressure

F. Lechermann, S. Bötzel, J. Gandolf, and **Ilya M. Eremin**

[1]*Institut für Theoretische Physik III, Ruhr-Universität Bochum, 44801 Bochum Germany*

Motivated by the report of superconductivity in bilayer $La_3Ni_2O_7$ at high pressure, we examine the interacting electrons and the resulting spin fluctuations in this system. First-principles many-body theory is utilized to study the normal-state electronic properties. Below 100K, a multi-orbital non-Fermi liquid state resulting from loss of Ni-ligand coherence within a flat-band dominated low-energy landscape is uncovered. The incoherent low-temperature Fermi surface displays strong mixing between Ni-d_{z2} and Ni-d_{x2-y2} orbital character. In a model-Hamiltonian picture, spin fluctuations originating mostly from the Ni-d_{z2} orbital give rise to strong tendencies towards a superconducting instability with either d_{x2-y2}-wave or interlayer s+-wave order parameter in pressurized $La_3Ni_2O_7$. We show that the bilayer structure of the spin response allows to elucidate the role of the interlayer interaction and the Cooper-pairing in a very efficient way. In particular, we demonstrate the key difference between the potential s+- and d-wave gaps, discussed recently, by comparing the corresponding response in the even and odd channels of the spin susceptibility. We show that mostly interlayer driven s+- Cooper-pairing produces a single large spin resonance peak in the odd channel whereas several resonances are predicted for the d-wave scenario.

In addition using advanced dynamical mean-field theory on a realistic level we compare the features of the conventional bilayer (2222) Ruddelsden-Popper crystal structure with those of a newly-identified monolayer-trilayer (1313) alternation. Both structural cases display Ni-dz2 flat-band character at low-energy, which drives an electronic instability with a wave vector qI=(0.25,0.25,qz) at ambient pressure, in line with recent experimental findings. The 1313 electronic structure exhibits significant layer selectivity, rendering especially the monolayer part to be Mott-critical. At high pressure, this layer selectivity weakens and the 1313 fermiology displays arcs reminiscent to those of high-Tc cuprates. In contrast to dominant inter-site self-energy effects in the latter systems, here the Fermi arcs are the result of the multiorbital and multilayer interplay within a correlated flat-band scenario.

References

1. Frank Lechermann, Jannik Gondolf, Steffen Bötzel, and Ilya M. Eremin, Phys. Rev. B, L201121 (2023).
2. Steffen Bötzel, Frank Lechermann, Jannik Gondolf, and Ilya M. Eremin Phys. Rev. B 109, L180502 (2024).
3. Frank Lechermann, Steffen Bötzel, and Ilya M. Eremin, Phys. Rev. Materials 8, 074802 (2024).

A critical nematic phase with pseudogap-like behavior in twisted bilayers

V. Gali[1], M. Hecker[1], R. M. Fernandes[1,2]

[1]School of Physics and Astronomy, University of Minnesota, MN 55455, USA
[1]Department of Physics, University of Illinois Urbana-Champaign, IL 61801, USA

Twisted bilayer systems provide a new platform to investigate correlated electronic phenomena. Because the emergent moiré superlattice can have quasi-crystallographic symmetries that are forbidden in bulk crystals by the crystallographic restriction theorem, novel effects with no counterpart in crystalline systems can be realized. In this talk, we will discuss the emergence, in hexagonal bilayers twisted by 30 degrees, of a critical nematic phase displaying quasi-long-range order, which can be tuned by an external magnetic field and is bounded by two BKT transitions. Nematic phase fluctuations in this critical phase strongly impact the electronic spectrum, giving rise to a pseudogap-like behavior. We also discuss the possible emergence of superconductivity near the putative quantum critical point associated with the critical nematic phase, and potential experimental realizations of this model.

[1] V. Gali, M. Hecker, R. M. Fernandes, arXiv:2401.01844 (2024).

Quantum gases in ultrastable magnetic fields: from False vacuum decay to zero magnetic field physics

authors: Chiara Rogora, Diego Andreoni, Cosetta Baroni, Riccardo Cominotti, Anna Berti, Alessio Recati, Iacopo Carusotto, Alessandro Zenesini, Giacomo Lamporesi, Gabriele Ferrari

Pitaevskii BEC Center, CNR-INO and Dipartimento di Fisica, Università di Trento, 38123 Trento, Italy

Metastability stems from the finite lifetime of a state when a lower-energy configuration is available but only by tunneling through an energy barrier. In classical many-body systems, metastability naturally emerges in a first-order phase transition and a prototypical example is a supercooled vapor. The extension to quantum field theory and quantum many-body systems has attracted significant interest in the context of statistical physics, protein folding, and cosmology, for which thermal and quantum fluctuations are expected to trigger the transition from the metastable state (false vacuum) to the ground state (true vacuum) through the probabilistic nucleation of bubbles. However, the theoretical progress in estimating the relaxation rate of the metastable field through bubble nucleation has not been validated experimentally. Here, we discuss the experimental observation of bubble nucleation in isolated and coherently coupled atomic superfluids, and we support our observations with numerical simulations. More generally, we will discuss our experiments on magnetism based on superfluid multicomponent gases in an ultrastable magnetic field environment, which recently became available.

Topological phases in one-dimensional superfluid Hubbard chains probed by entanglement measures

M. Sanino[1], **I. M. Carvalho**[1], **F. Iemini**[2,3], **and V. V. França** [1]

[1] *Institute of Chemistry, São Paulo State University, Araraquara, Brazil*
[2] *Institute of Physics, Federal Fluminense University, Niterói, Brazil*
[3] *Institute for Physics, Johannes Gutenberg University Mainz, D-55099 Mainz, Germany*

Quantum simulations involving ultracold atoms confined by optical potentials provide an ideal platform for investigating quantum phase transitions driven by atomic interaction strength, particle density, and geometry − challenging to be probed and explored in solid-state systems. In this work, we investigate the one-dimensional attractive Hubbard model under optical confinement using Density Matrix Renormalization Group calculations. We consider not only the BCS regime, characterized by weakly coupled Cooper pairs, but also the strongly dimer regime, BEC, and the BCS-BEC crossover driven by the strength of the atomic interactions. Besides density, probabilities and superconducting order parameter profiles, we also analyze both single-site and half-chain bipartite entanglement for several densities, interaction and confinement strengths. Our findings reveal that the harmonic confinement induces a quantum phase transition from a superfluid sample to a topological insulator − composed by an insulator bulk with superfluid edges − induced by the harmonic confinement. We numerically depict a phase diagram routing the parameters for optimizing this topological superfluidity structure which could be explored in future quantum devices.

Non-Fermi liquid, superconductivity and pair density wave in a doped Mott insulator: Lessons from a 2D exactly solvable model

Hermann Freire[1]

[1]*Instituto de Física, Universidade Federal de Goiás, 74.690-900, Goiânia-GO, Brazil*

In this talk, we will examine the current progress in investigating the strongly correlated Hatsugai-Kohmoto (HK) model on a square lattice, which describes both a Mott insulator at half-filling and a non-Fermi liquid phase with an instability towards superconductivity upon doping. Through the solution of this exactly solvable model with the inclusion of small pairing interactions, we will also discuss the possible emergence of a new pair density wave phase [1] (i.e., where Cooper pairs have a finite center-of-mass momentum for zero magnetic field) within a particular region of its phase diagram displaying the corresponding repulsive interaction U versus the doping parameter x. Moreover, it has been recently put forward that the metal-insulator transition of the HK model belongs to the same universality class as the Mott transition of the paradigmatic Hubbard model [2], which is generally assumed to be central for capturing the essence of the physics of many unconventional high-Tc superconductors. Therefore, we believe our results may thus shed light on a possible (universal) microscopic mechanism regarding the formation of such a finite-momentum pairing state, whose fluctuations have been argued to be relevant for understanding, e.g., the physics of the cuprate superconductors in the underdoped regime [3]. Lastly, we will end with the analysis of a scenario that emerges from our results and, additionally, we will provide an outlook of some future directions of our present work.

References:

[1] I. M. Froldi, C. E. S. P. Corsino, and H. Freire, *to be submitted* (2024).

[2] E. W. Huang, G. L. Nave, and P. W. Phillips, Nature Physics **18**, 511 (2022).

[3] P. A. Lee, Phys. Rev. X **4**, 031017 (2014).

Relaxation of an out-of-equilibrium closed quantum system: Experimental observations of decay of turbulence and the stages to reach equilibrium

A. R. Fritsch[1], M. A. Moreno-Armijos[1], L. Madeira[1], A. D. García-Orozco[1], S. Sab[1], G. Telles[1], Y. Zhu[2], S. Nazarenko[2], V. S. Bagnato[3,4]

1-Instituto de Física de São Carlos, Universidade de São Paulo, São Carlos, Brazil
2-Université Côte d’Azur, CNRS, Institut de Physique de Nice (INPHYNI), Nice, France
3-Department of Biomedical Engineering, Texas A&M University, College Station, USA
4 -Department of Physics & Astronomy, Texas A&M University, College Station, USA

The temporal evolution of a non-equilibrium quantum system is the most crucial aspect of its dynamics. We introduce excitations in a 87Rb Bose-Einstein condensate, which, under certain conditions, induce turbulence in the system. Once this non-equilibrium state is achieved, the system is allowed to evolve until it reaches equilibrium. Throughout this dynamic process, the characteristic particle cascade is observed, featured by the appearance of a power law in the momentum distribution along with temporal windows of meta-stability showing the emergence of universal scaling. Subsequently, the system reaches a pre-thermalization stage with minimal variation, followed by an inverse cascade that forms a new condensate with fraction and temperature different from the initial one. This allows the assessment of various physics inputs during relaxation. The system is investigated under different initial conditions and represents a closed system suitable for investigating many phenomena.

[1] Moreno-Armijos, M. A. et al. Observation of relaxation stages in a non-equilibrium closed quantum system: decaying turbulence in a trapped superfluid, arXiv:2407.11237 (2024).

[2] Madeira, L. et al. Universal scaling in far-from-equilibrium quantum systems: An equivalent differential approach, PNAS, 121 (30) (2024).

[3] García-Orozco, A. D. et al. Universal dynamics of a turbulent superfluid Bose gas, Phys. Rev. A 106, 023314 (2022).

Shapiro steps in a ^{6}Li Fermi superfluid Josephson junction

M. Frometa,[1,2,*] G. Del Pace,[1] D. Hernandez-Rajkov,[1,2]
N. Grani,[1,2] G. Nesti,[1] and G. Roati[1,2]

[1] *LENS and Dipartimento di Fisica e Astronomia, Università di Firenze 50019 Sesto Fiorentino, Italy*
[2] *Istituto Nazionale di Ottica del Consiglio Nazionale delle Ricerche (INO-CNR) 50019 Sesto Fiorentino, Italy*

Josephson junctions represent a powerful tool to probe macroscopic phase coherence in different systems. They are also fundamental for atomtronics circuits, thanks to their well defined current-chemical potential and current-phase. In our experimental system, we create atomic Josephson junctions using Fermi superfluids of lithium-6, realized by coupling two quasi-two-dimensional atomic clouds with a tunneling barrier. By moving the tunneling barrier across the junction while modulating the position at a given frequency, we are able to inject an alternate current. Then, measuring the chemical potential imbalance developed across the junction after a few modulation periods, we can study the dynamics resulting in the system. Our experimental results show that the AC driving of the barrier introduces a step-like behavior in the current-chemical potential curve, with a number of plateaus at a chemical potential value that is an integer multiple of the driving frequency [1]. This behavior is the analog of Shapiro steps observed in superconducting Josephson junctions illuminated by an external electromagnetic field [2]. We studied the AC response for a molecular BEC and a unitary Fermi gas junction, finding that in both cases the plateaus in the current-chemical potential characteristic coincides with the emission of a well-defined number of vortices, suggesting that the stabilization of the current in the plateaus is operated by phase slippage processes.

[1] V. Singh *et al.*, *Phys. Rev. Lett.* (2024).
[2] S. Shapiro, *Phys. Rev. Lett.* **11**(2) p. 80 (1963).

* marcia.frometa@lens.unifi.it

Stability of Bose-condensed mixtures in a shell trap and Faraday waves induced by a Rabi coupling

Alex Andriati[1], Leonardo Brito[1], Lauro Tomio[2], and Arnaldo Gammal[1*]
[1] *Instituto de Física, Universidade de São Paulo, 05508-090 São Paulo, Brazil.*
[2] *Instituto de Física Teórica, Universidade Estadual Paulista, 01156-970 São Paulo, SP, Brazil.*
(Dated: August 7, 2024)

We review the dynamical stability of Bose-Einstein-condensed binary mixtures trapped on the surface of an ideal two-dimensional spherical bubble. Further we analyze how the Rabi coupling between the species can modulate the interactions leading to parametric resonances. In this spherical geometry, the discrete unstable angular modes drive both phase separations and spatial patterns, with Faraday waves emerging and coexisting with an immiscible phase. In the context of discrete kinetic energy spectrum, the only parameters to drive the emergence of Faraday waves are the contact interactions and the Rabi coupling. Analytical solutions for homogeneous population dynamics are obtained and the stability is investigated through Floquet methods and compared with full numerical solutions applied to the corresponding time-dependent equations.

[1] A. Andriati, L. Brito, L. Tomio, A. Gammal, Phys. Rev. A **104**, 033318 (2021).
[2] L. Brito, L. Tomio, A. Gammal, Phys. Rev. A **108**, 053315 (2023).

* gammal@if.usp.br

Lattice bosons with non-local interactions: from Bose metals to supersolids and string-ordered phases of matter

Tobias Grass[1,2]

[1]DIPC – Donostia International Physics Center, San Sebastián, Spain
[2] IKERBASQUE – Basque Foundation for Science, Bilbao, Spain

In a system of bosons, short-range interactions produce a phase transition from a superfluid condensate into an insulating state. The landscape of possible bosonic phases of matter gets significantly enriched through the presence of long- or finite-range interactions: Both condensed and insulating phases may then undergo a symmetry-breaking transition and exhibit crystalline order, giving rise to supersolid or charge-density-wave phases[1,2]. There is also an intriguing possibility of non-local order: The Haldane phase is characterized by string order, and is known to appear in the insulating regime of bosons interacting in a 1D lattice via finite-range interactions. The co-existence of such string order and superfluidity, however, has remained an open question. The presence of exchange interactions in a 2D lattice (or a ladder) may also produce a transition from a condensed phase into a metal-like bosonic phase.

Using DMRG calculations, we have theoretically examined this variety of bosonic phases of matter in chain- or ladder-like lattices in the presence of non-local interaction terms. This provides new insights in the experimental feasibility of exotic bosonic phases and in the existence of string-ordered superfluids. Experimental platforms where these phases can be observed are discussed, specifically the recent experimental case of an extended Bose-Hubbard model with dipolar excitons[1]. We also show that a chain of three-level ions may provide a promising platform to implement the physics related to ring-exchange interactions, giving rise to a kind of Bose-metal behavior.

References

[1] C. Lagoin, U. Bhattacharya, T. Grass, R. Chhajlany, T. Salamon, K. Baldwin, L. Pfeiffer, M. Lewenstein, M. Holzmann, F. Dubin: *Extended Bose-Hubbard model with dipolar excitons*, Nature 609, 485 (2022)

[2] Y. Watanabe, U. Bhattacharya, R. W. Chhajlany, J. Argüello-Luengo, M. Lewenstein, T. Grass: *Competing order in two-band Bose-Hubbard chains with extended-range interactions*, Phys. Rev. B 109, L100507 (2024)

Unconventional Superconductivity overview and Planar Tunneling into Kondo Lattices

Laura H. Greene
National MagLab and Florida State University
1800 E. Paul Dirac Drive, Tallahassee, FL 32310 USA

Unconventional superconductors differ from conventional superconductors in that they typically exhibit a ubiquitous phase diagram with intriguing, correlated electron phases that break the symmetry of the underlying lattice at temperatures well above T_c. These non-Fermi liquid phases remain some of the greatest unsolved problems in physics. After this overview, I will present some of our work on planar tunneling into the Kondo insulators SmB6 [1], and a possible new paring mechanism in the heavy-fermion superconductor CeCoIn5 [2].

References:

1. W.K. Park, L. Sun, A. Noddings, D.-K. Kim, Z. Fisk, and L.H. Greene, "Planar tunneling spectroscopy of the topological surface states in Kondo insulator SmB_6" Proceedings of the National Academy of Sciences, **113**, 24 (2016). DOI: https://doi.org/10.1073/pnas.1606042113
2. K. Shrestha, S. Zhang, L.H. Greene, Y. Lai, R.E. Baumbach, K. Sasmal, M.B. Maple, and W.K. Park "Spectroscopic Evidence for the Direct Involvement of Local Moments in the Pairing Process in the Heavy-Fermion Superconductor $CeCoIn_5$" Physical Review B **103**, 224515 (2021). DOI: https://doi.org/10.1103/PhysRevB.103.224515

Small Pockets and the Origin of the Low Superfluid Density in the Underdoped Cuprates

N. Harrison[1], M. K. Chan[1,2]

[1]*Los Alamos National Labs, Los Alamos, New Mexico 87545, USA*
[2]*National Science Foundation, 2415 Eisenhower Avenue Alexandria, Virginia 22314, USA*

The underdoped high temperature superconducting cuprates have been shown to exhibit anomalously small carrier and superfluid densities in the pseudogap regime, together with an approximate scaling of the superconducting transition temperature with the density of doped holes [1,2]. One possibility that has been suggested is that the Fermi surface upon which pairing occurs consists of small Fermi surface pockets. Angle-resolved photoemission spectroscopy has only seen Fermi surface arcs instead of pockets [3], whereas quantum oscillation studies have revealed small pockets only at very low temperatures inside what is thought to be a charge-density wave state [4]. Here, we report using angle-resolved magnetoresistance oscillation measurements at very high temperatures above T_c, revealing direct evidence for small Fermi surface pockets in this regime. Such an observation tightly constrains possible models for the pseudogap and enables us to understand the origin of the small superfluid density.

References

1. Y. J. Uemura *et al*., *Phys. Rev. Lett*. **62**, 2317 (1989).
2. S. Badoux *et al*., *Nature* **531**, 210 (2016).
3. M. R. Norman *et al*., *Nature* **392**, 157 (1998).
4. S. E. Sebastian, N. Harrison, G. G. Lonzarich, *Rep. Prog. Phys*. **75**, 102501 (2012).

Density controlled BCS-BEC crossover in a 2D superconductor

Yoshi Iwasa

RIKEN Center of Emergent Matter Science, Wako 351-0198, Japan

Email: iwasay@riken.jp

The Bardeen-Cooper-Schrieffer (BCS) condensation and Bose-Einstein condensation (BEC) are the two limiting ground states of paired Fermion systems, and the crossover between these two limits has been a source of excitement for both fields of high temperature superconductivity and cold atom superfluidity [1]. Here we report the two-dimensional (2D) BCS-BEC crossover realized in a gate-controlled superconductor, electron doped layered material ZrNCl, and the vortex dynamics across the crossover. To observe this phenomenon, we utilized an ionic gating method, which is well known as a powerful tool to control the carrier density in a large scale and induced 2D superconductivity [2].

We have succeeded in controlling the carrier density in ZrNCl devices by nearly two-orders of magnitude, and establishing an electronic phase diagram through the simultaneous experiments of resistivity and tunneling spectra [3]. We found T_c exhibits dome-like behavior, and more importantly, a wide pseudogap phase in the low doping regime. In the low carrier density limit, T_c scales as $T_c/T_F = 0.12$, where T_F is the Fermi temperature, which shows fair agreement with the theoretical prediction for the 2D BEC-BEC crossover [4,5]. Furthermore, through the systematic Hall effect measurements, we have clarified the evolution of vortex dynamics along the crossover combined with the time-dependent Ginzburg-Landau theory [6]. These results demonstrate that the Li intercalated ZrNCl and its gate-controlled superconductivity are ideal platforms towards investigations of unexplored properties in BEC superconductors.

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Sound and amplitude modes in trapped dipolar supersolids

Jens Hertkorn[1], Philipp Stürmer[2], Koushik Mukherjee[2], Kevin SH Ng[1], Paul Uerlings[1], Fiona Hellstern[1], Lucas Lavoine[1], Stephanie Reimann[2], Tilman Pfau[1], Ralf Klemt[1]

[1]5. Physikalisches Institut and Center for Integrated Quantum Science and Technology, Universität Stuttgart, Pfaffenwaldring 57, 70569 Stuttgart, Germany [2]Division of Mathematical Physics and NanoLund, LTH, Lund University, Box 118, SE-221 00 Lund, Sweden

About five years ago, the emergence of supersolid properties was observed in harmonically trapped dipolar quantum gases in three groups in Pisa, Innsbruck and Stuttgart [1-3]. Since then, many additional experimental and theoretical studies have shed light on the nature of this novel phase including studies on the superfluid to supersolid phase transition, the coherence in the system including the emergence and structure of the low energy collective modes [4] and the appearance of quantized vortices [5].
In this talk, I will review these developments, with a particular focus on the experimental and theoretical study of defining sound and amplitude modes. In addition, I will also present very recent results from our group in Stuttgart [6]:
In a numerical study, we have investigated how uncoupled amplitude and sound excitations emerge in a dipolar torus supersolid. The Higgs amplitude mode manifests itself as a pure amplitude oscillation of the order parameter while the sound modes of the superfluid splits up into two branches in the supersolid phase, which we interpret as first and second sound. This study allows us to unify previous notions of modes in finite trapped supersolids and allows us to establish a direct correspondence to infinitely extended linear supersolids.
I will also present a protocol for selectively probing theses modes in upcoming experiments and will give an update our current efforts towards a new generation Dysprosium quantum gas experiment in Stuttgart.

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Coherence and dephasing in driven-dissipative condensates of light

Hans Kroha
Physikalisches Institut
University of Bonn
Nussallee 12
53115 Bonn
Germany

Bose-Einstein condensates of photons have been realized in high-finesse optical cavities, coupled to a bath of externally driven dye-molecule excitations. In the BEC phase, the photon condensate coexists with a cloud of non-condensed photons. We investigate the time evolution of the coupled system of coherent photon BEC and non-condensed cloud by means of a Lindblad formalism and semianalytic solutions. We find that the photon BEC always decays to zero in the long-time limit, i.e. it dephases, while a finite non-condensed photon density is stabilized by the balance of loss and nonlinear driving. However, the dephasing time associated with the BEC decay can be several orders of magnitude longer than the bare time scales of the photon-bath system, indicating time evolution under a nearly conserved quantity associated with the coherence of the BEC. We analyze the corresponding, nearly conserved eigenmode of the photon-bath system. The long dephasing time in of the photon Bose-Einstein condensate reconciles the necessary dephasing of the dissipative system with the experimentally observed stability of the photon condensated at experimentally accessible observation times. This is contrasted by a lasing regime characterized by strong external pumping, molecule population inversion and non-zero coherent photon amplitude even in the long-time limit. We map out the phase diagram of nearly conserved BEC, fast decaying BEC dynamics and lasing regime.

A Succesful Theory for High-Tc Superconductivity in Cuprates

Eduardo Marino

Federal University of Rio de Janeiro, Institute of Physics, Rio de Janeiro, Brasil

Numerous theories for the superconductivity in cuprates, have been proposed in the almost 40 years that have elapsed since that discovery was made. A common feature of these theories, however, is the scarce number, or even the absence, of quantitative predictions that could be compared to a vast number of experimental data, which are available for these materials. Such theories are, consequently non-testable. In this lecture, We are going to describe the foundations and numerous applications of a comprehensive theory for High-Tc Superconductivity in cuprates, which we proposed recently. that besides being testable, has proven to meet successfully all the tests to which it has been submitted so far. After a judicious choice of the most convenient degrees of freedom apt to represent the system, we consider the relevant basic interactions among them, which are synthesized in an effective Hamiltonian, out of which we obtain the thermodynamic potential that will describe the whole physics. We obtain analytical expressions for the transition lines delimiting the multiple phases of the cuprates, thereby obtaining an accurate description of the T ×doping phase diagram. We also obtain explicit analytic functions determining the influence of an applied external pressure, as well as the number of CuO2 planes. Finally, we obtain analytical expressions for the resistivity and magneto-resitivity in the different normal phases.

Exploring the BCS-BEC Crossover Regime in FeSe-based superconductors

Yuji Matsuda

Department of Physics, Kyoto University, Kyoto 606-8502, Japan

The crossover between weak-coupling BCS and strong-coupling BEC limits provides a unified framework for understanding quantum-bound (superfluid) states of interacting fermions. The BCS-BEC crossover phenomenon has been extensively investigated in ultracold atomic systems. However, its manifestation in solid-state systems has posed significant experimental challenges due to the inherent complexity of crystalline materials and the difficulty in tuning relevant parameters. Recent advancements in materials science and experimental techniques have enabled the realization of this crossover regime in a limited number of solid-state platforms. We presents evidence that superconducting $Fe(Se_{1-x}S_x)$ offers access to the previously unexplored regime where the Fermi energy (ε_F) and superconducting gap (Δ) become comparable, indicating that this system lies deep within the BCS-BEC crossover regime. Through scanning tunneling microscopy and laser-excited angle-resolved photoemission spectroscopy, we demonstrate that ε_F of $Fe(Se_{1-x}S_x)$ is extremely small, with the ratio $\Delta/\varepsilon_F \sim 0.3$-$1$ for all bands. We discuss several unusual superconducting properties associated with the crossover, including non-Gaussian superconducting fluctuations, pseudogap, quantum vortex core, FFLO phase, and unusual Bogoliubov quasiparticle band dispersions. Some of these properties are not expected for single-band superconductors, which calls for a new mechanism of BCS-BEC crossover in the multiband system.

Imaging strongly correlated and superconducting phases in twisted trilayer graphene

Stevan Nadj-Perge[1]

1) Thomas J. Watson, Sr, Laboratories of Applied Physics, California Institute of Technology, Pasadena, CA, USA.

Magic-angle twisted trilayer graphene (MATTG) exhibits several strongly correlated electronic phases that spontaneously break its underlying symmetries. Despite great experimental efforts, the microscopic nature of these phases, their relationship as well as residual symmetries are still elusive. In this talk, I will present our latest results on scanning tunneling microscopy experiments investigating correlated phases of MATTG in which we identified striking signatures of interaction-driven spatial symmetry breaking [1,2]. Over a filling range of about two to three electrons or holes per moiré unit cell, we observed atomic-scale reconstruction of the graphene lattice that accompanies a correlated gap in the tunneling spectrum. This structure appears spatially as a Kekulé supercell -- implying spontaneous inter-valley coherence --- and persists in a wide range of magnetic fields and temperatures that coincide with the development of the gap. In particular, I will discuss the potential origins of this reconstruction, highlight current outstanding questions, and discuss possible connections between inter-valley coherence and insulating and superconducting phases in MATTG.

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Nature **623**, 942–948 (2023).

Attractive Hubbard model: recent advances

Thereza Paiva

Instituto de Física, Universidade Federal do Rio de Janeiro

In its simplest form, the attractive Hubbard model (AHM) is composed of fermions moving in a single band subject to an on-site interaction $U < 0$, which favors the formation of local pairs. Over the years this model has played an important role in describing many aspects of superconductivity. It naturally contemplates Cooper pair formation within a certain temperature scale $T_p \gtrsim T_c$, where T_c is the critical temperature for superconductivity when pairs actually condense. This behavior, absent in the Bardeen-Cooper-Schrieffer (BCS) pairing theory, has been suggested to be relevant to pseudogap phenomena in high-temperature cuprate superconductors.

Recent experiments with ultracold fermionic atoms in optical lattices have provided a tuneable and clean realization of the attractive Hubbard model. In view of this, several physical properties may be thoroughly studied across the crossover between weak (BCS) and strong (BEC) couplings. Here we report on extensive determinant Quantum Monte Carlo studies of the AHM from which several different quantities have been calculated and should be useful as a road map to experiments. Scenarios which could lead to higher critical temperatures, closer to an experimentally accessible range are also discussed.

Interface- and defect-induced quantum phases in nickelate thin films and superlattices

Rossitza Pentcheva[1]

[1] *Department of Physics, University of Duisburg-Essen, Lotharstr. 1, 47057 Duisburg*

The nickelate family hosts a variety of intriguing phenomena, including magnetic, structural and metal-to-insulator transitions [1]. The recently discovered superconductivity in infinite-layer nickelates [2] has spurred intensive research to unravel its origin. Based on insight from density functional theory calculations with a Hubbard *U* term, I will focus on the role of the film geometry [3], the recently resolved unexpected structure of the interface [4], as well as the magnetic interactions in the system [5]. Moreover, starting from confined perovskite superlattices, I will address the role of oxygen vacancies giving rise to a stripe antiferromagnetic order [6].

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Nonlinear Effects on Charge Fractionalization in Critical Chains

Flávia Braga Ramos[1]

[1]Physics Department and Research Center OPTIMAS, University of Kaiserslautern-Landau, 67663 Kaiserslautern, Germany

We investigate the fractionalization of one-particle excitations in a strongly correlated chain via an out-of-equilibrium protocol [1]. Starting from a Gaussian wave packet with finite energy and momentum, we find that the time evolution splits the wave packet into at least three descendant humps: two counterpropagating low-energy modes and an additional high-energy contribution. We show that these fractional excitations provide a direct measurement of interaction parameters that govern threshold singularities of dynamic response functions in the nonlinear Luttinger liquid (nLL) theory. Remarkably, in agreement with the conventional Luttinger liquid, the nLL theory predicts the correct dynamics at low energies. Our results uncover a simple strategy to probe the nonlinear regime of critical chains in ultracold-atom and tunneling spectroscopy experiments.

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Hydrodynamic Energy Spectrum from Wave Turbulence

M A G dos Santos Filho[1] and F E A dos Santos[1]

[1] *Department of Physics, Federal University of São Carlos, Rod. Washington Luís, km 235 - S/n - Jardim Guanabara, São Carlos - SP, 13565-905, São Carlos, Brazil. Contact Phone: +55 16 3351-9634*

Contact Email: santos@ufscar.br

Bose–Einstein condensates with their superfluidity property provide an interesting parallel to classical fluids. Due to the Kolmogorov spectrum of homogeneous turbulence the statistics of the incompressible velocity field is of great interest, but in superfluids obtaining quantities such as the statistics of the velocity field from the macroscopic wavefunction turns out be a complicated task; therefore, most of the work up to now has been numerical in nature. We made use of the Weak Wave Turbulence (WWT) theory, which provides the statistics of the macroscopic wavefunction, to obtain the statistics of the velocity field, which allowed us to produce a semi analytical procedure for extracting the incompressible energy spectrum in the WWT regime. This is done by introducing an auxiliary wavefunction that preserves the relevant statistical and hydrodynamical properties of the condensate but with a homogeneous density thus allowing for a simpler description of the velocity field.

Collective excitations and vortices in Fermi superfluids

J. Tempere, S. N. Klimin

TQC, Universiteit Antwerpen, Universiteitsplein 1, B2610 Antwerp, Belgium

Excitations of superfluid Fermi gases can be categorized into fermionic pair-breaking excitations and bosonic phase and amplitude modes. In addition, topological excitations such as vortices (or solitons in 1D) are present. In this talk we investigate the lifetime and dispersion of these excitations as a function of interaction strength, both for the neutral and the charged Fermi gas [1], bridging the gap between superfluids and superconductors. Similarly, we explore the properties of vortices in the Fermi superfluids [2] and contrast their properties to that of vortices in Bose-Einstein condensates on the one hand, and superconducting vortices on the other hand. We show how interactions between vortices leads to dynamics from which the drag coefficients can be characterized. Finally we discuss the possibility of using impurities in superfluids as a probe of the excitations of the superfluid, and as heralds of exotic superfluid phases.

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Superconductors with Fermi surfaces

C. Timm

Institute of Theoretical Physics, TU Dresden, 01062 Dresden, Germany

Conventionally, we think of Fermi surfaces as being the hallmark of normal metals, whereas superconductors have a gap towards quasiparticle excitations. In this talk, I will show that not only can superconductors have Fermi surfaces but these appear *generically* for inversion-symmetric multiband superconductors that break time-reversal symmetry [1,2]. Since the states at these Fermi surfaces do not describe bare electrons but Bogoliubov quasiparticles they are called Bogoliubov Fermi surfaces. I will give an overview of the physics of this phenomenon, including its physical explanation in terms of a pseudomagnetic field and the associated topological invariants [1,2], as well as its potential instability against lattice deformations [3] and towards other superconducting states [4]. Moreover, I will contrast the phenomenon to Bogoliubov Fermi surfaces in materials without inversion symmetry [5,6]. Candidate materials will also be mentioned.

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Superfluids along the BEC-BCS crossover in time-controlled disorder

Jennifer Koch[1], Sian Barbosa[1], Benjamin Nagler[1], Felix Lang[1], Giuliano Orso[2], and Artur Widera[1]

[1]RPTU Kaiserslautern-Landau, Physics Department, and State Research Center OPTIMAS, 67663 Kaiserslautern, Germany
[2] Laboratoire Matériaux et Phénomènes Quantiques, Université de Paris, CNRS, F-75013 Paris, France

The combination of local perturbation, on the one hand, and interactions in a quantum many-body system, on the other hand, is a central problem in quantum science. An exciting situation arises when the system is rendered time-dependent, and the perturbation changes its properties on time scales faster than the typical many-body time scales of the quantum system.

Experimentally, we investigate the impact of a time-controlled external perturbation on a Fermi gas in different scenarios. The perturbation is realized as a repulsive speckle potential. The time dependence can be induced either as a fast quench of the speckle amplitude or as a finite correlation time of the speckle. The quantum gas is realized as an ultracold gas of fermionic Lithium atoms in the two lowest Zeeman sub-states. This system features a broad Feshbach resonance, where very different superfluid states can be prepared, such as molecular Bose-Einstein condensate, a unitary Fermi gas, or a Bardeen-Cooper-Schrieffer (BCS)-type superfluid. Additionally, a spin-polarized noninteracting Fermi gas can be realized.

We will report on our experimentally studies how the microscopic pair structure affects the macroscopic superfluid response to a quickly switched disorder potential. We record the gases' ability for hydrodynamic expansion, which we interpret as a measure for long-range coherence. Unlike the static, weak-disorder case, where the UFG has been shown to exhibit largest critical velocity and thus resilience against perturbations, we find that for the strong nonequilibrium disorder quench, the UFG is permanently destroyed while the BEC can condense again and re-establish quantum properties.

We interpret this behavior as a consequence of the pair size, where the disorder can induce local excitations and perturbations of the wave function in the BEC regime, which can decay and "heal" macroscopic quantum properties. On resonance by contrast, the pairs size in the UFG becomes comparable to the disorder's correlation length, and the pairs' binding energies of the order of the quench energy. Hence, pairs can be broken and they destroy macroscopic quantum properties on a microscopic level.

Vortex Dynamics in Binary Superfluids

Omar Moutamani, Elizabeth Farr, Ilian Despard, and Kali E. Wilson

University of Strathclyde, Glasgow, UK

I will present an overview of the experimental capabilities under development at the University of Strathclyde to enable studies of vortex dynamics in binary superfluids. Quantum mixtures formed of ultracold atoms provide an extremely clean and well-controlled system for studies of the cooperative behavior inherent in superfluidity and subsequent superfluid dynamics, with exquisite control over interactions, geometry, and rotation (vorticity). In particular, experimental control of interspecies interactions has enabled recent demonstrations of beyond-mean-field phenomena such as quantum droplets and Lee-Huang-Yang gases. Quantised vortices, topologically-protected defects, are ideal probes of the cooperative behaviour inherent in superfluid systems, as their nucleation, internal structure, and dynamics depend directly on the microscopic physics at play. Furthermore, vortices play an integral role in the dissipation of energy in these systems. I will discuss how vortices may be used to probe binary superfluids and quantum-fluctuation-enhanced regimes, and how this might be implemented experimentally.

Optimal work storage across the fermionic superfluid-insulator transition

Krissia Zawadzki
São Carlos Institute of Physics, University of São Paulo

Guilherme A. Canella and Vivian V. França
Institute of Chemistry, São Paulo State University, Brazil

Irene D'Amico
Department of Physics, University of York, UK

Many-body interacting systems display interesting work fluctuations and entanglement properties across a quantum phase transition. In a variety of models, it has been shown that the average work and its variance exhibit discontinuities following a sudden quench in the critical parameter, a similar behavior observed in measures of bipartite entanglement. From this implicit connection, one can ask if it is possible to and how to optimize the work extraction or storage from a correlated system by manipulating its entanglement. Here, we address this question in the context of the fermionic superfluid-to-insulator transition (SIT), which is modeled by the attractive Fermionic Hubbard model in the presence of randomly distributed impurities. We study two quench protocols triggering the SIT: one in which the concentration C of impurities is increased and the other in which its disorder strength V is varied. We show that for disorder strengths sufficiently large to overcome the Coulomb attraction, besides the mean and variance of the work distribution, the skewness also shows a kink at the critical parameters C or V. These are the same points in which the single site entanglement is minimal or vanishes. The protocol in which the SIT is triggered by increasing the concentration is more efficient, allowing it to maximize the average work absorption and minimize its fluctuations at C_C. We also investigate the effects of the temperature and discuss the robustness of these protocols to thermal fluctuations, proposing as an application a quantum battery.

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Posters

Posters

1	Abouelela, Aya	**Fluctuation and dephasing in driven-dissipative photon Bose-Einstein condensates**
2	Aquino, Rui	**Impact of nematic fluctuations on the Hall viscosity of electronic fluids**
3	Araújo, Maykon	**Charge and spin correlations of the Hubbard Model on an anisotropic triangular lattice**
4	Attie, Jorge	**Solitons in superfluids with curved geometries**
5	Balaz, Antun	**Effects of quantum depletion and gradient corrections on the critical atom number of dipolar droplets**
6	Basu, Pradosh	**Information Flow of Ultracold Matter Waves in Engineered Optical Lattices**
7	Bezerra, Victor	**Competing antiferromagnetic and superfluid phases in the Feshbach-Hubbard model**
8	Bobadilla Valencia, Ana	**Synthesis and characterization of the structural and magnetic properties of the system Zr0.96-XV0.04B2+X (X={Y,Ba})**
9	Brand, Joachim	**Odd-frequency superfluidity from a particle-number-conserving perspective**
10	Braz, Lauro	**Interlayer interaction-driven s±-to-dxy-wave superconductivity in La3Ni2O7 under pressure**
11	Calazans de Brito, Luis Filipe	**Number of solitons produced from a large initial pulse in the generalized NLS dispersive hydrodynamics theory**

Posters

12	Cappellaro, Alberto	**Environment-limited transfer of angular momentum in Bose liquids**
13	Da Silva, Willdauany	**Exploring the impact of the electronic interaction nature on the thermoelectric properties of two-dimensional systems**
14	Froldi, Igor	**Pair density wave in the Hatsugai-Kohmoto model**
15	Dos Santos Silva, Gustavo Henrique	**Vortex production and drag calculation in quantum fluids through a Gaussian obstacle**
16	Hernández Ruiz, Edgar Sebastian	**YBaCuO superconducting nanoparticles and reentrant superconductivity**
17	Kannan, Rajaswathi	**Dynamics and Stability of Dark-Bright Solitons in Spin-Orbit Coupled Bose-Einstein Condensates**
18	Kaschewski, Nikolei	**Non-perturbative corrections to the weakly interacting two-component Fermi gas**
19	Krauss, Joshua	**Hydrodynamic Description of Vortices in Photon Bose-Einstein Condensates**
20	Miller, Lachlan	**Phononic crystals for inertial sensing with dilute gas superfluids**
21	Mukherjee, Koushik	**Supersolid States in Anti-Dipolar Bose-Einstein Condensates: Insights into Phase Diagram, Collective Excitation Spectra and rotational properties**
22	Pelster, Axel	**Unravelling Interaction and Temperature Contributions in Unpolarized Trapped Fermionic Atoms in the BCS Regime**
23	Pinilla Realpe, Juan Pablo	**Systematization for the World-Line Quantum Monte Carlo algorithm**

Posters

24	Rajat, Rajat	**Temperature-induced supersolidity in spin-orbit-coupled Bose gases**
25	Ray, Sayak	**Temporal Bistability in the Dissipative Dicke-Bose-Hubbard System**
26	Reyes, Daniel	**Interplay between charge density wave and superconductivity in multiband intermetallic systems**
27	Sallatti, Raphael	**Multiple excitations in Bose-Einstein condensate on curved surfaces**
28	Sanino, Marina	**BCS and FFLO superconducting states in ultracold atomic gases**
29	Santiago Mares, Jefter	**Entanglement as a quantum energy resource**
30	Soares, Jonata	**Fluctuations in an interacting Bose gas confined in a ring**
31	Turaev, Michael	**Non-Hermitian phase transition in a pumped bulk solid state system**
32	Vargas Roco, José Antonio	**Rymax One: A neutral atom quantum processor to solve optimization problems**
33	Vileirine Ribeiro, Juliana	**Simulations using Bose-Einstein condensate theory and Monte Carlo method**
34	Young Silva, Luis Ever	**Linear-mode and scissor-mode oscillations of a 1D and 2D supersolid crystalline structure of droplets in dipolar Bose-Einstein Condensate**

Abstracts of Posters

(in alphabetical order)

Fluctuation and dephasing in driven-dissipative photon Bose-Einstein condensates

Aya Abouelela[1], Sayak Ray[1], Michael Turaev[1], and Johann Kroha[1,2]

[1]Physikalisches Institut, Rheinische Friedrich-Wilhelms-Universität Bonn
[2]School of Physics and Astronomy, University of St. Andrews

In this work, we investigate the driven-dissipative dynamics of open photon Bose-Einstein condensates in a single-mode microcavity filled with dye molecules using the Lindblad master-equation approach. In contrast to previous works, we perform a systematic cumulant expansion of the master equation. This provides the temporal dynamics of the condensate amplitude, of the photon fluctuation and molecule excitation densities, and all other cumulants up to second order, including coupled dynamics of photon-molecule correlators. The temporal dynamics, in the weakly driven case, exhibits the presence of a long-lived photon BEC with finite coherent photon amplitude followed by a decoherence due to the driven-dissipative nature of the system. The lifetime of the condensate can be controlled by the system parameters, such as pump rate and the coherent coupling strength, and can be made much longer compared to the experimentally accessible time scales. In the strongly driven regime, we also obtain a steady state with finite coherent photon amplitude and a population inversion in the molecule excitation, which is, however, the reminiscence of a laser.

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Impact of nematic fluctuations on the Hall viscosity of electronic fluids

Rui Aquino*,[1] Rafael M. Fernandes,[2] and Jörg Schmalian[3,4]

[1]*ICTP – South American Institute for Fundamental Research and Instituto de Física Teórica, Universidade Estadual Paulista – UNESP, São Paulo, Brazil.*

[2]*School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55455, USA*

[3]*Institute for Theoretical Condensed Matter Physics, Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany*

[4]*Institute for Quantum Materials and Technologies, Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany*

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Electronic nematic order and fluctuations are of great importance to a wide class of correlated electronic materials, such as unconventional superconductors, doped topological insulators, and twisted moiré systems. Because of the intertwining between nematicity and elasticity, the manifestations of nematic fluctuations on elastic properties of the lattice, such as the shear modulus, have been widely investigated. In this talk, we explore the impact of nematic fluctuations on the elastic properties of the electronic fluid itself. In particular, we focus on the Hall viscosity coefficient, which is the electronic counterpart of the dissipationless generation of stress by a time-varying strain in the presence of time-reversal symmetry-breaking. We consider the case of graphene, which is a model electronic fluid, and compute the contribution to the Hall viscosity arising from electronic nematicity, highlighting the role played by dynamic nematic fluctuations.

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Charge and spin correlations of the Hubbard Model on an anisotropic triangular lattice

M.V.Araújo[a], **N.C.Costa**[b], **Thereza Paiva**[b]

[a] *Universidade Federal do Piauí-UFPI, Teresina, Brazil*
[b] *Universidade Federal do Rio de Janeiro-UFRJ, Rio de Janeiro, Brazil*

A great deal of interest has been given to low-dimensional frustrated systems over the past decades, in particular because of the occurrence of exotic phases like topological insulators, valence bond order states and quantum spin liquid. When such systems are combined with disorder or anisotropy, the degree of complexity is further increased, and the nature of their ground state is less clear. As the standard model to investigate these correlation effects, the Hubbard model describes electrons with on-site interaction, whose Hamiltonian reads as

$$\mathcal{H} = -t \sum_{\langle \mathbf{i},\mathbf{j}\rangle,\sigma} \left(c^{\dagger}_{\mathbf{i},\sigma} c_{\mathbf{j},\sigma} + \text{H.c.}\right) + U \sum_{\mathbf{i}} (n_{\mathbf{i},\uparrow} - 1/2)(n_{\mathbf{i},\downarrow} - 1/2),$$

with $c^{\dagger}_{\mathbf{i}\sigma}$ ($c_{\mathbf{i}\sigma}$) being creation (annihilation) operators of electrons on a given site $\mathbf{i}$, and spin σ, while $n_{\mathbf{i}\sigma} \equiv c^{\dagger}_{\mathbf{i}\sigma} c_{\mathbf{i}\sigma}$ are number operators. The first term on the right-hand side of the Hamiltonian corresponds to the kinetic energy of the electrons, while the second term describes the on-site (Coulomb) repulsive interaction between them, with interaction strength U. Despite its simplicity, this model has no exact solution for $D > 1$. Therefore, a renewed interest was gained with the recent development of high-quality optical lattice experiments, that emulate the Hubbard model, offering new routes to further investigate the properties of correlated systems, in particular on frustrated lattices. Indeed, optical kagome lattices were recently realized for bosonic atoms [1], while triangular lattices were implemented for fermionic systems [2, 3]. Within this context, and as an attempt to anticipate their experimental findings when anisotropy takes place, here we investigate finite temperature properties of the Hubbard model on the triangular lattice with hopping anisotropy. To this end, we perform unbiased Quantum Monte Carlo simulations [4] at the half-filling regime, where the Mott insulating phase is expected to emerge. Among other quantities, we investigate the charge-charge $\langle \rho(\mathbf{r})\rho(\mathbf{r}')\rangle$ and spin-spin $\langle \mathbf{S}(\mathbf{r})\cdot\mathbf{S}(\mathbf{r}')\rangle$ correlation functions for near neighbor sites. Additionally, we also examine three-point correlation functions, given by $C_3\left(\boldsymbol{r_3}, \boldsymbol{r_2}, \boldsymbol{r_1}\right) = \left\langle \hat{Z}_3 \hat{Y}_2 \hat{X}_1 \right\rangle - \left\langle \hat{Z}_3 \right\rangle \left\langle \hat{Y}_2 \hat{X}_1 \right\rangle - \left\langle \hat{Y}_2 \right\rangle \left\langle \hat{Z}_3 \hat{X}_1 \right\rangle - \left\langle \hat{X}_1 \right\rangle \left\langle \hat{Z}_3 \hat{Y}_2 \right\rangle + 2\left\langle \hat{Z}_3 \right\rangle \left\langle \hat{Y}_2 \right\rangle \left\langle \hat{X}_1 \right\rangle$ where $\hat{X}_1, \hat{Y}_2$, and $\hat{Z}_3$ are spin and charge operators. This allows us to further understand the nature of the magnetic and charge correlations at finite temperatures for such a frustrated system, as well as may shed light on important parameters and energy scales for future experiments in cold atoms.

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Solitons in superfluids with curved geometries

*J. A. G. Attie, E. A. L. Henn1
Instituto de Física de São Carlos da Universidade de São Paulo

The study of perturbations in superfluids, including Bose-Einstein condensate (BEC), is an interesting and active research area in modern nonlinear dynamics [1]. One of these manifestations of perturbation is solitons [2–4], which consists of a pulse with finite and localized energy states, maintaining a constant shape and velocity for a long travel distance. The observation of such nonlinear objects was first documented by the scottish engineer John Scott Russel in 1834, under the term “solitary wave”, depicting a water pulse in the canal between Edinburgh and Glasgow [5]. Since then, solitons have been observed and studied in various platforms, such as optical fibers [6], waveguide [7, 8], electric transmission lines [5], among others including bosonic atomic gases [9, 10]. In the case of bosonic gases, there remains an open window of investigation regarding gases in curved geometries, as their existence and stability in such contexts are not yet clear [11], making the research of solitons in curved settings a promising and challenging area both theoretically and experimentally. In this presentation, I will discuss the fundamental concepts and the state of the art of solitons in superfluids, especially in cases involving curved geometries.

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Effects of quantum depletion and gradient corrections on the critical atom number of dipolar droplets

Milan Radonjić[1,2], Axel Pelster[3], and Antun Balaž[2]

[1]I. Institute of Theoretical Physics, University of Hamburg, Germany
[2]Scientific Computing Laboratory, Center for the Study of Complex Systems, Institute of Physics Belgrade, University of Belgrade, Serbia
[3]Department of Physics and Research Center OPTIMAS, Rheinland-Pfälzische Technische Universität Kaiserslautern-Landau, Germany

The first experimental realization of quantum droplets in dipolar condensates [1] has highlighted the importance of quantum fluctuations [2,3], which were later shown to be the main source of system's stability against the dipolar collapse. The droplets were predicted and shown to be self-bound beyond the critical atom number even without the trap. However, there is a systematic difference in theoretical estimates of the critical atom number and experimental results [4]. Here we use an approach based on the extended Gross-Pitaevskii equation, which includes quantum depletion and beyond-LDA gradient corrections, to numerically and variationally study their effects on the critical atom number.

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Information Flow of Ultracold Matter Waves in Engineered Optical Lattices

Pradosh Basu*, Utpal Roy†

Indian Institute of Technology Patna, Bihta, Patna-801106, India

*pradosh_2021ph23@iitp.ac.in, †uroy@iitp.ac.in

Optical lattices (OLs) with geometrical frustrations manifest localization of a Bose-Einstein condensate (BEC) in the disordered lattice sites. OLs can be designed to generate frustrations at different spatial positions with varied depths. The freedom to change the trap geometries using varying intensities and periods of the trapping lasers further encourages the control on the information flow of the condensate. For the coherently moving BEC, the exponential localization profile [i.e., Anderson localization (AL) cloud] traverses across the lattice and gradually mingles with the solitonic profile. The AL state gets revived in a different lattice site for suitably calculated trap parameters. In this study, we provide the exact analytical method to study OLs with two, three, and four lattice periods and comment on the effects of tuning parameters over AL. We further extend our study towards engineering AL state in both positive and negative absolute temperature domains.

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Victor H. F. Bezerra
Friedrich-Engels-Gymnasium, Emmentalerstraße 67, 13407 Berlin, Germany

Axel Pelster
Fachbereich Physik, Teschnische Universität Kaiserslautern,
Erwin Schrödinger Straße, 67663 Kaiserslautern, Germany

Due the the seminal realization of novel experiments by the cold atom community such the realization of antiferromagnetic phases and quantum gas microscopy alongside revolutionary experiments such BEC and Mott insulating phase in both Fermi and Bose-Hubbard model, simulation of quantum systems by means of cold atom experiments is very near to be achieved. In this scope, we present some theoretical results concerning a two dimensional two channels Hubbard-model at zero temperature where in addition to the repulsive fermionic Hubbard coupling between the fermionic particles, Feshbach bosons are present. The bosons are responsible for a BCS coupling-type interaction between the fermions. We have approached this model by means of a mean-field theory, in which a antiferromagnetic AF and a superfluid order-parameter are present. Thus mean-field theory yields to a competition between the AF-phase and superfluid phase. In the obtained phase diagram, there is no coexistence between the two over mentioned phases. We have observed a interplay between them. Further, the interplay yields to a first order phase transition, in accordance with the Landau-Paradigm. In addition to the interplaying phases, we have observed the existence of the conventional BEC-BCS crossover as well the AF-phase, when the fermionic channel is half-filled. In general, if the fermionic density is equal to the unity, the system can be either in a superfluid phase or an AF-phase for different value of the physical parameters, and the interplay is also present. We have also studied the model for general particle filling, in this case the AF phase only competes with the SC on the BCS side of the BCS-BEC crossover and if the particle filling is near the unity. For particle filling between one and two we have observed a reentrant behavior of the BCS-BEC crossover. Such a model could be interesting in simulating the novel picnitides high-temperature superconductors, once these also presents an interplay between AF and superconducting phase and their excitation spectrum has the same symmetry that we observed in the model studied here.

PACS numbers:

“Synthesis and characterization of the structural and magnetic properties of the system $Zr_{0.96-X}V_{0.04}B_{2+X}$ (X={Y,Ba})”

A. Karla Bobadilla Valencia, R. Ezquiel Lopez Romero, R. Escudero Derat, I. Israel Tellez Aranda

Instituto de Investigaciones en Materiales, Ciudad de México, México.

ABSTRACT

This study presents the solid-state synthesis of a polycrystalline material $Zr_{0.96-X}V_{0.04}B_{2+X}$ by means of an electric arc furnace with a controlled argon atmosphere, where X represents the doping elements (Y or Ba) with concentrations of 0.03, 0.12 and 0.2. Structural characterization through X-ray diffraction (XRD) and lattice parameter refinement with FullProf revealed a reduction in the ZrB_2 crystal structure, indicating limited solubility with increasing Ba and Y doping. Furthermore, micrographs obtained by scanning electron microscopy (SEM) exhibit homogeneous laminar growth in the studied systems. Finally, the magnetic characterization is presented, demonstrating superconducting behavior with a critical temperature (Tc) of 8K.

Odd-frequency superfluidity from a particle-number-conserving perspective

K. Thompson,[1, 2] U. Zülicke,[1, 3] J. Schmalian,[4, 5] M. Governale,[1] and J. Brand[6]

[1]MacDiarmid Institute, School of Chemical and Physical Sciences, Victoria University of Wellington, PO Box 600, Wellington 6140, New Zealand
[2]Cavendish Laboratory, JJ Thomson Avenue, Cambridge CB3 0HE, United Kingdom
[3]Dodd-Walls Centre for Photonic and Quantum Technologies, School of Chemical and Physical Sciences, Victoria University of Wellington, PO Box 600, Wellington 6140, New Zealand
[4]Institute for Theory of Condensed Matter, Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany
[5]Institute for Quantum Materials and Technologies, Karlsruhe Institute of Technology, 76126 Karlsruhe, Germany
[6]Dodd-Walls Centre for Photonic and Quantum Technologies, Centre for Theoretical Chemistry and Physics, New Zealand Institute for Advanced Study, Massey University, Private Bag 102904, North Shore, Auckland 0745, New Zealand

We investigate odd-in-time — or *odd-frequency* — pairing of fermions in equilibrium systems within the particle-number-conserving framework of Penrose, Onsager and Yang, where superfluid order is defined by macroscopic eigenvalues of reduced density matrices. We show that odd-frequency pair correlations are synonymous with even fermion-exchange symmetry in a time-dependent correlation function that generalises the two-body reduced density matrix. Macroscopic even-under fermion-exchange pairing is found to emerge from conventional Penrose-Onsager-Yang condensation in two-body or higher-order reduced density matrices through the symmetry-mixing properties of the Hamiltonian. We identify and characterise a transformer matrix responsible for producing macroscopic even fermion-exchange correlations that coexist with a conventional Cooper-pair condensate, while a generator matrix is shown to be responsible for creating macroscopic even fermion-exchange correlations from hidden orders such as a multi-particle condensate. The transformer scenario is illustrated using the spin-balanced s-wave superfluid with Zeeman splitting as an example. The generator scenario is demonstrated by the composite-boson condensate arising for itinerant electrons coupled to magnetic excitations. Structural analysis of the transformer and generator matrices is shown to provide general conditions for odd-frequency pairing order to arise in a given system. Our formalism facilitates a fully general derivation of the Meissner effect for odd-frequency superconductors that holds also beyond the regime of validity for mean-field theory.

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Interlayer interaction-driven $s^{\pm}$-to-d_{xy}-wave superconductivity in $La_3Ni_2O_7$ under pressure

Lauro B. Braz[1], George B. Martins[2], Luis G. G. de V. D. Da Silva[1]

[1]Instituto de Física, Universidade de São Paulo,
Rua do Matão 1371, São Paulo, São Paulo 05508-090, Brazil
[2]Instituto de Física, Universidade Federal de Uberlândia, Uberlândia, Minas Gerais 38400-902, Brazil

Experimental and theoretical progress on the normal-state properties of the high-temperature superconductor $La_3Ni_2O_7$ has provided evidence of strong interlayer interactions. Considering an itinerant electron model and within the matrix random-phase approximation, we find that interlayer interactions enhance the interorbital pairing and induce d_{xy}-wave superconductivity over the $s^{\pm}$-wave. To match the d_{xy}-wave solution, the minimal model for pressurized $La_3Ni_2O_7$ needs to include all three Fermi surface pockets and, therefore, the two orbitals $d_{x^2-y^2}$ and $d_{3z^2-r^2}$.

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Number of solitons produced from a large initial pulse in the generalized NLS dispersive hydrodynamics theory

L. F. Calazans de Brito[1], A. M. Kamchatnov[2,3,4]

[1] Instituto de Física, Universidade de São Paulo, 05508-090, São Paulo, SP, Brasil
[2]Higher School of Economics, 20 Myasnitskaya ul., Moscow, 101000, Russia
[3]Institute of Spectroscopy, Russian Academy of Sciences, Troitsk, Moscow, 108840, Russia
[4]Skolkovo Institute of Science and Technology, Skolkovo, Moscow, 143026, Russia

We show that the number of solitons produced from an arbitrary initial pulse of the simple wave type can be calculated analytically if its evolution is governed by a generalized nonlinear Schrödinger equation provided this number is large enough. The final result generalizes the asymptotic formula derived for completely integrable nonlinear wave equations like the standard NLS equation with the use of the inverse scattering transform method.

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Environment-limited transfer of angular momentum in Bose liquids

Alberto Cappellaro, Giacomo Bighin, Igor Cherepanov and Mikhail Lemeshko

Institute of Science and Technology Austria (ISTA), Am Campus 1, Klosterneuburg 3400, Austria

Impurity motion in a many-body environment has been a central issue in the field of low-temperature physics for decades. The onset of superfluidity naturally provides a well-defined region in the parameter space where dissipationless flow is achieved, with no drag force experienced by the impurity. However, most existing approaches assume a structureless object, with dissipation then being solely related to the exchange of linear momentum with the environment. On the contrary, in this work we consider a rotating impurity, with the aim of exploring how angular momentum is exchanged with the surrounding bosonic environment. By employing a quasiparticle approach based on the angulon theory, we uncover how impurity dressing by environmental excitations can establish an exchange channel, whose effectiveness crucially depends on the initial state of the impurity. Remarkably, we find that there is a critical value of initial angular momentum, above which this channel effectively freezes.

Exploring the impact of the electronic interaction nature on the thermoelectric properties of two-dimensional systems

Willdauany C. F. da Silva[1], M. A. Habitzreuter[2], Natanael de C. Costa[1] and Thereza Paiva[1]

[1]Universidade Federal do Rio de Janeiro, , Rio de Janeiro, RJ 21941-972, Brazil
[2]Instituto de Física - Universidade Federal do Rio Grande do Sul, Porto Alegre, RS 91501-970, Brazil

The influence of electronic correlations on the thermoelectric efficiency of compounds, which is characterized by the Seebeck coefficient, is an open issue in Condensed Matter and Material Physics areas. In particular, compounds such as Na_xCoO_2 and $FeSb_2$ exhibit unusual large thermopower response, a feature hardly comprehended by their (noninteracting) electronic structure. Another instance are the experimental study of the thermopower of superconducting cuprate, which different compounds displaying very similar behavior with a sign change of the Seebeck coefficient near the maximum critical temperature. This nearly universal behavior has been the subject of theoretical interest, being ascribed to a possible underlying critical point.Indeed, recent theoretical findings for the Hubbard model in two-dimensional systems pointed out to the fact that an on-site electron-electron interaction largely enhances the Seebeck coefficient around the region where the Mott gap opens, with the effects on the Power Factor being less clear [1]. Despite this interesting result, the effects of other types of interactions, whether on-site or long-ranged, whether purely electronic or mediated by boson (phonon or photon) fields is so far unknown. In order to bridge this gap, here we explore the effects of additional interactions, namely, attractive on-site interactions (by the attractive Hubbard Model), near-neighbor interactions (by the extended Hubbard Model), and phonon interactions (by the Hubbard-Holstein Model) to the Seebeck coefficient. To this end, we perform unbiased quantum Monte Carlo simulations to these different types of models at the square lattice. One of our main results is the large enhancement of the Seebeck coefficient near half filling for the extended Hubbard model. In particular, it happens when the system has large charge-charge correlations, instead of spin-spin ones. In addition, we also find an anomalous response at the quarter filling for the same model. On the other hand, the phonon mediated models exhibit an almost disregardable enhancement for the Seebeck, due to their small charge gap. This provides hints that the most significant effect on the thermopower is given by the size of the Mott/Peierls gap, which are stronger for Coulombian interactions.

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Pair density wave in the Hatsugai-Kohmoto model

Igor de M. Froldi[1],* Carlos Eduardo S. P. Corsino[1], and Hermann Freire[1]

[1] *Instituto de Física, Universidade Federal de Goiás, 74.690-900, Goiânia-GO, Brazil*

Due to their exceptional properties and potential applications, high-temperature superconductors have captivated current research in condensed matter systems. Understanding these materials often involves comparing different theoretical frameworks. While the 2D Hubbard model has been extensively used to describe electron-electron interactions in many lattice systems via approximate methods and in certain regimes, the 2D Hatsugai-Kohmoto (HK) model offers a non-perturbative and exact approach to understanding strongly correlated systems[1]. The present work investigates the emergence of superconductivity with finite momentum pairing, also known as Pair-Density Wave, through the lens of the HK model. Using an exact solution provided by this model, we aim to uncover new mechanisms behind those pairing states and their potential contribution to describing some high-temperature superconductors. This analysis underscores the value of such an exact solution in providing deeper insights into superconductivity, compared to approximate techniques applied to the 2D Hubbard model.

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* Igordmelof@gmail.com

Vortex production and drag calculation in quantum fluids

G Santos, A Gammal

University of São Paulo. São Paulo, Brazil

This study explores the properties of quantum interactions in many-body systems, with a focus on the so-called "quantum droplets." These systems have proven to be crucial for understanding complex physical phenomena such as superfluidity and superconductivity. Following Petrov's pioneering work in 2015, which introduced the addition of the Lee-Huang-Yang (LHY) term to condensates, a series of subsequent investigations have been conducted to explore the characteristics of these systems, allowing for the consideration of interactions beyond the mean-field (MF) regime. Notably, studies by Jørgensen, Bruun, and Arlt have demonstrated the feasibility of investigating systems where only quantum interactions are considered, completely neglecting the mean-field term. The objective of this work is to analyze the behavior of quantum droplets in the presence of a Gaussian obstacle, focusing on vortex production and the calculation of the induced drag, comparing these results with the predictions of the mean-field model.

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“YBaCuO SUPERCONDUCTING NANOPARTICLES AND REENTRANT SUPERCONDUCTIVITY”

E. Sebastian Hernández Ruiz, R. Escudero Derat, R. Ezequiel López Romero and A. Karla Bobadilla Valencia

Instituto de Investigaciones en Materiales, Ciudad de México, México.

ABSTRACT:

YBaCuO superconducting nanoparticles were synthesized by mechanical grinding from an initial volumetric sample synthesized by solid state reaction, in a "top-down" synthesis process, which were oxygenated at a temperature of 950°C. Morphological analysis were made by scanning electron microscopy, to know the structural changes of the particles as a function of grinding time, nanoparticles with sizes between 384-827nm were obtained. Additionally, X-ray diffraction analysis were carried out. Magnetic measurements showed a reentrant superconducting effect in both ZFC and FC measurement modes, below 10K in the smallest nanoparticle.

Dynamics and Stability of Dark-Bright Solitons in Spin-Orbit Coupled Bose-Einstein Condensates

K. Rajaswathi[1], R. Ravisankar[2], R. Radha[3], P. K. Mishra[4] and P. Muruganandam[1]
[1]Department of Physics, Bharathidasan University, Tiruchirappalli 620 024, Tamil Nadu, India. [2]Department of Physics, Zhejiang Normal University, Jinhua 321004, PR China. [3]Centre for Nonlinear Science (CeNSc), Government College for Women (Autonomous), Kumbakonam 612001, Tamil Nadu, India. [4]Department of Physics, Indian Institute of Technology Guwahati, Guwahati 781039, Assam, India.

We investigate dark-bright solitons in Bose-Einstein condensates with spin-orbit coupling and Rabi coupling, confined by harmonic and box traps. Solitons are localized wave packets with particle-like properties and are well-suited for study in Bose-Einstein condensates due to their tunable inter-atomic interactions. The presence of spin-orbit coupling can disrupt the stability of solitons, leading to changes in their shape. By utilizing numerical solutions of the Gross-Pitaevskii equations, we analyze how interactions, spin-orbit coupling, and Rabi coupling affect the behaviour of solitons. In a harmonic trap, we observe stable dark-bright solitons; however, spin-orbit interaction induces soliton motion. We also explore the reflections of single and multiple solitons without energy loss in a boxlike trap. The inclusion of spin-orbit coupling leads to soliton oscillations. Additionally, we perform stability analysis using the Bogoliubov-de Gennes excitation spectrum and explore non-equilibrium dynamics by simulating varying strengths of spin-orbit coupling.

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Non-perturbative corrections to the weakly interacting two component Fermi gas

N. Kaschewski[1], A. Pelster[1] and C. A. R. Sá de Melo[2]

[1]*Physics Department and Research Center OPTIMAS, University of Kaiserslautern-Landau, Kaiserslautern, Germany*
[2] *School of Physics, Georgia Institute of Technology, Atlanta, USA*

A simplified mean-field description of fermionic systems relies on the Hartree-Fock-Bogoliubov (HFB) approach, where the two-particle interaction is decomposed into three distinct channels. A major issue with this method is that the separation between the channels is somewhat arbitrary. Depending on the physical situation to be described, different channels turn out to be important.
We present a self-consistently generalized mean-field theory, which is based on introducing a separate weighting factor for each channel. This ansatz removes the arbitrariness of the channel separation by providing an extremization principle for their optimal partitioning.
The power of our technique is illustrated by considering the example of two unpolarized fermionic species with contact interaction. In this case the Fock contribution vanishes, and we obtain a coupling between Hartree and Bogoliubov channel. This results non only in first beyond mean-field corrections [1,2] already at the mean-field but also decreases the critical temperature in qualitative agreement to particle-hole fluctuations [3]. Due to the non-perturbative nature of the channel coupling we also obtain results which are not captured by any fluctuation theory in one channel alone. This requires the introduction of an effective interaction range as a new length scale and should become relevant for large enough densities. With this our formalism builds a natural theoretical bridge between fermionic superfluidity in ultracold atomic gases and superconductivity in condensed matter physics as well as the realm of nuclei and neutron matter.

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Hydrodynamic Description of Vortices in Photon Bose-Einstein condensates

Joshua Krauß[1], Marcos dos Santos Filho[1,2], F. Ednilson A. dos Santos[2],and Axel Pelster[1]

[1] Department of Physics and Research Center OPTIMAS, RPTU Kaiserslautern-Landau, Germany
[2] Department of Physics, Federal University of São Carlos, Brazil

Open dissipative systems of quantum fluids, especially in presence of vortices, are well studied numerically in Refs. [1-3]. Motivated by that we strive for finding a corresponding approximate analytical description of photon Bose-Einstein condensates in the presence of vortices. To this end we consider the complex Gross-Pitaevski equation of Ref. [3] and extend the variational approximation to open dissipative systems [4,5] in such a way that it is not only working for specific functions. To this end we develop a variational projection method and combine it with known methods from hydrodynamics. With this we approximately obtain a vortex solution and its corresponding velocity field, where depend on the respective open system parameters and have the same properties as obtained numerically in Ref. [2].

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Phononic crystals for inertial sensing with dilute gas superfluids

L. Miller[1], C. W. Woffinden[1], A. J. Groszek[1], H. Rubinsztein-Dunlop[1,2], T. W. Neely[1]
[1]Australian Research Council Centre of Excellence for Engineered Quantum Systems, The University of Queensland, St Lucia Brisbane QLD 4072
[2]Australian Research Council Centre of Excellence for Quantum Biotechnology The University of Queensland, St. Lucia, Brisbane, QLD 4072

Ultracold atom interferometry for inertial sensing in GPS/GNSS-denied environments presents a sensitive and potentially calibration-free alternative to light-based interferometers. While free-space atom interferometers have approached commercial scale implementation, trapped cold atoms platforms will offer greater advantages in compactness and robustness to accelerating platforms. However, trapped atom interferometers are potentially limited by increased phase-diffusion caused by two-body interactions at high densities.

Marti et al. [1] developed a collective excitation interferometry method in a toroidal Bose-Einstein condensate sensor that measured rotation using the interference of counterpropagating phonons in a 2D ring geometry. They demonstrated a proof-of-concept device operating at the high densities and small volumes of trapped Bose-Einstein condensed gases [1]. In their setup, both atom number and the integer azimuthal phonon mode were limited by the small size of the ring. Building on this work, we recently explored the sensing limits of a similar trapped atom system, experimentally finding an improved sensitivity of 0.3 rad s^{-1} with a larger ring and finer control of the spatial varied phonon imprinting potential with a digital micromirror device [2]. Numerical modelling found that four-wave mixing and thermal damping limit the lifetime of the imprinted phonons, as well as the achieved quality factor of the oscillator due to the low interrogation time [2].

In this presentation, I discuss how we increase the quality factor with the implementation of a resonant phononic crystal geometry, based on our previous work with atomtronic Helmholtz resonators [3]. We simulate the evolution of the system in this new geometry with the Gross-Pitaevski Equation, investigating the role of geometry on the lifetime of imprinted phonons and hence the quality factor. Experimentally, confining the atoms to novel geometries and limiting the thermal background may improve the performance of the rotation sensor for finer measurement precision via a significantly increased interrogation time.

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Supersolid States in Anti-Dipolar Bose-Einstein Condensates: Insights into Phase Diagram, Collective Excitation Spectra and rotational properties

Koushik Mukherjee, Tiziano Arnone Cardinale, Mikael Nilsson Tengstrand, Stephanie M. Reimann

Mathematical Physics and NanoLund, Lund University, Box 118, 22100 Lund, Sweden

Supersolidity is a highly counterintuitive phenomenon in which a system spontaneously breaks translational symmetry, resembling a solid, while maintaining the frictionless flow characteristic of a superfluid. Although numerous recent studies have focused on regular dipolar condensates, where atoms attract in a head-to-tail arrangement and repel in a side-by-side configuration, anti dipolar condensates—with reversed interactions—also hold the promise of revealing new and nontrivial phenomena. While the excitation spectra and phase diagram across the superfluid-to-supersolid transition remain qualitatively similar to those of regular dipolar supersolids, unique rotational properties can emerge for anti-dipolar condensates in a ring geometry due to the formation of stacked ring crystals. Specifically, under the influence of a rotating asymmetrical potential barrier, it is possible to create superfluid persistent currents selectively in a few layers, while others rotate like a rigid body. This can lead to the observation of Josephson vortices and has significant implications for the development of novel atom circuits.

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Unravelling Interaction and Temperature Contributions in Unpolarized Trapped Fermionic Atoms in the BCS Regime

S. Yong, S. Barbosa, J. Koch, F. Lang, A. Pelster, and A. Widera

Physics Department and Research Center OPTIMAS,
RPTU Kaiserslautern-Landau, Germany

In the BCS limit density profiles for unpolarized trapped fermionic clouds of atoms are largely featureless. Therefore, it is a delicate task to analyze them in order to quantify their respective interaction and temperature contributions. Temperature measurements have so far been mostly considered in an indirect way, where one sweeps isentropically from the BCS to the BEC limit. Instead we suggest here a direct thermometry, which relies on measuring the line density and comparing the obtained data with a Hartree-Bogoliubov mean-field theory combined with a local density approximation. In case of an attractive interaction between two-components of ^{6}Li atoms trapped in a tri-axial harmonic confinement we show that minimizing the error within such an experiment-theory collaboration turns out to be a reasonable criterion for analyzing in detail measured densities and, thus, for ultimately determining the sample temperatures. The findings are discussed in view of various possible sources of errors.

SYSTEMATIZATION FOR THE WORLD-LINE QUANTUM MONTE CARLO ALGORITHM

Juan Pablo Pinilla Realpe[1], *Karen Rodríguez Ramírez*[1]
[1]*Departamento de Física, Universidad del Valle, A.A. 25360, Cali, Colombia*

juan.pinilla@correounivalle.edu.co

The junction between optical lattices and ultra-cold particles constitutes highly controllable systems that serves as extraordinary quantum simulators, particularly for the study of strongly correlated systems [1,2]. Moreover, due to the particle's internal degrees of freedom novel ground-state physics arise [3]. For instance, spin-1 bosons trapped on optical lattices and in the presence of a magnetic field exhibits multiple induced quantum phases, making them suitable to study quantum phase transitions and quantum magnetism [4,5]. Even so, the role of the quadratic Zeeman effect in the phase transitions of spin-1 particles remains largely unexplored in the context of one-dimensional potentials [6,7]. In this work we present the physics of our system: Strongly interacting spin-1 bosons trapped on a one-dimensional periodic potential in presence of a quadratic magnetic field, described by the Bilinear-Biquadratic Heisenberg model. In the low-energy regime, we restrict ourselves to the specific case of one boson per site and interactions just to nearest neighbors. Then, we implement the World-Line Quantum Monte Carlo algorithm to perform measurements on the system and characterize the ferromagnetic and nematic quantum phases through local and non-local observables, such as the energy, the quadrupolar density, the occupation profile and two types of spin correlations.

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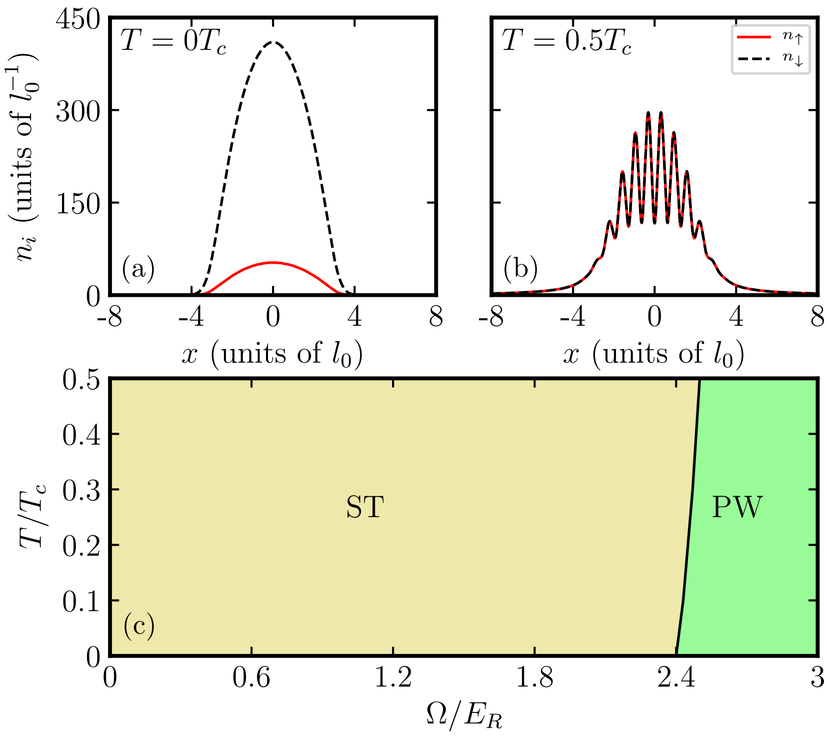
Temperature-induced supersolidity in spin-orbit-coupled Bose gases

[a]Rajat, [a]Ritu, [b]Arko Roy, [a]Sandeep Gautam

[a]*Department of Physics Indian Institute of Technology Ropar Rupnagar-140001 Punjab India*
[b]*School of Physical Sciences Indian Institute of Technology Mandi Mandi-175075 (H.P.) India*

Close to the superfluid, plane-wave (PW) - supersolid stripe (ST) phase transition point of a zero temperature quasi-one-dimensional spin-orbit-coupled Bose gas, we find that an increase in temperature induces a phase transition to the supersolid phase with a broken translational symmetry from the superfluid plane-wave phase. We use the Hartree-Fock- Bogoliubov theory with the Popov approximation to investigate the effect of thermal fluctuations on the collective excitation spectrum and investigate the softening of the spin- dipole mode corresponding to the shift in the quantum critical point. This is in stark contrast to the PW-ST phase transition in a homogeneous system where non-zero temperatures facilitate the melting of the stripe phase.



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Temporal Bistability in the Dissipative Dicke-Bose-Hubbard System

Tianyi Wu[1], Fredrik Vermeulen[1], Sayak Ray[1] and Johann Kroha[1,2]

[1]*Physikalisches Institut, Rheinische Friedrich-Wilhelms-Universität Bonn, Nussallee 12, 53115 Bonn, Germany*
[2]*School of Physics and Astronomy, University of St. Andrews, North Haugh, St. Andrews, KY16 9SS, United Kingdom*

We consider a driven-dissipative system consisting of an atomic Bose-Einstein condensate loaded into a two-dimensional Hubbard lattice and coupled to a single mode of an optical cavity. Due to the interplay between strong, repulsive atomic interaction and the atom-cavity coupling, the system exhibits several phases of atoms and photons including the atomic superfluid (SF) and supersolid (SS). We investigate the dynamical behaviour of the system, where we include dissipation by means of the Lindblad master-equation formalism. Due to the discontinuous nature of the Dicke transition for strong atomic repulsion, we find a extended co-existence region of different phases. Such a co-existence, in the limit of vanishing dissipation, is further investigated from the underlying Ginzburg-Landau free energy landscape. We study the resulting, temporal switching dynamics, particularly between the coexisting SF and SS phases, which eventually become damped due to the dissipation.

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Interplay between charge density wave and superconductivity in multiband intermetallic systems

Daniel Reyes[1*], Nei Lopes[2], Natanel C. Costa[3], Mucio A. Continentino[4], Christopher Thomas[5]

[1] *Instituto Militar de Engenharia - Praça General Tibúrcio 80, 22290-270 Praia Vermelha, Rio de Janeiro, Brazil*

[2] *Departamento de Física Teórica, Universidade do Estado do Rio de Janeiro, Rua São Francisco Xavier 524, Maracanã, 20550-013 Rio de Janeiro, RJ, Brazil*

[3] *Instituto de Física, Universidade Federal do Rio de Janeiro, Rio de Janeiro, RJ 21941-972, Brazil*

[4] *Centro Brasileiro de Pesquisas Físicas, Rua Dr. Xavier Sigaud 150, Urca, 22290-180 Rio de Janeiro, Brazil*

[5] *Instituto de Física, Universidade Federal do Rio Grande do Sul, 91501-970 Porto Alegre, Brazil*

Abstract

In this work we study the interplay between charge density wave (CDW) and superconductivity (SC) in a two-band model system in a square lattice. One of the bands has a net attractive interaction (J_d) that is responsible for SC. The model includes on-site Coulomb repulsion between quasiparticles in different bands (U_{dc}) and the hybridization (V) between them. We are interested in describing intermetallic systems with a d-band of moderately correlated electrons, for which a mean-field approximation is adequate, coexisting with a large sp-band. For simplicity, all interactions and the hybridization V are considered site-independent. We obtain the eigenvalues of the Hamiltonian numerically and minimize the free energy density with respect to the relevant parameters to obtain the phase diagrams as function of J_d, U_{dc}, V, band-filling (n_{tot}), and the relative depth of the bands ϵ_{d0}. The model reproduces most of the experimental features of high dimensionality (D > 1) metals with competing CDW and SC states, including the existence of first - and second-order phase transitions in their phase diagrams. Our results also show that the CDW and SC orders compete, but depending on the parameters of the model these phases may coexist [1, 2].

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Simulations using Bose-Einstein condensate theory and Monte Carlo method

RIBEIRO, V. Juliana[1]

[1]Latin American Institute of Life and Nature Sciences - ILACVN/UNILA, Foz do Iguaçu, Brazil

Starting from the basic review of the initial conditions describing the Bose-Einstein condensate, relate the identified parameters of behaviour of particles at low temperature with the variables of disordered systems. This work aims to explore the available Monte Carlo methods to solving problems of disordered systems and out-of-equilibrium potential. Finally discuss range of applications in the numerical solution to calculate the identified parameters by modelling computer simulations of thermodynamic interactions.

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Multiple excitations in Bose-Einstein condensate on curved surfaces

R Sallatti, A Gammal

University of São Paulo. São Paulo, Brazil

Systems of multiple vortices are a topic of extreme importance for better understanding the phenomenon of turbulence present in both classical and quantum systems. Bose-Einstein condensation is ideal for studying this phenomenon due to its mean-field description given by the Gross-Pitaevskii equation (GPE) [1,2,3]. The GPE is a nonlinear equation that does not have a simple analytical solution but can be solved using numerical methods[4]. Recently, an experiment trapped a condensate on the surface of a bubble, bringing much attention to the topic of condensates on curved surfaces[5]. The objective of this work is to describe a system of multiple vortices on the surface of a sphere.

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BCS and FFLO superconducting states in ultracold atomic gases

M. Sanino[1], I. M. Carvalho[1] and V. V. França[1]

[1]*Institute of Chemistry, São Paulo State University, 14800-090, Araraquara, São Paulo, Brazil.*

Ultracold fermionic gases in optical lattices offer a significant opportunity for exploring novel states. Among them is the phase separation induced by a trapping potential between different superfluid phases. The types and sequences of these emerging phases in such structures may depend on spin-imbalance, trap shape, and on-site interaction strength. Here, we investigate the properties of such structures within an attractive fermionic Hubbard model loaded into the optical lattice, considering the presence of the trapping potential and their relation to the phase diagram of the homogeneous system. Our preliminary results show the emergence of a core-shell structure within a system featuring a harmonic trap, which includes both the BCS (conventional Cooper pairs superfluidity) and FFLO (Fulde-Ferrell-Larkin-Ovchnnikov exotic superfluid) states. More interestingly, by calculating the second derivative of the on-site energy term with respect to the polarization, we observe a negative magnetic susceptibility-like behavior in the FFLO phase, which may be related to magnetic shielding. Additionally, we show that the system's magnetic susceptibility decays to its minimal value around the universal critical polarization $P_c = 1/3$.

Entanglement as a Quantum Energy Resource

Jefter Santiago[1], Krissia Zawadzki[2]
[1]Instituto de Física de São Carlos, Universidade de São Paulo, São Carlos, Brazil

Understanding how entanglement can be used as an energy resource is essential for developing efficient quantum technologies. In this work, we aim to understand the relationship between entanglement and its potential use in work production and extraction within quantum systems. Specifically, we consider a fermion chain undergoing a superfluid-to-insulator transition (SIT) phase. We explore two distinct quench protocols: one involving variations in the concentration of impurities within the chain and the other addressing the introduction of increasing disorder. These protocols, previously established in the literature, were reproduced in this study, with additional exploration of finite-time dynamics. Previous work with the SIT at sudden quenches reveals that in the ground state with minimal entanglement, the average work is maximized at a critical impurity concentration, and the moments of the work distribution are minimized. In the context of non-ideal measurements, fluctuations become significant, and the moments of the work distribution do not necessarily vanish. These results offer insights into the SIT phase and demonstrate the potential for manipulating entanglement to optimize work production.

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Fluctuations in an interacting Bose gas confined in a ring

J. S. Soares, A.Pelster, A Gammal

University of São Paulo. São Paulo, Brazil

In general, the experiments involving the Bose-Einstein condensation are done with many particles [1], but recently we have experiments realized with a finite number of particles [2,3,4], where theoretically, the canonical ensemble is a great approach to this situation [5]. Here we apply the idea for an interacting case in a ring confinement calculating the condensed fraction and ground-state fluctuations in the Bogoliubov canonical regime [6] comparating its with other statistical distributions and seeing the long cylinder case [7] that is the result which can be obtained when we have a long ring.

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Non-Hermitian phase transition in a pumped bulk solid state system

Michael Turaev[1] and Johann Kroha[1,2]
[1] *Physikalisches Institut and Bethe Center for Theoretical Physics, Universität Bonn, Nussallee 12, 53115 Bonn, Germany*
[2] *School of Physics and Astronomy, University of St. Andrews, North Haugh, St. Andrews, KY16 9SS, United Kingdom*

Non-equilibrium physics explores systems driven far away from equilibrium, where unique phenomena and states emerge, which cannot be realized in equilibrium. Unlike in equilibrium, a non-equilibrium quantum phase transition is characterized by an exceptional point where two eigenvalues, which may be complex, become degenerate and the respective eigenstates coalesce. One of the first experimental realizations of such a non-Hermitian phase transition was in a photon Bose-Einstein condensate in a microcavity [1].

Here we propose that a non-equilibrium quantum phase transition can also be realized in a pump probe experiment of a bulk solid-state system. In such experiments, the pump, usually a short pulse, drives the system away from equilibrium, while the probe measures how the system responds to the pump pulse as a function of time. In a recent pump-probe experiment [2], the reflectivity properties of stoichiometric EuO were investigated across its ferromagnetic transition. Upon varying the base temperature, two distinct behaviors in the relaxation dynamics were observed. In the ferromagnetic phase a bi-exponential behavior is seen, deep in the paramagnetic regime at a critical temperature T_X a damped oscillatory behavior is observed. In the present work we model this scenario using the Lindblad formalism, where we develop rate equations for the magnons and the excitons which are excited by the pump. We find the occurrence of an exceptional point deep in the paramagnetic regime. As a characteristic of the exceptional point the oscillation frequency depends on the base temperature as $\sqrt{(T-T_X)/T_X}$, in agreement with the experimental data.

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Rymax One: A neutral atom quantum processor to solve optimization problems

José Vargas[1], Benjamin Abeln[1], Tobias Ebert[1], Silvia Ferrante[1], Kapil Goswami[1], Jonas Gutsche[2], Hendrik Koser[1], Rick Mukherjee[1], Jens Nettersheim[2], Martin Schlederer[1], Jonas Witzenrath[2], Niclas Luick[1], Thomas Niedersprüm[2], Dieter Jaksch[1], Henning Moritz[1], Herwig Ott[2], Peter Schmelcher[1], Klaus Sengstock[1], and Artur Widera[2]

[1]Institut für Quantenphysik, Universität Hamburg, Germany
[2]RPTU Kaiserslautern-Landau, Kaiserslautern, Germany

To explore the potential of quantum computing processors for real-world applications such as the efficient distribution of workload in industrial manufacturing plants, and short vehicle routes for parcel delivery, we are building Rymax One, a quantum processor designed to solve hard optimization problems. By using ultracold neutral Ytterbium atoms trapped in optical tweezer arrays with arbitrary spatial distribution, we aim for hardware-efficient encoding of optimization tasks. Alkaline-earth hyperfine structure level provides qubit realizations with long coherence times, Rydberg-mediated interactions, and high fidelity gate operations, allowing us to experimentally realize a scalable platform for quantum processing. The latter will open up the performance of novel quantum algorithms to tackle real-world problems.

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Linear-mode and scissor-mode oscillations of a 1D and 2D supersolid crystalline structure of droplets in dipolar Bose-Einstein Condensate

Luis Ever Young Silva[1] and Sadhan Kumar Adhikari[2]

[1]Grupo de Modelado Computacional, Facultad de Ciencias Exactas y Naturales, Universidad de Cartagena, Cartagena de Indias, Colombia. [2]Instituto de Física Teórica, UNESP - São Paulo State University, São Paulo, Brazil.

A supersolid, or a superfluid solid [1], is a quantum state of matter simultaneously possessing the properties of both a solid and a superfluid. Hence, a supersolid has a spatially-periodic crystalline structure as a solid, breaking continuous translational invariance, and also enjoys frictionless flow like a superfluid, breaking continuous gauge invariance. The study of supersolids has recently gained new momentum among research workers in various fields [2], after the experimental observation of supersolids in a quasi-one-dimensional (quasi-1D) and in a quasi-two-dimensional (quasi-2D) dipolar Bose-Einstein condensate (BEC). In this work we demonstrate numerically the dipole-mode and scissors-mode oscillations of a supersolid crystal composed of dipolar droplets arranged on a one-dimensional (1D) or two-dimensional (2D) lattice to establish the robustness of its crystalline structure under translation and rotation, using an improved mean-field model including a quantum-fluctuation Lee-Huang-Yang (LHY) type interaction to prevent the collapse in the case of an appropriate mixture of contact and dipolar interactions [3]. The dipole-mode oscillation starts when a small linear translation is given to the harmonic trap along the x direction. To start the scissors-mode oscillation, a small angular rotation is given to the harmonic trap around the z direction. We prove that a stable dipole-mode oscillation is possible in the case of both quasi-1D and quasi-2D dipolar supersolids, whereas a sustained angular scissors-mode oscillation is possible only in the case of a quasi-1D dipolar supersolid between a maximum and a minimum of trap anisotropy in the x-y plane. In both cases, without any visible distortion of the lattice structure of droplets, tests of both the superfluidity and the robustness of the crystalline structure of the dipolar supersolid under translation and rotation hence confirm the supersolidity of these states and with present knowhow the results of this study can be an ideal candidate for future experimental observation.

References

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