Book of Abstracts

MultiSuper 2023

Multicomponent Superconductivity and Superfluidity

MultiSuper Network
International Network on Multi- component Superconductivity and Superfluidity

Leiden Cryogenics
Leader in Low Temperature Techniques

Universiteit Antwerpen

UNICAM Università di Camerino 1336

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Contents

About

MultiSuper 2023 : Multicomponent Superconductivity and Superfluidity

This international conference provides an excellent forum for presenting and discussing recent developments and novel ideas in diverse fields of superconductivity and superfluidity, in the beautiful seaside town of San Benedetto del Tronto, in the south of Le Marche region of Italy. During the conference we will discuss opportunities to establish large collaboration efforts or empowering existing ones, as well as to plan joint participation to international projects. Young participants will be able to look and discuss opportunities for doctoral or post doc positions. Cross-fertilization and merging of capacities and methods will be encouraged in a very interactive atmosphere.

Topics of interest

- Fluctuations and BCS-BEC crossover phenomena in low dimensional systems.
- Hybrid systems, superconductivity at the interfaces, and coexistence of phases.
- Highly nonlinear phenomena: Josephson and Andreev effects, topological defects, skyrmions and solitons, vortex states.
- Novel phenomena in multicomponent / multigap superconductors and superfluids.
- Innovative numerical methods

Organizing committee

Roberta Citro, University of Salerno
Milorad V. Milosevic, University of Antwerp, Belgium
David Neilson, University of Antwerp, Belgium and FLEET, Australia
Andrea Perali, University of Camerino, Italy

Local organizers

Luis A. Peña Ardila and Andrea Perali, University of Camerino, Italy

Timetable

CT=invited talk

Friday – September 8

14:30–15:00	**Welcome remarks**		
15:00–15:30	CT	**Roberta Citro**	A novel platform for topological superconductivity in multiband and multiorbital systems
15:30–16:00	CT	**Yukio Hasegawa**	2D superconductivity vs. disorder: Pb monolayer superconductors formed on vicinal Si(111) substrates
16:00–16:30	CT	**Jonas Bekaert**	The road to superconducting MXenes
16:30–17:00	**Break and discussions**		
17:00–17:30	CT	**Dario Daghero**	Protonation-induced superconductivity in 1T-TiSe 2
17:30–18:00	CT	**Tommaso Confalone**	Twisted cuprate van der Waals heterostructures with controlled Josephson coupling
18:00–18:30	CT	**Stefano Lupi**	The Electrodynamics Properties of Superconducting Nd0.8Sr0.2NiO2 Nickelate
18:30-19:00	CT	**Patric Holmvall**	Robust and tunable coreless vortices and fractional vortices as direct signature of chiral d-wave superconductivity

Saturday – September 9

9:30–10:00	CT	**Sergio Caprara**	Competition between superconductivity and charge order in cuprates: a thermodynamic phase diagram
10:00–10:30	CT	**Antonio Bianconi**	Engeenering new artificial high-Tc superlattices tuned at the Fano-Feshbach resonance by quantum design
10:30–11:00	CT	**Massimo Capone**	Electron-boson coupling in multiorbital quantum materials
11:00–11:30	**Coffee Break**		
11:30–12:00	CT	**Christopher Vale**	Amplitude oscillations in ultracold Fermi gases
12:00–12:30	CT	**Tasakada Shibauch**	Unusual BCS-BEC crossover and exotic superconducting states in FeSe-based materials
12:30–13:00	CT	**Andrii Kuibarov**	Superconducting arcs in PtBi2
13:00–15:00	**Lunch Break**		
15:00–15:30	CT	**Giovanni Midei**	Sweeping across the BCS-BEC crossover, reentrant, and hidden quantum phase transitions in two-band superconductors by tuning the valence and conduction bands
15:30–16:00	CT	**Jordi Boronat**	Liquid and solid phases of dipolar atoms in a multilayer
16:00-16:30	CT	**Serghei Klimin**	Low-lying collective excitations of superconductors and charged Fermi superfluids in the BCS-BEC crossover
16:30-17:00	CT	**Leonardo Pisani**	Josephson effect and Landau critical velocity in the BCS-BEC crossover
17:00–18:30	**Poster session with drinks and snacks.**		
20:00	**Conference dinner at “XXX” Restaurant.**		

Sunday – September 10

10:30-11:00	CT	**Gianni Profeta**	Unveiling the pairing symmetry of the superconducting Sn/Si(111) via angle-resolved THz pump spectroscopy
11:00-11:30	CT	**Claudio Guarcello**	Thermoelectric signatures of order-parameter symmetries in iron-based superconducting tunnel junctions
11:30–12:00	CT	**Sathish Kumar Paramavisam**	High-Tc BKT superconducting transition in 2D systems with coupled deep and quasi-flat electronic bands with vHs
12:00–12:30	CT	**Hiroyuki Tajima**	Multi-component Quantum Gases in Ultracold Atoms, Condensed Matter, and Nuclear Systems

12:30–13:00	CT	**Bilal Tanatar**	Density and pseudo-spin rotons in a bilayer of soft-core bosons
13:00–15:00	**Lunch Break**		
15:00–15:30	CT	**Davide Valentinis**	Fermi-liquid to non-Fermi liquid crossovers in the superconducting Yukawa-SYK model on a lattice
15:30–16:00	CT	**Andrea Richaud**	Making ghost vortices visible in two-component Bose-Einstein condensates
16:00–16:30	CT	**Alice Bellettini**	Relative dynamics of quantum vortices and massive cores in binary BECs
16:30–17:00	**Coffee Break**		
17:00–17:30	CT	**Milorad V. Milosevic**	Vortex matter in multicomponent superconductors
17:30–18:00	CT	**Andrea Perali**	Screening of pair fluctuations in multiband superconductors: a mechanism to stabilize higher-Tc superconductivity

List of Abstracts – Talks

Talks (in alphabetic order)

The road to superconducting MXenes

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I will present our first-principles roadmap for superconductivity in MXenes – an emerging materials family comprising two-dimensional transition metal carbides and nitrides – constructed over several years of research [1-3]. With our seminal exploration of superconductivity in pristine MXene monolayers as the point of departure [1], we will navigate through various ways to achieve enhanced superconductivity in MXenes by functionalization with hydrogen [2] and other functional atoms (e.g., chlorine and sulfur) [3], and by applying strain and gating [3]. Along the way, I will demonstrate how the intricate interplay between electrons and phonons leads up to the emergence of superconductivity in MXenes. Finally, I will discuss recent experimental efforts that successfully realized superconductivity in diverse functionalized MXenes.

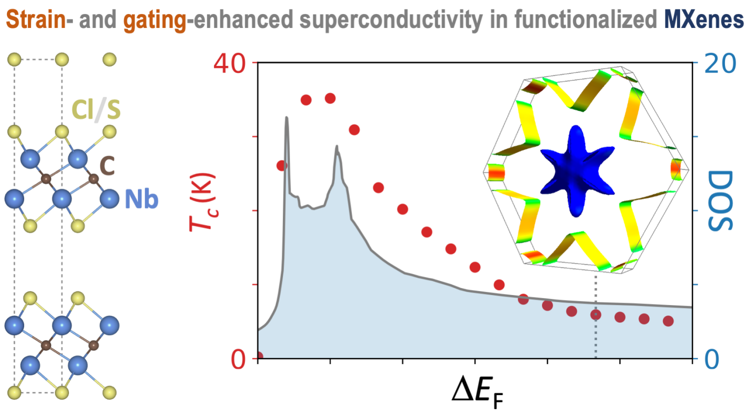

Figure 0.1: Strain- and gating-enhanced superconductivity in functionalized niobium-carbide MXenes [3].

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[3] C. Sevik, J. Bekaert, and M. V. Milosevic, “Superconductivity in functionalized niobium-carbide MXenes”, Nanoscale 15, 8792 (2023).

Relative dynamics of quantum vortices and massive cores in binary BECs

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We study vortices with massive cores [1], [2] in binary mixtures of Bose-Einstein condensates. We consider the case of a simple 2D disc geometry. Taking up the work of Richaud et al. [3], [4], we introduce a point-vortex model where quantum vortices in the majority species are coupled to the corresponding core masses, i. e. local peaks of the minority species. The point-like dynamics is obtained via a variational Lagrangian approach. In parallel, we validate our analytical results via the numerical resolution of two coupled Gross-Pitaevskii equations. Conversely to the previous works [3], [4], where a vortex centre was assumed coincident with the centre of its massive core, we instead introduce a more refined dynamical model: here, the two objects are described by independent sets of dynamical variables and coupled by an harmonic term. Consequently, we study the effect of the new degree of freedom on the vortex-mass relative motion and average dynamics.

As already observed, the first striking effect of the second species is a change of trajectory. Whereas a massless vortex in a 2D disc moves of uniform circular motion, in presence of a second species some radial oscillations may arise. Specifically, our new model brings to a more articulated normal mode analysis, and improves the previous model thanks to the dependency of the small oscillations on the inter-species coupling parameter g_{ab}. This dependency could not be appreciated in the previous model as it did not include the parameter g_{ab} at all. On the other hand, we confirm that, within the physical ranges of the coupling parameters, there is no significant relative motion of the vortex with respect to its core mass.

References

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Engeenering new artificial high-Tc superlattices tuned at the Fano-Feshbach resonance by quantum design

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While the search for new high-temperature superconductors was driven for decades by the empirical "trials and errors" method, recently the synthesis of Artificial High- T_c Superlattices (AHTS) designed by quantum mechanics theory at the nanoscale opening the roadmap for engineering a new class of high temperature superconductors has been reported [Logvenov et al, Condenseed Matter (2023)]. Following the predictions of quantum theory [Mazziotti M.V., et al., Journal of Applied Physics 132, 193908 (2022)] we nanoscale superlattices of quantum wells with their high- T_c superconducting dome have designed by controlling via the conformational parameter of the superlattice geometry, Using molecular beam epitaxy (MBE) many AHTS sampleswe have been grown made of first layers of stoichiometric $\mathrm{La_2CuO_4(LCO)}$ units of thickness L, electronic doped by interface space charge, intercalated by second non-superconducting layers $\mathrm{La_{1.55}Sr_{0.45}CuO_4}$ (LSCO) of thickness W forming a superlattice of period d. The agreement between the experimental superconducting dome with the theoretical dome predicted by the Bianconi Perali Valletta (BPV) theory [A. Perali et al. Solid State Cmmuniaations 100, 181 (1996), A. Bianonii Physica C 296,, 269 (1998) for AHTS validates the prediction that the superconducting dome is due to a Fano-Feshbach or shape resonance in multigap superconductivity driven by quantum nanoscale confinement while for decades it nature remained elusive and object of controversy inspite it was considered the hallmark of the strange metal phase giving high temperature superconductivity.

Liquid and solid phases of dipolar atoms in a multilayer

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We show that ultradilute quantum liquids can be formed with ultracold bosonic dipolar atoms in a bilayer geometry. Contrary to previous realizations of ultradilute liquids, there is no need of stabilizing the system with an additional repulsive short-range potential. The advantage of the proposed system is that dipolar interactions on their own are sufficient for creation of a self-bound state and no additional short-range potential is needed for the stabilization. We perform quantum Monte Carlo simulations and find a rich ground state phase diagram that contains quantum phase transitions between liquid, solid, atomic gas, and molecular gas phases. The stabilization mechanism of the liquid phase is consistent with the microscopic scenario in which the effective dimer-dimer attraction is balanced by an effective three-dimer repulsion. The equilibrium density of the liquid, which is extremely small, can be controlled by the interlayer distance. From the equation of state, we extract the spinodal density, below which the homogeneous system breaks into droplets. Our results offer a new example of a two-dimensional interacting dipolar liquid in a clean and highly controllable setup [1]. Going from a bilayer to a multilayer geometry, we observe that a crystal phase, of very low density, can be stabilized due to the increase of attraction between atoms in different layers [2].

References

[1] G. Guijaro, G. E. Astrakharchik, and J. Boronat, Phys. Rev. Lett. **128**, 063401 (2022).
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Electron-boson coupling in multiorbital quantum materials

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Competition between superconductivity and charge order in cuprates: a thermodynamic phase diagram

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We argue that there is a specific value of the doping in the temperature vs. doping phase diagram of cuprates, such that a charge-ordered and a superconducting phase are degenerate in energy, but are separated by an energy barrier. We discuss a Monte Carlo analysis of a model that is apt to capture this physics, without and with quenched disorder. While in the absence of disorder charge order and superconductivity are separated by a first-order line which is nearly independent of temperature, in the presence of quenched disorder, charge order is fragmented into domains separated by superconducting filaments reminiscent of the supersolid behavior in ^{4}He. The behavior of various physical quantities and the resulting phase diagram are in good agreement with the experiments.

References

[1] Giulia Venditti, Ilaria Maccari, Jose Lorenzana, Sergio Caprara, arXiv:2306.17094 (2023).

A novel platform for topological superconductivity in multiband and multiorbital systems

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I will first review the properties of toy-models for topological superconductivity, the Kitaev chain and its generalizations. After discussing the topological phase diagram of the isolated system, using a scattering technique within the Bogoliubov–de Gennes formulation, I will discuss the differential conductance properties as a function of all relevant model parameters[1]. The relevant problem of implementing local spectroscopic measurements to characterize the Majorana fermions useful in quantum technologies is also addressed. Then, I will present a novel platform for topological superconductivity based on 2DEGs at LAO/STO interface. Here the interplay of spin-orbit interaction and intrinsic superconductivity may induce a topological phase transition in an applied magnetic field with strong orbital character[2,3]. The conclusions will address the design of various nanowire-based mesoscopic devices for topological computation[4,5].

References

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Twisted cuprate van der Waals heterostructures with controlled Josephson coupling

Tommaso Confalone[1,2], **Mickey Martini**[1,2], **Yejin Lee**[1,2], **Sanaz Shokri**[1,2], **Christian N. Saggau**[1], **Daniel Wolf**[1], **Genda Gu**[3], **Kenji Watanabe**[4], **Takashi Taniguchi**[5], **Domenico Montemurro**[6], **Valerii M. Vinokur**[7,8], **Kornelius Nielsch**[1,2,9], **and Nicola Poccia**[1]

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Twisted van der Waals heterostructures comprising high temperature $Bi_2Sr_2CaCu_2O_{8+\delta}$ cuprate superconductors represent an ideal platform for controlling the efficient Josephson coupling between the layers. However, the tendency of the material to lose doping oxygen and its high reactivity to moisture makes the realization of interfaces with preserved superconductivity extremely challenging. Our work focuses on the superconducting properties of twisted $Bi_2Sr_2CaCu_2O_{8+\delta}$ Josephson Junctions, created combining the cryogenic dry stacking method and the encapsulation technique, which blocks detrimental disorder at the interface throughout the entire fabrication process. The obtained junctions display a high superconducting transition temperature and a Josephson critical current strongly dependent on the twisting angle, in agreement with the anisotropic d-wave superconducting order parameter of the crystal. The Josephson critical current I_c has a maximum value at low twist angles, comparable to that of the bulk intrinsic Josephson junctions, and is reduced by two orders of magnitude near 45 degrees, where direct Cooper pair tunneling is suppressed due to the mismatch between the two order parameters.

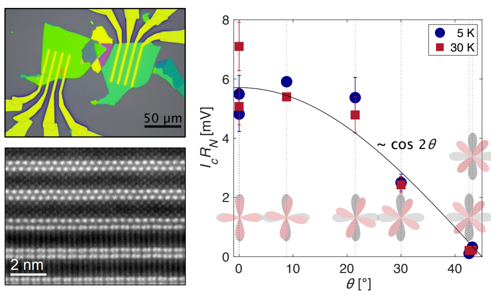

Figure 0.2: Up left: Optical micrograph of a representative device. Bottom left: TEM image displaying the cross-section of a twisted junction. Right: Josephson coupling, defined as the critical current times normal resistance, versus twist angle.

References
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Protonation-induced superconductivity in $1T-TiSe_2$

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The recent discovery of near-room temperature superconductivity (SC) in hydrides under pressure has highlighted the potential of hydrogen as a dopant and a knob for tuning the electronic and the phononic spectra of a material $[1,2]$. One of the routes to create H-rich materials is protonation induced by ionic liquid gating [3], which makes it possible to insert H atoms in crystallographic positions unattainable by a conventional synthesis approach. Here, we demonstrate that electric field-driven hydrogen intercalation via the ionic-liquid-gating method allows the non-volatile control of the electronic ground state of titanium diselenide (1T-TiSe 2) leading to the appearance of a new SC phase in $\mathrm{H}_x\mathrm{TiSe}_2$ with $\mathrm{T_c} \sim 3.6\,\mathrm{K}$. Thanks to the stability over time of this phase, we were able to carry out many different transport and spectroscopic characterizations of the SC state [3]. Fully protonated $H_\mathrm{x}\mathrm{TiSe}_2$ crystals $(x \approx 2)$ display negligible structural alterations with respect to the pristine compound, vestigial CDW signatures in the resistivity curve $\rho(T)$, and robust bulk superconductivity with $T_c \cong 3.6\,\mathrm{K}$. The superconducting transition temperature T_c and the temperature of CDW onset, $T_{CDW} \cong 200\,\mathrm{K}$, are actually independent of the gating time, i.e. of the H concentration x, while the intensity of the CDW anomaly in the $\rho(T)$ curve decreases on increasing x. This suggests a phase separation rather than a coexistence of the two orders. The temperature dependence of the critical field, for $\mathrm{H//ab}$ or $\mathrm{H//c}$, suggests the SC phase to be multi-band and quasi-2D, and is compatible with the BCS-based model for the upper critical field of multiband dirty superconductors [4]. Preliminary measurements of point-contact spectroscopy in $H_\mathrm{x}\mathrm{TiSe}_2$, carried out at $300\mathrm{mK}$, seem to confirm this picture.

References

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Thermoelectric signatures of order-parameter symmetries in iron-based superconducting tunnel junctions

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Over the fifteen years since their discovery, iron-based superconductors (FeSCs) have been investigated with many experimental tools and different theoretical models. Despite the amount of efforts, the precise symmetry of the superconducting order parameter still remains under dispute. The mostly accepted pairing state falls within the standard weak-coupling s^{+-} paradigm, however the multiband character of FeSCs offers chances for more exotic pairing states. Here we demonstrate that an opportunity to address the unanswered question above is potentially provided by *thermoelectric* (TE) *effect*, offering a venture into unexplored directions [1]. Intriguingly, we show that linear TE effects in tunnel junctions with FeSCs, at low temperatures provide information about the superconducting order parameter symmetry. In particular, nodal order parameters present a maximal TE effect at temperatures one order of magnitude lower than nodeless cases. TE measurements may be very effective to investigate the gap symmetry in Fe-based systems, overcoming the difficulties of conventional phase-sensitive Josephson experiments with unconventional pairing symmetries. Furthermore, we demonstrate that superconducting tunnel junctions between a Fe-based and a conventional BCS superconductors could provide astounding TE figures of merit, which may be relevant for energy harvesting applications and quantum technologies.

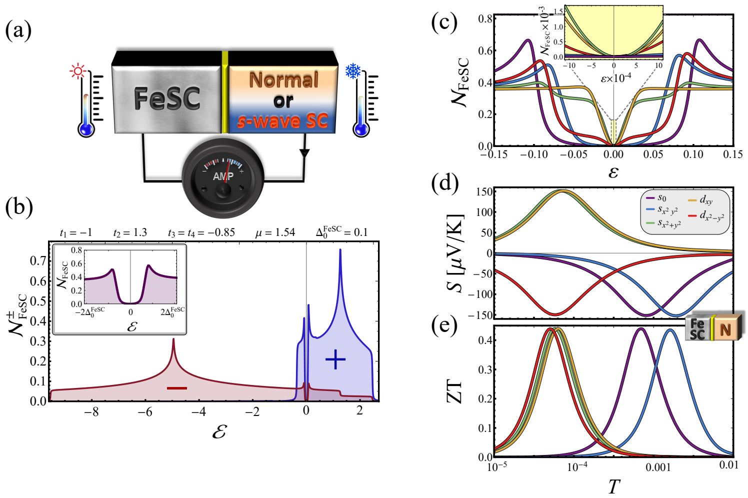

Figure 0.3: (a) Cartoon of the thermally-biased tunnel junction formed by an FeSC and a normal or a s-wave superconducting electrode. (b) Electron-like ($+$, blue curve) and hole-like ($-$, red curve) band contributions to the DoS, $\mathcal{N}^{\pm}_{\rm FeSC}(\varepsilon)$. (c) DoS, $\mathcal{N}_{\rm FeSC}(\varepsilon)$, (d) Seebeck coefficient, $S(T)$, and (e) figure of merit, ZT(T) by changing the symmetry of the order parameter. The inset in (a) illustrates the low-energy behaviour of the DoSs. The legend in panel (d) refers to all the right panels.

References

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$2D$ superconductivity vs. disorder: Pb monolayer superconductors formed on vicinal Si(111) substrates

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Two-dimensional (2D) superconductors undergo transition into insulator by the application of magnetic fields and/or the introduction of disorder even at zero temperature. As one of quantum phase transitions, the superconductor-insulator transition (SIT) has been investigated extensively, and recent studies on highly crystalline 2D superconductors formed by molecular beam epitaxy, mechanical exfoliation, gating through ion liquid, etc, various unique quantum phases such as quantum metallic phase and quantum Griffiths phase have been reported. However, microscopic understandings on these curious phases are not sufficient yet since most of the experimental investigations are performed basically by transport methods, which is fundamentally macroscopic. In this presentation, we will report on our effort trying to understand the transition and quantum phases microscopically using scanning tunneling microscopy (STM). We investigated superconductivity of Pb striped-incommensurate (SIC) phase, one of the stable mono-layer superconducting phases of the Pb/Si(111) system, and compared the results with those obtained by electron transport measurements. Since the ultimately-thin Pb superconductor was formed on various vicinal substrates, high density of steps, which work as a disorder and a Josephson coupling, was introduced into the superconductor, and the density can be well-controlled by adjusting the tilted angle. Through the observation of vortices under out-of-plane magnetic field we investigated the role of high density steps on its superconductivity.

Robust and tunable coreless vortices and fractional vortices as direct signature of chiral d-wave superconductivity

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Two outstanding problems in condensed matter physics are the direct measurement of the superconducting pairing symmetry and topological invariants, especially in multi-component and chiral superconductors. Chiral superconductors belong to the class of integer quantum hall systems, with a Chern winding number related to the winding of the superconducting order parameter, and the appearance of topologically protected chiral edge modes. Interestingly, chiral d-wave superconductivity was recently proposed in a range of different materials, but characteristic experimental fingerprints are largely lacking. We show that quadruply quantized coreless vortices appear and offer a direct signature of both the Chern number and pairing symmetry, measurable with scanning-tunneling spectroscopy and magnetometry techniques [1]. Coreless vortices are defined by a closed domain wall decorated with fractional vortices, such that superconductivity is everywhere finite and non-singular. We find that the coreless vortex shape can easily be tuned, and the experimental signature enhanced, by e.g. changing temperature and external magnetic fields. We also find that the signature is robust against disorder, anisotropy, and for more general models [2].

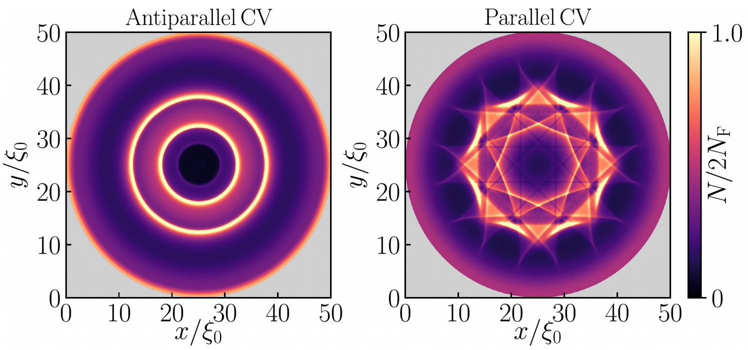

Figure 0.4: Left (right): local density of states of a coreless vortex with antiparallel (parallel) chirality and vorticity, and with conserved (spontaneously broken) axial symmetry, in a chiral d-wave superconductor.

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Low-lying collective excitations of superconductors and charged Fermi superfluids in the BCS-BEC crossover

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We investigate theoretically the momentum-dependent frequency and damping of collective excitations of superconductors and charged superfluids in the BCS-BEC crossover regime [1-8]. The study is based on the Gaussian pair-and-density fluctuation method for the propagator of Gaussian fluctuations of the pair and density fields. Eigenfrequencies and damping rates are determined in a mutually consistent nonperturbative way as complex poles of the fluctuation propagator.

The present talk is particularly focused on the case typical for most existing superconductors, where the plasma frequency strongly exceeds the gap [7, 8]. Consequently, collective excitations whose frequencies are comparable with the pair-breaking threshold, are low-lying with respect to plasmons. Even in this case, the Coulomb interaction substantially influences spectra of these collective modes. Special attention is paid to new features in relation to previous theoretical studies, which were devoted to collective excitations of superconductors in the far BCS regime. We find that at a sufficiently strong coupling, new branches of collective excitations appear, which manifest different behavior as functions of the momentum and the temperature.

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Superconducting arcs in $PtBi_2$

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An essential ingredient for the production of Majorana fermions, which can be used for quantum computing, is the presence of topological superconductivity [1]. As bulk topological superconductors remain elusive, the most promising approaches exploit proximity-induced superconductivity [2] making systems fragile and difficult to realize [3]. Weyl semimetals, due to their intrinsic topology, belong to potential candidates too [1]. However the search for Majorana fermions has always been connected with the superconductivity in the bulk, leaving the possibility of intrinsic superconductivity of the Fermi surface arcs themselves practically without attention, even from the theory side.

Here, by means of angle-resolved photoemission spectroscopy and ab-initio calculations, we unambiguously identify topological Fermi arcs on two opposing surfaces of the non-centrosymmetric Weyl material $PtBi_2$. We demonstrate that these states become superconducting at different temperatures, approximately 10K. Remarkably, the corresponding coherence peaks appear as the strongest and sharpest excitations ever detected by photoemission from solids, suggesting significant technological relevance. Our findings indicate that topological superconductivity in $PtBi_2$ occurs exclusively at the surface, which not only makes it an ideal platform to host Majorana fermions but may also lead to a unique quantum phase - an intrinsic topological SNS Josephson junction.

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The Electrodynamics Properties of Superconducting $\mathrm{Nd_{0.8}Sr_{0.2}NiO_2}$ Nickelate

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The intensive search for alternative non-cuprate high-transition-temperature (Tc) superconductors has taken a positive turn recently with the discovery of superconductivity in infinite-layer nickelates. This discovery is expected to be the basis for disentangling the puzzle behind the physics of high Tc in oxides. In the unsolved quest for the physical conditions necessary for inducing superconductivity, we report on a broad-band optical study of a $\mathrm{Nd_{0.8}Sr_{0.2}NiO_2}$ film measured using optical and Terahertz spectroscopy, at temperatures above and below the critical temperature $\mathrm{T_c} \sim 13\,\mathrm{K}$. The normal-state electrodynamics of $\mathrm{Nd_{0.8}Sr_{0.2}NiO_2}$, can be described by a scattering time at room-T $(\tau = 1.3 \times 10^{-14}\,\mathrm{s})$ and a plasma frequency $(\omega_p = 5500\,\mathrm{cm^{-1}})$ in combination with an absorption band in the Mid-Infrared (MIR), characteristics of transition metal oxides, located around $\omega_0 \sim 2500\,\mathrm{cm^{-1}}$ and with an amplitude ω_{MIR} of about $8000\,\mathrm{cm^{-1}}$. The degree of electronic correlation can be estimated using the ratio $\omega_p^2/(\omega_p^2 + \omega_{\mathrm{MIR}}^2)$. In the present system, this value is about 0.32 indicating a strong electron correlation in the $\mathrm{NiO_2}$ plane with a similar strength as cuprates. From $300\,\mathrm{K}$ to $20\,\mathrm{K}$, we observe a spectral weight transfer between the Drude and MIR band, together with a strong increase in the Drude scattering time, in agreement with DC resistivity measurements. Below Tc, a superconducting energy gap $2\Delta \sim 3.3\mathrm{meV}$ can be extracted from the Terahertz reflectivity using the Mattis-Bardeen model at finite temperature.

Sweeping across the BCS-BEC crossover, reentrant, and hidden quantum phase transitions in two-band superconductors by tuning the valence and conduction bands

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Two-band electronic structures with a valence and a conduction band separated by a tunable energy gap [1] and with pairing of electrons in different channels can be relevant to investigate the properties of two-dimensional multiband superconductors and electron-hole superfluids, such as monolayer FeSe, recently discovered superconducting bilayer graphene [2], and double-bilayer graphene electron-hole systems. This electronic configuration also allows us to study the coexistence of superconductivity and charge-density waves in connection with underdoped cuprates and transition metal dichalcogenides. By using a mean-field approach to study the system mentioned above, we have obtained numerical results for superconducting gaps, chemical potential, condensate fractions, coherence lengths, and superconducting mean-field critical temperature, considering a tunable band gap and different fillings of the conduction band, for a parametric choice of the pairing interactions. By tuning these quantities, the electrons redistribute among valence and conduction band in a complex way, leading to a new physics with respect to single-band superconductors, such as density-induced and band-selective BCS-BEC crossover, quantum phase transitions, and hidden criticalities [3]. At finite temperature, this phenomenon is also responsible for the nonmonotonic behavior of the superconducting gaps resulting in a superconducting-normal state reentrant transition, without the need of disorder or magnetic effects [4].

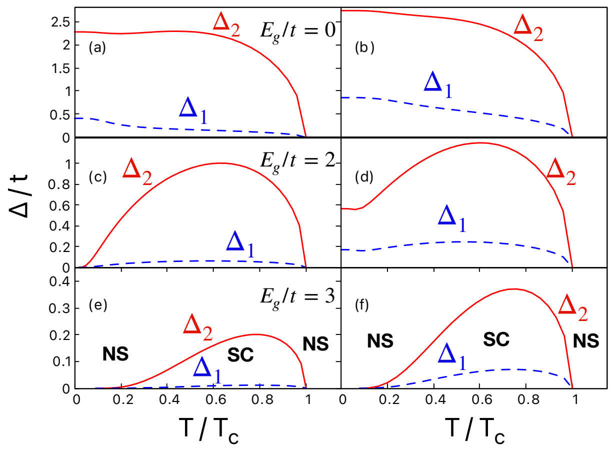

Figure 0.5: Temperature dependence of the superconducting gaps opening in the conduction Δ_2/t and valence Δ_1/t bands, for different values of the energy shift between the bands.

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Vortex matter in multicomponent superconductors

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High - T_c BKT superconducting transition in 2D systems with coupled deep and quasi-flat electronic bands with vHs

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In the pursuit of higher critical temperature superconductivity, quasi-flat electronic bands and van Hove singularities in two dimensions (2D) have emerged as a potential approach to enhance Cooper pairing on the basis of mean-field expectations. However, their implementation has posed challenges as they suppress the superfluid stiffness and, hence, the Berezinskii-Kosterlitz-Thouless (BKT) transition in 2D superconducting systems. Here, we address this issue by considering a 2D superconducting system with a quasi-flat band having a strong coupling strength for pairing of electrons coupled to a deep band having weak coupling of its electrons. Owing to multiband effects, here we demonstrate a screening-like mechanism circumventing the suppression of the superfluid stiffness and explore the optimal conditions for achieving a large enhancement of the BKT transition temperature by tuning the intraband couplings and the pair-exchange coupling between the band-condensates.

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Screening of pair fluctuations in multiband superconductors: a mechanism to stabilize higher-Tc superconductivity

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The superconductivity in iron-based, magnesium diborides, and other high-Tc superconducting materials, including indications of high-Tc superconductivity in the organic potassium doped paraterphenyl, has a strong multi-band, multi-gap, and resonant character. Recent experiments support a BCS-BEC crossover induced by strong-coupling and proximity of the chemical potential to the band edge of one of the bands, with evidences for Lifshitz transitions associated with changes in the Fermi surface topology [1,2,3].

Here we study the BCS-BEC crossover, superconducting fluctuations, and complex pseudogap phenomena in a two-band / two-gap superconductor, considering tunable interactions, including mean-field and fluctuations effects. When the gap is of the order of the local chemical potential, superconductivity is in the crossover regime of the BCS-BEC crossover and the Fermi surface of the small band is completely smeared by the gap opening. In this situation, small and large Cooper pairs coexist in the condensate, which is the optimal condition for very high-Tc superconductivity, thanks to the screening of superconducting fluctuations generated by the deep band, showing in addition unexpected consequences on the pseudogap phenomenon above the critical temperature [4].

We discuss different physical systems in which the multigap and multiband BCS-BEC crossover can be realized, pointing toward very high-Tc superconductivity. As an example we consider here superconducting stripes in which shape resonances and multigap physics at the band edge play a cooperative role in enhancing superconductivity in the crossover regime of pairing [4,5,6,7]. A key prediction of the above discussed physics is recalled and discussed in comparison with experiments: the isotope effect of the superconducting critical temperature in the vicinity of a Lifshitz transition, which has a unique dependence on the energy distance between the chemical potential and the Lifshitz transition point [6].

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Josephson effect and Landau critical velocity in the BCS-BEC crossover

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Recent experiments in ultra-cold Fermi gases on the Josephson effect call for a theoretical approach whereby pairing fluctuations, that are crucial for a reliable description of the BCS-BEC crossover, must be combined with non-trivial inhomogenous geometries, that is the simultaneous presence of a barrier and a trap. Such unique task is achieved here by performing a spatial coarse-graining of the Bogoliubov-deGennes equations and by embedding pairing fluctuations via the associated current density. The results of this approach are shown to compare favourably with recent experiments in ultra-cold Fermi gases on the Josephson effect and on the Landau critical velocity throughout the BCS-BEC crossover at low and finite temperature [1,2].

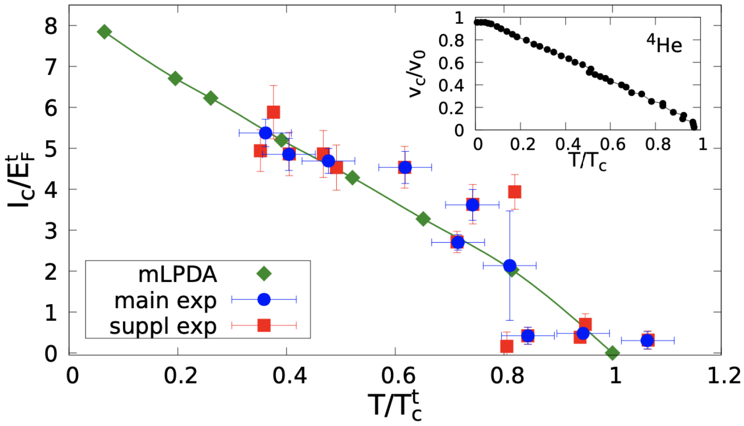

Figure 0.6: Temperature dependence at unitarity of the Josephson critical current I_c. The theoretical results obtained from the mLPDA equation of Ref. [2] (green diamonds) are compared with the experimental data from the main text (blue dots with error bars) and the supplemental material (red squares with error bars) of Ref. [3]. For comparison, the inset shows the critical velocity of superfluid 4He (normalized to its zero-temperature value).

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Unveiling the pairing Symmetry of the superconducting Sn/Si(111) via angle-resolved THz pump spectroscopy

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The 1/3 monolayer coverage of heavy atoms, like Sn and Pb on Si(111) surface displays a $\sqrt{3} \times \sqrt{3}R30^{\circ}$ reconstruction, where the adatoms, occupy the T_4 site in an triangular lattice which is called the α phase, which provides a surprisingly rich platform to study the competition between strongly correlated phenomena, spin transport and lattice reconstruction. The recent discovery of superconductivity in the Sn/Si(111) hole-doped with boron, with critical temperatures of the order of $T_c \sim 4-5$K opens new research lines to explore the physics of strongly correlated phases. Even though the pairing mechanism is still an open question, it is believed that Sn/Si(111) displays unconventional superconductivity of electronic origin, driven by the non-local Coulomb interactions, but the present state of the art challenges a deeper understanding of the nature of the SC pairing observed in the Sn/Si(111) and the engineering of new experimental protocols to determine the symmetry of the SC gap. In this talk we present results of theoretical study of superconductivity in the doped Sn/Si(111), assuming that the Cooper pairing is induced by AFM interactions. At the mean field level, we find two almost degenerate ground states, one with chiral $d_{x^2-y^2} + id_{xy}$-wave symmetry and the other with pure d-wave and by computing the non-linear current induced by a THz light pulse as a function of the polarization of the incident light, we show that the third harmonic generation is $\pi/3$-periodic for the $d_{x^2-y^2} + id_{xy}$-wave and π-periodic for the pure d-wave. Our work proposes the angle-resolved THz pump spectroscopy as an experimental tool to unveil the symmetry of the superconducting order parameter in the Sn/Si(111).

Making ghost vortices visible in two-component Bose-Einstein condensates

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Ghost vortices constitute an elusive class of topological excitations in quantum fluids since the relevant phase singularities fall within regions where the superfluid density is almost zero.

In this talk, I will present a platform that allows for the controlled generation and observation of such vortices. Upon rotating an imbalanced mixture of two-component Bose-Einstein condensates, one can obtain necklaces of real vortices in the majority component (ψ_a) whose cores get filled by particles from the minority one (ψ_b). The wavefunction describing the state of the latter is shown to harbor several ghost vortices (black crosses) which are crucial to support the overall dynamics of the mixture. Their arrangement typically mirrors that of their real counterpart (black stars), hence resulting in a "dual" ghost- vortex necklace, whose properties are thoroughly investigated in the present paper.

We also present a viable experimental protocol for the direct observation of ghost vortices in a $^{23}\mathrm{Na} + ^{39}\mathrm{K}$ ultracold mixture. Quenching the inter-component scattering length, some atoms are expelled from the vortex cores and, while diffusing, swirl around unpopulated phase singularities, thus turning them directly observable.

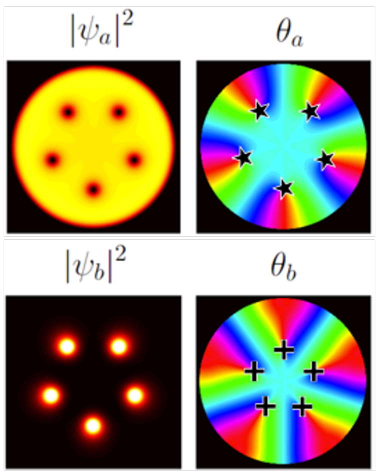

Figure 0.7: A necklace of real vortices in the majority component (first row) comes with a dual necklace of ghost vortices in the minority component (second row).

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CANCELLED TALK:
Shell-shaped Bose-Einstein condensates

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Motivated by the recent achievement of ultracold shell-shaped atomic gases in microgravity on board of the International Space Station [1], we investigate the thermodynamics of a Bose-Einstein condensate on the surface of a sphere [2,3]. We determine analytically the critical temperature and the condensate fraction of a noninteracting Bose gas. Then we consider the inclusion of a zero-range interatomic potential, extending the noninteracting results at zero and finite temperature by using a path integral approach [2]. Both in the noninteracting and interacting cases the crucial role of the finite radius of the sphere is emphasized, showing that in the limit of infinite radius one recovers the familiar two-dimensional results [2]. We also investigate the Berezinski-Kosterlitz-Thouless transition driven by the proliferation of quantized vortices on the surface of the sphere, analyzing the interplay of condensation and superfluidity in this finite-size system [2,3]. We describe the occurrence of this topological transition by conceptually extending the theory of Berezinskii, Kosterlitz, and Thouless to our finite-size system [3]. Finally, considering the general topic of low-dimensional quantum gases in curved spatial geometries, we delineate the study of vortices, the few-body physics, and the search for analog models in various curved geometries as the most promising research areas [4].

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Unusual BCS-BEC crossover and exotic superconducting states in FeSe-based materials

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The physics of the crossover between weak-coupling Bardeen–Cooper–Schrieffer (BCS) and strong-coupling Bose–Einstein condensate (BEC) limits gives a unified framework of quantum-bound (superfluid) states of interacting fermions. Recently, FeSe semimetal with hole and electron bands emerged as a high-transition-temperature (high-T_c) superconductor located in the BCS-BEC crossover regime, owing to its very small Fermi energies [1]. Here we discuss the superconducting phase diagram of $FeSe_{1-x}S_x$, which indicates very different superconducting states separated by the nematic quantum critical point at $x \approx 0.17$ [2]. Especially, the thermodinamic measurements reveal very large superconducting fluctuations near T_c, evidencing BEC-like superconducting state in the tetragonal phase ($x > 0.17$). Moreover, the tetragonal $FeSe_{1-x}S_x$ exhibits unusually large low-energy excitations in the zero-temperature limit [2-4], indicating an exotic superconducinng state with Bogoliubov Fermi surface recently suggested by theoretical calculations [5].

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Multi-component Quantum Gases in Ultracold Atoms, Condensed Matter, and Nuclear Systems

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The quantum many-body problem is one of the most important subjects in modern physics. Remarkable examples include superconductivity and superfluidity. The mechanism of conventional superconductors is microscopically explained by the Bardeen-Cooper-Schrieffer (BCS) theory, which has been nowadays extended and applied to various strongly-correlated systems including ultracold Fermi gases and nuclear systems. On the other hand, multiple degrees of freedom such as band geometries, spins, isospins, and colors lead to non-trivial phenomena that go beyond the BCS paradigm. Nevertheless, many-body physics may exhibit several similarities across various interdisciplinary fields.

In this contribution, we will discuss an intersection among ultracold atoms, condensed-matter systems, and nuclear systems in terms of strongly-interacting multi-component fermionic systems. We show several recent studies of an interdisciplinary connection among Fermi polarons in cold atomic mixtures [1], polaronic protons in neutron-star matter [2], and $^3P_0$ neutron superfluid in spin-polarized neutron matter [3], and unexpected similarities among superfluid Bose-Fermi mixtures [4], two-band superconductors [5,6], and hadron-quark crossover [7], if time allows.

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Density and pseudo-spin rotons in a bilayer of soft-core bosons

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We study the dynamics of a bilayer system of bosons with repulsive soft-core Rydberg-dressed interactions within the mean-field Bogoliubov-de Gennes approximation. We find roton minima in both symmetric and asymmetric collective density modes of the symmetric (equal layer densities) bilayer. Depending on the density of bosons in each layer and the spacing between two layers, the homogeneous superfluid phase becomes unstable in either or both of these two channels, leading to density and pseudo-spin-density wave instabilities in the system. Breaking the symmetry between two layers, either with a finite counterflow or a density imbalance renormalizes the dispersion of collective modes and makes the system more susceptible to density-wave instability. Further details of our calculations can be found in the recent publication [1].

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Fermi-liquid to non-Fermi liquid crossovers in the superconducting Yukawa-SYK model on a lattice

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Strongly interacting electrons can form non-Fermi liquids (NFLs), devoid of sharp quasiparticle excitations [1-4]. Prominent examples are found in the "strange-metal" phase of cuprate superconductors, as well as in pnictides and heavy fermions. Even more surprising is the abundance of low-temperature, partially coherent superconducting states, born out of incoherent normal-state spectra. Understanding the dynamics of Cooper pairing in NFLs entails the development of controlled theoretical approaches. The Sachdev-Ye-Kitaev (SYK) approach [5-7], based on all-to-all interactions among N fermion species ("flavors") in 0-dimensional dot, is a promising route for building toy models of NFL physics. A superconducting instability in the single dot emerges by coupling fermions to M flavors of identical bosonic modes (the Yukawa-SYK model), which are at once responsible for Cooper pairing and for the incoherent nature of the normal state [8,9].

In this work, we generalize the Yukawa-SYK model to a lattice with random hopping parameters [10,11]. We exactly solve the model in the spin-singlet large-N limit, at N=M and at particle-hole symmetry, we construct the phase diagram, and we characterize the FL to NFL crossovers both numerically and analytically, in the normal and superconducting states. We compute both thermodynamic (e.g., entropy, critical temperature, superfluid stiffness, condensation energy) and spectroscopic observables (e.g., spectral functions, electromagnetic kernel and AC conductivity), in the normal and superconducting states. In the FL regime, we find that increasing hopping exponentially decreases the critical temperature, which is maximal in the single-dot NFL limit at given coupling. However, the phase stiffness and the condensation energy are maximal precisely at the NFL/FL crossover. Such correlation is reminiscent of a striking feature of superconducting cuprates, where the coherence-peak spectral weight, the superfluid stiffness, and the condensation energy, all correlate with each other as a function of temperature and doping [12]. Our results offer an analytically controlled scenario to study the interplay between NFL and FL phases in unconventional and quantum-critical superconductors.

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Amplitude oscillations in ultracold Fermi gases

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Gases of ultracold atoms with tunable interactions provide a versatile setting to investigate non-equilibrium dynamics in quantum systems. Here, we study Fermi gases following a rapid quench of the interaction strength. Within the superfluid phase, these quenches excite oscillations of the order parameter, which we observe using Bragg spectroscopy. These amplitude oscillations provide a direct measure of the pairing gap through the BCS to BEC crossover and decay consistent with a power law with a damping exponent that depends stronngly on the interactions.

Posters

Relative dynamics of quantum vortices and massive cores in binary BECs

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We study vortices with massive cores [1], [2] in binary mixtures of Bose-Einstein condensates. We consider the case of a simple 2D disc geometry. Taking up the work of Richaud et al. [3], [4], we introduce a point-vortex model where quantum vortices in the majority species are coupled to the corresponding core masses, i. e. local peaks of the minority species. The point-like dynamics is obtained via a variational Lagrangian approach. In parallel, we validate our analytical results via the numerical resolution of two coupled Gross-Pitaevskii equations. Conversely to the previous works [3], [4], where a vortex centre was assumed coincident with the centre of its massive core, we instead introduce a more refined dynamical model: here, the two objects are described by independent sets of dynamical variables and coupled by an harmonic term. Consequently, we study the effect of the new degree of freedom on the vortex-mass relative motion and average dynamics.

As already observed, the first striking effect of the second species is a change of trajectory. Whereas a massless vortex in a 2D disc moves of uniform circular motion, in presence of a second species some radial oscillations may arise. Specifically, our new model brings to a more articulated normal mode analysis, and improves the previous model thanks to the dependency of the small oscillations on the inter-species coupling parameter g_{ab}. This dependency could not be appreciated in the previous model as it did not include the parameter g_{ab} at all. On the other hand, we confirm that, within the physical ranges of the coupling parameters, there is no significant relative motion of the vortex with respect to its core mass.

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Giant amplification of Berezinskii-Kosterlitz-Thouless transition temperature in superconducting systems characterized by cooperative interplay of small-gapped valence and conduction bands

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Two-dimensional superconductors [1] and electron-hole superfluids in van der Waals heterostructures [2] having tunable valence and conduction bands in the electronic spectrum are emerging as rich platforms to investigate novel quantum phases and topological phase transitions. In this work, by adopting a mean-field approach considering multiple-channel pairings and the Kosterlitz-Nelson criterion [3], we demonstrate giant amplifications of the Berezinskii-Kosterlitz-Thouless (BKT) [4] transition temperature and a shrinking of the pseudogap for small energy separations between the conduction and valence bands and small density of carriers in the conduction band. The presence of the holes in the valence band, generated by intra-band and pair-exchange couplings, contributes constructively to the phase stiffness of the total system, adding up to the phase stiffness of the conduction band electrons that is boosted as well, due to the presence of the valence band electrons. This strong cooperative effect avoids the suppression of the BKT transition temperature for low density of carriers, that occurs in single-band superconductors where only the conduction band is present. Thus, we predict that in this regime, multi-band superconducting and superfluid systems with valence and conduction bands can exhibit much larger BKT critical temperatures with respect to single-band and single-condensate systems.

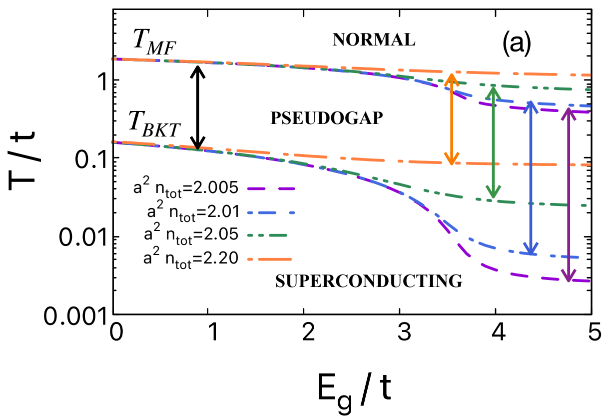

Figure 0.8: Phase diagram of the system in the temperature T/t vs band-gap energy E_g/t, for different values of the total density.

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Josephson effect and superfluidity in electron-hole bilayer heterostructures

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We analyze the superfluid characteristics and crossover physics for Josephson junctions [1] in electron-hole bilayer TMD semiconductors [2]. We determine the critical current across junctions of different potential barrier heights [3,4]. We show that the crossover physics in the narrow barrier region controls the critical current throughout. We find that the ratio between the critical current and the carrier density exhibits an observable maximum at the density of the switchover from bosonic excitations to pair-breaking fermionic excitations [5]. This provides, for the first time in a semiconductor system, an experimental measure for the position of the boundary separating the BEC and BCS-BEC crossover regimes.

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Poster II: Intralayer correlations in electron-hole bilayers superfludity

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We investigate the effect of the intralayer exchange correlations in electron-hole bilayer superfluid using the Hartree-Fock (HF) self-energy correction [1]. The inclusion of the HF term leads to an amplification of the number of pairs participating in the screening process [2]. We found that the mean-field gap energy, the condensate fraction and the chemical potential results with the HF term are closer to the Quantum Monte Carlo results [3] respect to the ones without the HF term, especially in the crossover regime. Then, we study the case of different interlayer distances finding that as the interlayer distance increases also the correction due to the HF term increases. We also show for the first time the behaviour of the pair size as a function of the density [4] for different interlayer distances, finding new insights about the nature of the BCS-BEC crossover in electron-hole bilayer superfluids.

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Experimental study of Berezinskii-Kosterlitz-Thouless (BKT) transition under applied magnetic field in NbN ultra-thin films.

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This work presents an in-depth investigation into the 3D-2D dimensional crossover in NbN ultra-thin films, resulting in a BKT superconducting transition approaching the 2D regime. The transition is experimentally observed in temperature-dependent resistivity curves and current-voltage (I-V) characteristics [1]. The 2D nature of the films is characterized by electrical resistivity analysis using the Cooper pair fluctuation model developed by Aslamasov and Larkin (AL) [3] and Maki and Thompson (MT) [4, 5]. Similarly, in I-V characteristics, an abrupt change in the α exponent (V proportional to I^{α}) at the transition [1,2], is observed which indicates a jump in the superfluid stiffness and confirming the presence of a BKT transition. Furthermore, the BKT transition is studied under an applied magnetic field, providing insights into the evolution of this phenomenon at low field intensities ranging from 5x10^{-4} to 1.6x10^{-2}T. However, the BKT effect begins to diminish at intensity as low as 10^{-3}T, disappearing completely at 10^{-2} T, suggesting the existence of a threshold in magnetic field intensity [7]. These findings suggest the existence of a threshold in the magnetic field intensity above which the influence of magnetic vortices surpasses any signs of BKT transition. A phenomenological model is currently being developed to explain the experimentally detected features in our thin NbN films.

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Superconducting state properties of iron based materials using a two-band BCS model

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We analyze the superconducting state properties for the case of a two-band self-consistent BCS model that considers an electron band structure suitable for iron based superconducting materials. The superconducting critical temperature T_c, band gap parameters $\Delta_{11}(T)$ and $\Delta_{22}(T)$, and the ratios Δ^0_{ii}/T_c are discussed as function of the material's original inter-orbital hopping parameter t_4 and the electron doping N. Our analysis accounts for the "interpolated" $s^{\pm}$-wave symmetry ($\Phi_\alpha(\vec{k}) = 1 + r\cos 2\phi$) or the $s^{\pm}$-wave symmetry ($\Phi_\alpha(\vec{k}) = 2\cos k_x \cos k_y$) of the system's attractive interaction terms and superconducting gap parameters. The main result of our work is a possible phase diagram that presents multiple local minima and maxima suggesting the possibility of *reentrant* superconductivity in iron based superconducting materials.

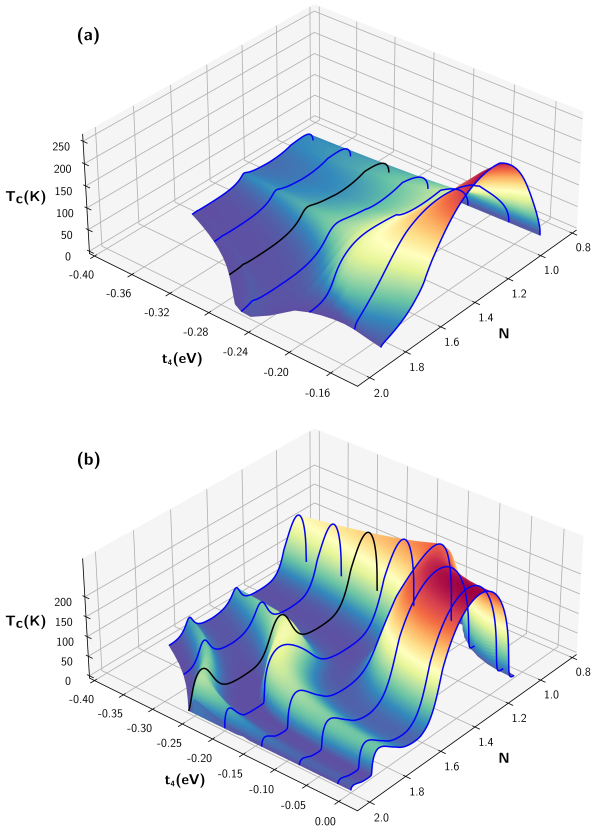

Figure 0.9: Phase diagram T_c vs N vs t_4 for (a) the "interpolated" $s^{\pm}$-wave symmetry and (b) the $s^{\pm}$-wave symmetry case. For both cases, the black line highlights the phase diagram for $t_4 = -0.260$ eV. ($t_1 = -0.330$ eV, $t_2 = 0.385$ eV, $t_3 = -0.234$ eV, $V_{11} = V_{22} = 0.15$ eV, $V_{12} = 0.10$ eV, $\omega_{D1} = \omega_{D2} = 0.10$ eV).

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Non-trivial topology and diode effect in Josephson junctions based on oxide nanochannels

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In a Josephson junction, the diode effect is the dependence of the critical current on the direction of current flow and the applied magnetic field. We study the diode effect and topological properties in Josephson junctions based on oxide nanochannels. We investigate the critical current behavior with a magnetic field applied perpendicular to the Rashba spin-orbit direction, while considering different junction geometries. We relate the observed critical current enhancement at small magnetic fields to a non-trivial topology, accompanied by Majorana bound states (MBSs) pinned at the edges of the superconducting leads. Our results allow to recognize fingerprints of topological superconductivity in non-centrosymmetric materials and confined systems with Rashba spin-orbit interaction.