MULTISUPER 2014 *International Conference on*

Multi-Condensate Superconductivity and Superfluidity in Solids and Ultracold Gases

24 - 27 June 2014, Camerino Italy

BOOK OF ABSTRACTS

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- **Multiband superconductivity in novel materials.**
- **Multi-component ultracold atoms and molecules.**
- **Electron-hole superfluidity in semiconducting and graphene systems.**
- **Low dimensional superconductors and superfluids: quantum size effects and shape resonances.**

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$Zr_{1-x}Nb_xB_2$ a possible new multiband superconductor

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Since the discovery of superconductivity in MgB_2 at 39 K, the interest in multiband superconducting materials has renewed. Among them MB_2 materials (M = Transition Metal) with the same prototype AlB_2-type structure have been considered as natural candidates for multiband superconductivity[1,2]. In this talk, Ill report on the structural, microstructural, electrical, thermal and magnetic studies of the new superconductor material $Zr_{1-x}Nb_xB_2$. Polycrystalline samples of $Zr_{1-x}Nb_xB_2$, 0.00 < x < 0.05 were prepared by arc-melting and characterized structurally by X-ray diffraction with Rietveld refinement. The XRD diffractograms of all sample present no impurity phase was detected. The samples materials were also characterized by Scanning Electronic Microscopy (SEM), and by specific heat, magnetization and resistivity measurements as a function of temperature. SEM micrographs with EDS analysis showed that the presents a uniform composition. Specific heat, magnetization and resistivity measurements confirmed that all prepared samples were superconducting. Specific-heat and lower critical field temperature dependence, as well as, the pressure dependence of the upper critical results suggest the possibility of unconventional superconductivity arising from multiband effects.

*In collaboration with M. D. R. Marques, L. E. Correa, S. T. Renosto, F. S. Portela, L. T. Corredor, A. Vagov, A. A. Shanenko, Soon-Gil Jung, G. Zhang, Johan Vanacken, Victor V. Moshchalkov, A. J. S. Machado.

This work was supported by the Brazilian science agencies CAPES, CNPq, FACEPE, and FAPESP.

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Applicability of excitonic description in a two component Coulomb gas.

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Electron-hole attraction leads to formation of excitons at low density in a two-component Coulomb gas. An important question is to which extent excitons can be approximated by composite bosons. Keldysh and Kozlov[1] point out that fermionic effects contribute already to the beyond mean-field terms of weakly interacting bosons. M. Combescot[2] argues that pure boson description always misses important exchange terms. We use fixed node diffusion Monte Carlo method to study ground state properties of equal mass spin polarized two component electron hole plasma. We calculate energies of four-body system under harmonic confinement and use them to extract exciton-exciton scattering length. Many-body homogeneous system is studied as a function of density. We find that in the low-density regime the equation of state can be described by a mean-field boson theory with the same s-wave scattering length as obtained from four-body trapped system. At larger densities we find that beyond-mean-field terms are well described by bosonic Lee-Huang-Yang theory. Bose-Einstein condensation of excitons is investigated through long-range asymptotic of the two-body density matrix. Condensate fraction of condensed excitons is reported along the crossover.

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Type-1.5 superconductivity in multicomponent systems

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I will present theoretical arguments and discuss experimental evidence that some of the newly discovered multicomponent materials can have several coherence lengths such that $\xi_1 < \lambda < \xi_2$ and as a consequence of it have a different kind of superconductivity, which breaks the type-1/type-2 dichotomy. It was recently termed "type-1.5 superconductivity". This is a state where type-1 and type-2 flows are not antogonistic but coexistent, in particular resulting in long-range attactive, short-range repulsive intervortex interaction. In external field such a material can exhibit a macroscopic phase separation into vortex clusters and domains of Meissner state. I will overview other properties resulting from the presence of multiple components with disparity in coherence lengths. This work is supported by the Swedish Research Council, by the Knut and Alice Wallenberg Foundation through the Royal Swedish Academy of Sciences fellowship and by NSF CAREER Award No. DMR-0955902. Some of the computations were performed on resources provided by the Swedish National Infrastructure for Computing (SNIC) at National Supercomputer Center at Linkoping, Sweden. The report work is done in collaboration with Johan Carlstrom, Julien Garaud, Mihail Silaev and Martin Speight. The overview of the field can be found in [1].

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Magnetic phase transition in coherently coupled Bose gases in optical lattices

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We describe the ground state of a gas of bosonic atoms with two coherently coupled internal levels in a deep optical lattice in a one dimensional geometry. In the single-band approximation this system is described by a Bose-Hubbard Hamiltonian. The system has a superfluid and a Mott insulating phase, which can both be either paramagnetic or ferromagnetic. We characterize quantitatively the quantum phase transitions at unit filling by means of a density-matrix renormalization group technique. The presence of the Ising-like transition modifies the Mott lobes. In the Mott insulating region the system maps to the ferromagnetic spin-1/2 XXZ model in a transverse field and the numerical results compare very well with the analytical results obtained from the spin model. In the superfluid regime quantum fluctuations strongly modify the phase transition with respect to the well established mean-field three dimensional classical bifurcation.

Electronic properties of the nematic superconductor state

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Recent measurements[1] of the Nernst effect in $YBa_2Cu_3O_y$ showed that the pseudo gap temperature coincides with the appearance of a strong in-plane anisotropy of electronic origin, compatible with the electronic nematic phase[2]. Moreover, a beautiful series of experiments[3, 4] have shown that the cuprate superconductor $La_{2-x}Ba_xCuO_4$ exhibits a dynamical layer decoupling behavior near the $x = 1/8$ "anomaly". In this regime the onset of static charge and spin stripe order coincides with the development of an extreme transport anisotropy. The remarkable layer-decoupling effect suggests that the inter-layer Josephson coupling is somehow frustrated when the superconductor (SC) order is forced to coexist with charge and/or spin stripe order. This effect can be naturally understood by postulating that the SC order also becomes "striped" and that all three orders rather than competing are intertwined [5, 6]. In the resulting striped SC state, a pair-density-wave (PDW), the SC pair field oscillates in space with an ordering wave vector.

In Refs. [7, 8], the phase diagram of these states was studied showing that, when nematic fluctuations are taken into account, the PDW order is suppressed by the proliferation of dislocations, favoring a homogeneous charged $4e$ SC phase having nematic character (N-SC). Deep in the N-SC phase, we find two types of topological configurations: isolated disclinations, and (half) vortices bounded to disclinations by means of an *attractive* logarithmic interaction. In this work we study fermionic properties of this phase. While the coupling of Fermions to the SC order parameter usually produces a gap in the quasiparticle spectrum, in the N-SC phase only the charge $4e$ field has an expectation value. This order parameter is equivalent to the condensation of a *quartet* of fermionic quasiparticles. Thus, in the N-SC, the pair field remains strongly fluctuating and uncondensed and there is no net energy gap. Nevertheless, the fluctuating pair field scatters quasiparticles resulting in a reduction of their spectral density, an effective "pseudogap". From a technical point of view, since nematicity is a fluctuation effect, no mean-field approach is suitable to treat it. Instead, we need to use a more refined approximation that retains, at least, $1/N$ terms in a large N expansion[9].

The Brazilian agencies, FAPERJ and CNPq are acknowledged for partial financial support.

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The Superfluid Mass Density

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This talk will focus on the theory of the superfluid mass density in neutral superfluids, superconductors, as well as excitonic condensed systems. Topics to be discussed include: the microscopic theory of the superfluid mass density in both neutral superfluids and superconductors, including its relation to the infrared structure of the single particle Green?s function [1]; the Landau criterion for superfluidity, and how its violation signals a decrease in the superfluid mass density – but not necessarily to zero – with connections to solitons and vortices in superfluids as well as critical currents in superconductors [2]; measurements of the superfluid mass density in ultracold paired fermionic atoms at unitarity, and their theoretical interpretation [3]; and more recent developments.

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Leggett modes in iron-based superconductors in proximity of a Time Reversal Symmetry Breaking

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The discovery of superconductivity in pnictides in 2008 renewed the theoretical interest in the physics of multiband superconductors. Indeed, since the very beginning it has been proposed that a possible source of pairing in pnictides is a spin-fluctuation mediated repulsion between electron and hole bands located at different positions of the Brillouin zone. In this sense, pnictides would be very different from other multiband superconductors, as e.g. MgB2, where the pairing has a dominant intraband character. This has profound consequences in the physical response of these systems, as we emphasized e.g. in the evaluation of the Hall effect above Tc[1]. In this talk I will address instead the consequences of the interband nature of the interaction for the behavior of the low-energy superconducting collective modes below Tc. In particular the so-called Leggett-like phase mode changes drastically when pairing is provided by an interband mechanism, which leads to the coexistence of bonding and antibodning superconducting channels. Indeed, in the usual two-band description of pnictides the Leggett mode is absent, and it becomes allowed only when a three-band description including the repulsion between the two hole bands is included. This has interesting and profound consequences on the recent on-going discussion on the possible presence of a time-reversal-symmetry-breaking superconducting state in pnictides, since the existence of a massless Leggett mode becomes a distinct signature of such a phase[2]. In addition, the Leggett mode is expected to have a very low mass in a wide region of the phase diagram, with possible measurable consequences on the temperature dependence of the superfluid density in proximity of the TRSB phase[3]. Besides its interest for pnictides, the general derivation we give of these results allows us to apply them in any multiband system which undergos a TRSB, as e.g. highly doped graphene, water-intercaled sodium cobaltates and locally noncentrosymmetric SrPtAs.

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Quantum phase transitions and momentum distributions in Bose-Fermi mixtures with resonant interactions

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We study a Bose-Fermi mixture with interspecies resonant interaction at zero temperature, by means of Quantum Monte Carlo methods. We explore the system from weak to strong boson-fermion interaction, for different concentrations of the bosons relative to the fermion component. For a boson density smaller than the fermion density, a first-order quantum phase transition is found from a state with condensed bosons immersed in a Fermi sea, to a Fermi-Fermi mixture of composite fermions and unpaired fermions. We obtain the equation of state and the phase diagram [1], and we find that the region of phase separation shrinks to zero for vanishing boson density, recovering the polaron-molecule transition, in marked contrast with resonant Fermi-Fermi mixtures. We study the peculiar role of the interspecies interaction in the depletion of the bosonic condensate, both in the polaronic branch and in the molecular branch. In the molecular limit [2] we show the occurrence of an indirect Pauli exclusion effect on the bosonic momentum distribution function, which completely depletes the occupancy of small momenta. In the polaronic regime across the resonance [3], we show that the bosonic momentum distribution is almost saturated by the corresponding quantity for the single polaron. Therefore, it is strongly renormalized by the interspecies interaction, while the concentration of the bosonic component and its intraspecies interaction only play a minor role.

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Multiple realizations of shape resonances in multi-condensates superconductors: a generic feature of high temperature superconductivity

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In this talk I show that all electronic systems confined in "heterostructures at atomic limit" [1, 2] made of planar atomic units : boron, graphene, CuO_2, FeAs, FeSe, BiS atomic layers intercalated by spacer layers which show high temperature superconductivity share a common feature. There are many practical realizations which a are different in each system. However the common feature is that the chemical potential is tuned to a shape resonance of the superconducting gaps in a multi-condensate superconductor. The material architecture is essential to generate al least two types of electrons with different symmetry which cross the Fermi level. The multi-condensate superconductivity involves multiple Fermi surface spots with different symmetry where a) the single electron hopping is forbidden while b) exchange-like interaction for pair transfer is allowed [3]-[6].

The key mechanism for high temperature superconductivity is to drive the chemical potential near a Liftshitz transition where the shape resonances in the superconducting gaps appear. The chemical potential can be tuned by pressure or chemical doping. Here the physics of the 2.5 Lifshitz transition at a metal-to-metal transition meets the configuration interaction of Fano scattering resonances. The many body configuration interaction between a BCS-like condensate and a Bose-like condensate gives origin to a particular case of Fano resonances and a particular BEC-BCS crossover.

We discuss the case of negative interference effects between the BCS and BEC condensates for weak repulsive negative interband pairing strength.

Finally we discuss how this quantum mechanism survives in the scenario of superstripes: a scale free complex topology of the oxide texture forming nanoscale percolative superconducting phases [7] of Josephson junctions which favors the shape-resonances for the amplification of the critical temperature in complex superconducting networks of superconducting units [8, 9].

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ARPES of iron-based superconductors: recent results and current understanding

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I will overview our recent results on iron-based superconductors obtained using Angle-Resolved Photoemission Spectroscopy at ultra-low temperatures. Our approach allows us to unravel the electronic structure of complicated many-band materials and determine their Fermi surfaces. Knowing the Fermi momenta with a high precision we then determine the superconducting gap thus gaining the knowledge about the structure and symmetry of the order parameter. Systematic ARPES studies of many families of iron-based superconductors clearly point to the key role of band structure anomalies located near the Fermi level in the formation of the superconducting state. Comparison of our experimental data with theories points to a possibility to single out the realistic pairing mechanism in iron-based superconductors.

Pair superfluidity in a bilayer of dipolar bosons

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I will report on recent results for the many-body physics of dipolar gases obtained in our group using quantum Monte Carlo (QMC) methods. Recent experimental realizations of ultracold Bose and Fermi gases with predominant dipolar interaction have opened the theoretical interest on these systems mainly due to two characteristics: anisotropy and quasi long range. I will show results on a bilayer composed by dipoles with a moment perpendicular to the plane. When the interlayer distance is small enough, up and down dipoles form bound states that break when this distance increases. We observe a transition between a regime of pair superfluidity and another one with only single-particle Bose-Einstein condensation. This offers a unique opportunity to observe pair superfluidity of bosons in the continuum, without an external optical lattice. In the second part, I will show as the anisotropy of the interaction induces the formation of a stripe phase in a system of tilted dipoles in a plane. Using QMC we have been able to determine the phase diagram of planar tilted dipoles as a function of both density and polarization angle, showing the stability limits of the new quantum stripe phase.

Study of Matching effects in anti-dot arrays of dis-ordered NbN thin films

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We investigate the origin of matching effect in dis-ordered superconducting NbN thin films with periodic array of holes. Matching effects can arise due to commensurate pinning (CP) where each hole traps an integer number of flux quanta and thereby enhances vortex pinning. It can also originate from the Little Parks like Quantum interference Effect (QI) seen in an array of superconducting loops where the super-current around each loop goes to zero at integral number of flux quantum. QI therefore manifests as oscillations in true thermodynamic quantities with magnetic field and usually dominates close to the superconducting transition temperature (T_C). In our experiments, all dynamical quantities which can be influenced by the flux line motion under an external drive like the magneto-resistance, critical current and screening response of the films to an AC magnetic field showed pronounced matching effects. However, the superconducting energy gap which is a true thermodynamic quantity did not show any periodic variation with magnetic fields for the same films. In addition the matching effect observed in the dynamical screening response measured using a newly developed "two-coil" mutual inductance technique [1] survived down to very low temperatures, as low as ~$0.09T_C$ for the most dis-ordered film. Our results indicate that CP leading to vortex-vortex interaction is the dominant mechanism for the observed matching effects in these superconducting anti-dot films.

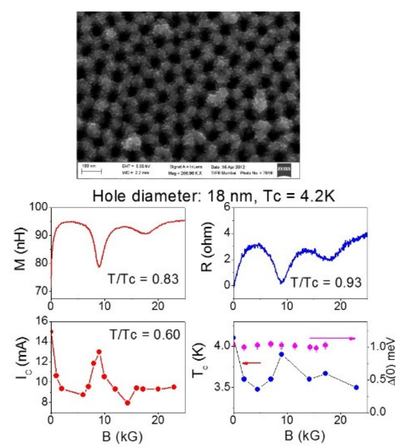

Figure 1: NbN film with periodic array of holes with diameter of 18nm. Matching effect observed in, screening response (M), resistance (R) critical current (Ic) and Tc. No matching effect observed in gap (Δ(0))

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Unveiling the hidden and selective Mottness in iron superconductors

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The phase diagram of the high-T_c cuprates is dominated by the Mott insulating phase of the parent compounds. As we approach it from large doping, a standard Fermi-liquid gradually turns into a bad non-Fermi liquid metal, a process which culminates in the pseudogap regime, in which the antinodal region in momentum space acquire a gap before reaching a fully gapped Mott state. The strong correlation effects are therefore believed to be the unifying element to understand both the anomalous normal state and the superconducting phase.

On the other hand, in iron-based superconductors the parent compounds are not Mott insulators, and the role of electron correlations is still unclear and debated.

Here we show that experiments for electron- and hole-doped $BaFe_2As_2$ support indeed a scenario very similar to that of the cuprates. The doping evolution of the effective mass is dominated by the influence of a Mott insulator that would be realized for half-filled conduction bands, while the metallic stoichiometric compound does not play a special role. Weakly and strongly correlated conduction electrons coexist in much of the phase diagram, an effect which increases with hole doping. We identify the reason for this behavior in a strong Hund's coupling, which decouples the different orbitals. Each orbital then behaves as an independent doped Mott insulator, where the correlation degree only depends on how doped is each orbital from half-filling. Our scenario reconciles contrasting evidences on the electronic correlation strength and establishes a deep connection with the cuprates.

This work is financed by European Research Council/FP7 through the Starting Grant SUPERBAD, Grant Agreement 240524

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Inhomogeneous superconductivity at $La(Al,Ti)O_3/SrTiO_3$ interfaces

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We shall argue that the peculiar *tailish* resistance of the two-dimensional electron gas formed at the $LaAlO_3/SrTiO_3$ (LAO/STO) or $LaTiO_3/SrTiO_3$ (LTO/STO) interface is due to the occurrence of a low-dimensional (e.g., filamentary) structure of the superconducting cluster with small long-distance connectivity, embedded in the two-dimensional metallic background [1, 2], yielding a percolative character of the transition to the zero resistance state [2]. We shall show that the assumption of an inhomogeneous superconducting state, with superconducting *puddles* embedded in a (weakly-localizing) metallic background, accounts for transport, superfluid density, and tunneling measurements at these interfaces.

Based on the evidence that two kind of carriers, with high and low mobility, coexist in these systems [3], and that the occurrence of superconductivity seems definitely to be related to the appearance of high-mobility carriers, we model intra-puddle superconductivity with a multi-band model, showing that superconductivity is of the weak-coupling BCS type, likely mediated by phonons [2].

Finally, we shall show that the assumption of an inhomogeneous superconducting state also accounts for the multiple quantum critical behavior observed when superconductivity is suppressed by means of a magnetic field [4].

As a possible source oh inhomogeneity, a scenario may be proposed where electronic phase separation is driven in the two-dimensional electron gas at the interface by a strong density-dependent Rashba spin-orbit interaction [5].

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Engineering of artificial multiband superconductors: unconventional behavior of [Nb/Sn] and Cr[Nb/Sn] superconducting multilayers

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Fabrication of superconducting layered systems offers fascinating possibilities to observe novel superconducting phenomena[1, 2]. In particular, a combination of multiple layers with drastically different superconducting properties opens new prospects of engineering artificial superconductors which are, in many respects, similar to recent multiband superconducting compounds [3]. In this work we investigate different proximity-coupled multilayer systems with the aim of a better understanding of the corresponding vortex dynamics.

In our experiment Nb(100 nm)/[Sn(50 nm)/Nb(50 nm)] x 7 multilayers were deposited by dc and rf magnetron sputtering. A thin Cr (10 nm) layer was also added, to check effects due to the presence of the bulk spin-density-wave element. Magnetic susceptibility, resistivity, and I-V characteristics have been measured as functions of the temperature and applied magnetic field, both perpendicular and parallel to the layers, at temperatures 1.4 K $<$ T $<$ 6 K and fields 0T $<$ H $<$ 2T for different applied-field rates up to 0.6T/min.

The critical temperatures of Nb[Nb/Sn] and Cr/Nb[Nb/Sn] have been extracted from the resistivity as $T_c = 5.05$ K and $T_c = 3.59$ K, respectively. Flux jumps have been observed in both parallel and perpendicular applied fields in the Nb[Nb/Sn] but not Cr/Nb[Nb/Sn] sample. Thus, strong Cr-induced effects have been revealed. The upper and lower critical fields as functions of temperature, as well as the critical current as a function of temperature/applied field exhibit clear unconventional behavior for both samples, which can possibly be attributed to the multiband nature of the systems. Additional studies, both experimental and theoretical, are needed to confirm this expectation.

This work was supported by Brazilian agencies CAPES, CNPq, and FACEPE under grant APQ-0589/1.05-08, by the Research Foundation Flanders (FWO), and CNPq-FWO cooperation program.

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Coherent dynamics of superconducting pairing in systems with non-trivial density of states

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Advances in ultra-short THz sources, which can now produce pulses both shorter than the intrinsic time scale for superconductors (SC) and with frequencies of the order of the superconducting gap,[1] made it possible to study coherent dynamics of pairing correlations in conventional SCs. Experimentally this has been realized mostly in cold atomic Fermi gases where the time-dependent pairing interaction can be readjusted almost instantaneously by magnetic field tuning through a Feshbach resonance in particle scattering. Recently an experimental study of the nonequilibrium BCS state dynamics by intense THz pulses in a superconducting NbN film was reported.[2] The used set up fulfills all the requirements necessary for the excitation of coherent dynamics. Furthermore, high-quality superconducting nanoscale systems have been fabricated,[3] which exhibit features of multiband superconductivity. Thus, a wide variety of novel phenomena associated with the dynamical interplay of the multiband nature, confined geometry and pairing correlations can become accessible.

Here we investigate the time evolution of the BCS condensate in superconducting multiband systems with a non-trivial density of states on a time scale that is short compared to the quasiparticles relaxation time, which are driven by ultra-short external electromagnetic pulses in the non-adiabatic regime. The modification of the density of states induced for instance by the quantization of the electronic degrees of freedom has been shown to lead to a number of qualitatively new phenomena, e.g. quantum-size oscillations/resonances.[4] We demonstrate that the resonances can also considerably affect the coherent dynamics of these systems. In particular, when the system is close to one of the resonances the long-time asymptotic of its dynamics changes and does no longer follow the $t^{1/2}$ dependence well known for bulk systems,[5] becoming t^{α} instead, where α depends on the dimensionality of the sample. The effective relaxation time changes and the dynamics of the order parameter may depart from the single frequency oscillation.

By varying the strength of the adiabatic perturbations we investigate the transition from the power law damped dephased oscillations regime to the regime with an exponentially vanishing long-time asymptotic pairing amplitude. We show that modifications in the DOS also adjust the transition critical value between these two regimes of the collisionless dephased pairing dynamics.

The calculations were performed done using the density-matrix formalism combined with the Bogoliubov-Hartree-Fock approach, which is sufficient for the investigation of the fast coherent dynamics of the system.[6]

M.D.C. acknowledges the support from the BELSPO Return to Belgium Grant.

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Point contact spectroscopy in Fe-based multiband superconductors: Recent advancements and future challenges

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Point-contact Andreev-reflection spectroscopy (PCARS) is a simple but versatile technique to study the number, amplitude and symmetry of the order parameter(s) (OPs) of superconductors. Here we show that, whenever the direction of current injection with respect to the crystallographic axes can be controlled, the capabilities of PCARS can be considerably improved if a 3D extension of the Blonder-Tinkham-Klapwijk (BTK) model [1], combined with ab-initio and Eliashberg calculations, is used to analyze the results.

Our early PCARS measurements in polycrystals of the Fe-based superconductors La-1111 and Sm-1111 showed two nodeless OPs together with electron-boson structures that, once analyzed within a combined BTK+ Eliashberg approach, turned out to be compatible with a pairing mediated by antiferromagnetic spin fluctuations (ASF) [1]. Two nodeless superconducting gaps were also observed in $Ba(Fe_{1-x}Co_x)_2As_2$ crystals with $x = 0.08$ [2] and *c*-axis oriented, epitaxial thin films with $0.04 \leq x \leq 0.15$ [3], together with structures due to the strong electron-ASF coupling. Both in crystals and films up to optimal doping, a zero-bias excess conductance was observed for *c*-axis current injection [4] that cannot be explained within the 3D BTK model if the Fermi surface (FS) calculated by DFT is used, and may thus have a different (possibly magnetic) origin.

PCARS spectra in $Ca(Fe_{1-x}Co_x)_2As_2$ crystals with $x = 0.06$ reproducibly showed a zero-bias maximum and broad shoulders at $5-6$ meV suggestive of a large isotropic gap and a small nodal (or strongly anisotropic) one. Moreover, a 2D-3D topological transition of the holelike FS turns out to be necessary to explain the PCARS results, and is indeed confirmed by DFT calculations. In the parent compound $CaFe_2As_2$, made superconducting by quasi-hydrostatic pressure, the 2D-3D transition of the holelike FS is associated with the stabilization of a low-temperature tetragonal phase T' against the non-superconducting collapsed-tetragonal phase. An excellent fit of the PCARS spectra was obtained by inserting in the 3D BTK model the calculated FS and the structure of the gap obtained through calculations of the spin susceptibility in a ten-orbital model [5].

The same approach, combining PCARS measurements with DFT and Eliashberg calculations, once applied to suitable compounds may help addressing open issues such as the interplay between magnetism and superconductivity, the nature of the frequently observed low-energy anomalies, and the conditions for the emergence of nodal gaps out of a nodeless $s\pm$ symmetry.

This work was done within the Collaborative EU-Japan Project "IRON SEA" (NMP3-SL-2011-283141). We thank J. S. Kim, Z. Bukowski, J. Karpinski, N. D. Zhigadlo, J. Jiang, K. Iida, F. Kurth for sample preparation, and G. Profeta, K. Suzuki for theoretical support.

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Statical and dynamical fractional vortex configurations in a two-band superconducting slab

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It has been predicted that multiband superconductors can present fractional vortices due to different winding numbers for each of the order parameters that can appear in the description of the multiple superconducting condensates. One of the difficulties in finding these fractional vortices in bulk two-band superconductors lies on the divergent energy related to such entities [1]. For mesoscopic two-condensate samples, thermodynamically stable fractional vortex states are found by varying parameters related to the interband Josephson coupling or to the magnetic coupling between bands [2]. In this work we consider a slab geometry whose surface has a stabilizing effect on the fractional vortex state [3]. Using the two-component Ginzburg-Landau (TCGL) approach, we predict unusual static vortex configurations and dynamical phases. First, for the static case, fractional vortex configurations emerge naturally from the magnetic history (M(H) curve) for both magnetic and finite Josephson coupling present in simulations. We find two kinds of vortex configurations (composite vortex configuration and composite plus fractional vortices near the surface) that have their origin in partial vortex penetration caused by the different thresholds for vortex entry within each band and in the stabilization of one of the two kinds of partial vortices near the surface. The effect of the surface on the flux carried by these stabilized vortices is discussed in the light of the M(H) curve and the vortex configurations found. For the dynamical case, we found different phases related to the motion of composite vortices induced by surface effects (and not by difference in vortex viscosity [4]) whose implications on the voltage-magnetic field (V-H) curve could be obtained in transport measurements.

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Niobium nano-SQUIDs based on sub-micron tunnel junction fabricated by three dimensional Focused Ion Beam sculpting

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In last years, there is a growing interest to investigate small cluster of magnetic nanoparticles, small spin population or magnetic nano-objects. The challenge is the measurement of the single atomic or molecule spin. In this framework nano superconducting quantum interference devices (nanoSQUIDs) having a flux capture area less than 1 µm2 are a powerful tool to study the magnetic properties of the nanoparticles at a microscopic level. In fact, a small capture area improves the magnetic coupling between the SQUID and the nano-object under investigation. Due to the ultra low intrinsic magnetic flux noise (less than l $mF_0/Hz^{1/2}$), it is able to detect few tens of elementary magnetic moment (Bohr magnetons) in the unit of bandwidth [1, 2]. Beside the nanomagnetism applications, these nanodevices have been proposed for spintronics, single photon and macromolecule detection, quantum computing, nanoelectronics including memory, quantum metrology and scanning magnetic microscopy with a very high spatial resolution. Typically, a dc nano-SQUID consists of a square loop having a side length less than 1 µm interrupted by two nanometric niobium constrictions (Dayem bridges). Contrary to the tunnel junctions, Dayem nanobridges can be easily fabricated by a single nanopatterning step. However, the difficulty to fabricate Dayem bridges having a non-hysteretic current-voltage characteristic, in a reliable and reproducible way, limits their application to the classical low noise readout scheme employed in the standard configuration where the SQUID is used as a magnetic flux to voltage converter. In the present work we report experimental results on fabrication and characterization of nanoSQUIDs based on sub-micron Josephson tunnel junctions (JTJ) fabricated by the Focused Ion Beam (FIB) sculpting [3]. JTJ nanoSQUIDs exhibit high modulation depths, ultra low noise and a better control of the critical current. The presented nanoSQUID are based on submicron Nb/Al-AlOx/Nb junctions and have been designed in a vertical configuration (loop and JTJs in the same plane). The loop area is 0.2 μm^2 and the square JTJs have a side length of 0.4 µm. Josephson junction's fabrication is carried out combining optical lithography to pattern trilayer and FIB sculpting technique to define the junctions' area. Two different etching processes were performed, resulting in a precise 3D structure. The nanodevices have been characterized at T = 4.2 K by using a low noise electronics and a electromagnetically shielded Dewar. Current vs voltage (I-V) and critical current vs external magnetic field (Ic-Φ) have been measured. The maximum Ic was of 360 µA with a modulation depth of 180 µA (50% of Ic). Due to the reliability and the performances of these nanosensors, we believe that the presented results are very encouraging in view of a wide employment of nanoSQUIDs in the nanomagnetism investigations.

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1D Hard-Core bosons with spin-orbit

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One of the most promising advances in manipulating ultracold atoms is the possibility of using artificial gauge fields that allow to generate tunable spin-orbit coupling and magnetic fields. Bosonic ladders are among the simplest models where to study the effect of these gauge fields [1] and can help us to disentangle the intrinsic spin-orbit physics also in more complicated systems.

Recently, it has been experimentally shown that increasing the coupling between the rung the chiral current increases up to a maximum value and saturates corresponding to transition from a vortex phase with partial screening of the applied magnetic field to a Meissner phase with full screening[2].

We have investigated ground state properties of a hard-core bosonic ladder in the presence of applied artificial magnetic field, using bosonization technique and the density-matrix renormalization group (DMRG). We estimate the region of stability of the Meissner phase against the vortex phase as a function of the spin-orbit interaction strength for different fillings. The momentum distribution [3], the chiral current have been estimated across the transitions together with estimates of the Luttinger parameters.

This work has been done in collaboration with:
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The role of quantum recurrence in superconductivity, carbon nanotubes and related gauge symmetry breaking

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Pure quantum phenomena are characterized by intrinsic recurrences in space and time. We use such an intrinsic periodicity as a quantization condition [1, 2, 3] to derive a novel description of the essential phenomenology of superconductivity [4]. The resulting description is based on fundamental quantum dynamics and geometrical considerations, rather than on microscopical characteristics of the superconducting materials. This allows us to investigate the related gauge symmetry breaking in terms of the competition between quantum recurrence and thermal noise. We also test the validity of this approach to describe the case of carbon nanotubes [5, 6].

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Multicomponent superconductivity, time-reversal symmetry, magnetism and topology

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An important concept in condensed matter physics is that of an order parameter, introduced by Lev Landau in the last century to describe the transition to the superconducting state. Interestingly, one of Landau's first proposals of an order parameter was the supercurrent, also suggested to exist in the microscopic superconducting ground state of Felix Bloch [1]. These ideas were soon dismissed since a spontaneous circulating supercurrent increases the kinetic energy. Nevertheless an excited but stable state with spontaneously circulating supercurrents is possible and we find one containing flow and counter flow even without the presence of an external magnetic field. This is a skyrmion state found to exist above the homogeneous state in a layered superconductor, described by a two-component order parameter. The decay of the skyrmion state into other configurations of lower free energy is prevented by its topological stability, which gives rise to an energy gap. The skyrmion state breaks the time reversal symmetry and produces a very weak magnetic field inside the superconductor due to the supercurrents. The gap above the ground state, the topological stability and the unusual magnetic order that breaks the time reversal symmetry leads us to suggest that the pseudogap of the layered superconductors is indeed a skyrmion state [2].

It is well-known that only multi-component order parameter theories can yield a time reversal broken state [3]. According to Volovik and Gorkov a state, described by an order parameter, with broken time reversal symmetry, has an accompanying magnetic order [4], associated to vectors analogous to the magnetic moment. These vectors imply a magnetic field near to the sample surface even in the absence of an external field. The skyrmion state yields this accompanying magnetic order in the bulk, which is made of two-dimensional layers. The pseudogap breaks the time-reversal symmetry [5] as dichroism is observed below its transition line [6]. For this reason there has been an intense search for the accompanying magnetic order associated to the pseudogap, and proposals have been made to explain it, such as by C. M. Varma [7], based on microscopic orbital currents. Indeed polarized neutron diffraction experiments [8] indicate a magnetic order below the pseudogap, but NMR/NQR [9] and μSR [10] experiments set a very restrictive limit to the maximum magnetic field inside the superconductor. Based on this value we estimative the energy density of the pseudogap in the cuprates near to optimal doping. The skyrmion state also produces, besides a magnetic order, a charge density wave in the layers.

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Vortex Dynamics in Spin-Orbit Coupled Bose-Einstein Condensates

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Spin-orbit coupled condensates typically have two or more components. This behavior allows for exotic vortices in which the circulation can differ in different components. As a specific example, I use the two-component system created by the NIST group [1] to study the dynamics of half-quantum vortices, in which one component has unit circulation and the other has zero circulation [2]. A time-dependent variational analysis suggests the existence of both closed orbits that remain in the condensate and open orbits that leave. In principle, a thermal quench [3] could create such exotic vortices, and the resulting dynamics would show these distinctive behaviors.

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Zero-Temperature Equation of State and Phase Diagram of Repulsive Fermionic Mixtures

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An important open issue in the investigation of two-components strongly interacting Fermi gases is the possibility to observe a ferromagnetic phase transition by tuning the repulsive interaction. Since the ferromagnetic transition corresponds to the equal-mass limit of the phase separation of a gas with mass-imbalanced components, it has been proposed to use mixtures of different atomic species as an alternative route to address itinerant ferromagnetism. However the critical interaction strength for phase separation in mass imbalanced mixtures has been determined so far only using mean-field theories [1], or with second-order perturbation theory [2] and Quantum Monte Carlo simulations [3] but only for mass-balanced systems.
In the present work we generalize the second-order perturbative calculation of [2] to the case of different masses. We compute the zero-temperature equation of state of a mixture of two fermionic atomic species with repulsive interspecies interactions.
We vary the interaction strength, the population and the mass imbalance, and we analyze the competition between different states: homogeneous, partially separated and fully separated. The canonical phase diagrams are determined for various mass ratios, including the experimentally relevant case of the Li-K mixture.
We find substantial differences with respect to the equal-mass case: the partially-separated state can be stabilized even for large population imbalance, and it can be realized in two forms, one with two partially-polarized domains and the other with one partially and one fully-polarized domain. We highlight the effects due to correlations by making comparison with previous mean-field results.

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Enhancing bulk superconductivity by engineering granular materials

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The quest for higher critical temperatures is one of the main driving forces in the field of superconductivity. Recent theoretical and experimental results indicate that quantum size effects in isolated nano-grains can boost superconductivity with respect to the bulk limit. Here [1] we explore the optimal range of parameters that lead to an enhancement of the critical temperature in a large three dimensional array of these superconducting nano-grains by combining mean-field, semiclassical and percolation techniques. We identify a broad range of parameters for which the array critical temperature, T_c^{Array}, can be up to a few times greater than the non-granular bulk limit, T_{c0}. This prediction, valid only for conventional superconductors, takes into account an experimentally realistic distribution of grain sizes in the array, charging effects, dissipation by quasiparticles and limitations related to the proliferation of thermal fluctuations for sufficiently small grains. For small resistances we find the transition is percolation driven. Whereas at larger resistances the transition occurs above the percolation threshold due to phase fluctuations.

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Quantum Monte-Carlo study of dipolar fermions in single and bilayer configurations

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Quantum degenerate gases interacting with long-range dipolar forces have become a fascinating new research direction in the field of ultracold atoms. In the seminar I will briefly review some of the recent experimental and theoretical progresses on this topic and then I will focus on the properties of dipolar fermions in two spatial dimensions. I will present results obtained using quantum Monte Carlo methods on the equation of state of the gas and crystal phase at zero temperature, corresponding respectively to the regime of low and high density, and on the quantum phase transition occurring between the two states. In the case of bilayer systems, we first investigate the problem of a single impurity in one layer coupled through dipolar interactions to either a Fermi liquid or a Wigner crystal in the second layer. The binding energy and the effective mass of the impurity is calculated as a function of the distance between the two layers and the transition of the transport properties of the impurity from a free-moving to a tightly bound regime are investigated. Finally we consider the bilayer system with equal populations in the two layers and we investigate interlayer pairing and the BCS-BEC crossover as a function of interlayer separation.

Reentrance of superconductivity in parallel fields

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I will present new results on the re-entrance of the superconducting state in systems placed into a parallel magnetic field. In recent experiments [1] on Molybdenum-Germanium it was observed that the magneto-resistance first increases with magnetic field, but at higher field drops again such that superconductivity is recovered. This effect is strongly temperature dependent and can lead to a suppression of resistance below the measurable threshold over a range of a few kG.

We study the vortex dynamics and magneto-resistance in this situation in the framework of a large-scale time-dependent Ginzburg Landau simulation. A small external current as well as the magnetic field are applied in the x-direction, the latter is then ramped up.

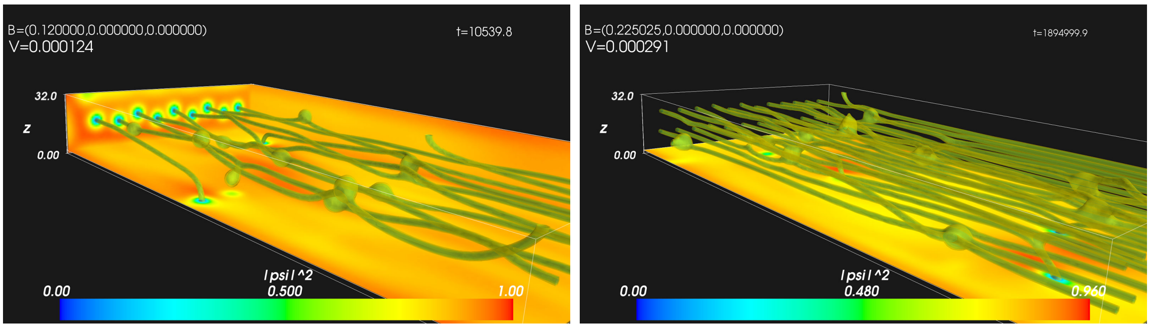

Figure 1: *Left:* Vortex configuration at intermediate fields, exhibiting a periodic dynamic resistive state, where vortex ends “travel” around the surface. *Right:* Vortex configuration at higher fields, where they straighten up and become “pinned” again.

Our simulations reveal the mechanism for the observed behavior: the intermediate resistive state is due to a vortex instability leading to an unwinding of twisted vortex configurations (see Fig. 1, left). This leads to a periodic dynamic resistive state. When the field increases these instabilities get stabilized and the resistance drops upon increasing the magnetic field due to a higher vortex concentration, leading to a vortex lattice “straightening” (see Fig. 1, right). An important factor in these consideration is the presence of a small amount of defects in the system: Without defects, vortices would just align with the current until thermal fluctuations bend them and the resulting Lorentz force leads to a resistive state. This would happen at relatively high fields. On the other hand, with a high concentration of defects, vortices never get the chance to straighten up and we observe only a resistive state above the depinning field.

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Band-edge BCS-BEC crossover in a two-band superconductor: physical properties and detection parameters

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Superconductivity in iron-based, magnesium diborides, and other novel superconducting materials has a strong multi-band and multi-gap character [1] and recent experimental evidences support the possibility for a BCS-BEC crossover induced by strong-coupling and proximity of the chemical potential to the band edge of one of the bands [2, 3]. Here we study the simplest theoretical model which accounts for the BCS-BEC crossover in a two-band superconductor, considering tunable interactions and different energy separations between the bands. Mean-field results for the condensate fraction, the correlation length, and the superconducting gaps are reported in typical crossover diagrams to locate the boundaries of the different BCS, crossover and BEC regimes when the band edge is approached. When the superconducting 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 total condensate, which is the optimal condition for high-T_c superconductivity [4]. The ratio between the gap and the Fermi energy in a given band results to be the best detection parameter for experiments to locate the system in the BCS-BEC crossover. Using available experimental data, our analysis shows that iron-based superconductors have the partial condensate of the small Fermi surface which is in the crossover regime of the BCS-BEC crossover [5], supporting in this way the recent ARPES findings [6, 7].

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Excitonic superfluidity in electron-hole bilayer systems

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Exciton bound states in solids between electrons and holes have been predicted to form a superfluid at high temperatures. The challenge is to confine the electrons and holes into two separate layers spaced close enough that the excitonic superfluid forms under experimentally accessible conditions, but not so close that the electrons and holes rapidly recombine. We theoretically study electron hole systems in three different heterostructures: (i) GaAs/AlGaAs double quantum wells, (ii) double bilayer graphene [1], and (iii) hybrid graphene–GaAs quantum well structures. We find that in the GaAs and bilayer graphene systems the sample parameters necessary to generate equilibrium superfluidity of the electron-hole pairs are close to values already achieved in experiments. Our results indicate that the superfluid transition temperatures should be above liquid helium in both cases. For the hybrid bilayer graphene–GaAs quantum well structure, we obtain chiral superfluid states with phase coherence across the graphene–GaAs interface.

A key controversy in performing such calculations is how to treat screening of the attractive Coulomb interaction between electrons and holes. In the past mean-field theories using different screening approximations have come to wildly different conclusions, with predictions of the superfluid transition temperature varying by more than 6 orders of magnitude for the same system. We resolve this issue by testing these different screening approximations against essentially exact recent diffusion quantum Monte Carlo results [2]. Our results will allow calculations to be extended to complicated lattices at finite temperatures, and non-equilibrium situations, impractical in Monte Carlo.

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Roles of atomic-scale defects in the superconducting proximity effect visualized by STM

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Using low-temperature scanning tunneling microscopy and spectroscopy, we have studied the proximity effect at the interfaces between superconducting Pb island structures and metallic Pb-induced striped-incommensurate (SIC) phase formed on a Si(111) substrate. Our real-space observation revealed that the step structures on the two-dimensional metallic layer exhibit significant roles on the propagation of the pair correlation; the propagation of the proximity effect is terminated by the steps, and in the confined area between the interface and the steps the effect is enhanced. The observed results are explained quantitatively with an elastic reflection of electrons at the step edges (reflectionless tunneling) based on calculations with the quasi-classical Greens function formulation using the Usadel equation.

This work has been done in collaboration with Shi-Zeng Lin and Matthias J. Graf, Los Alamos National Laboratory, USA, and Takeo Kato, ISSP, Univ. Tokyo, Japan.

Novel Josephson Phenomena in TRSB superconductors

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There has been a rapidly growing interest in multi-band superconductors stimulated by the discovery of MgB_2 and iron pnictides, in which superconducting condensates in different bands couple to each other. In a two-band superconductor with order parameters $\{ \Delta_1, \ \Delta_2 \}$, an attractive Josephson-like interband coupling leads to in-phase order parameters while an repulsive coupling causes out-of-phase order parameters. The situation becomes more interesting in a three-band superconductor, where a frustrated state is possible as a compromise of three repulsive interband couplings. In this case, interband phase differences are neither 0 nor π, leading to broken time-reversal symmetry (TRS) [1, 2].

In this work, we consider a Josephson junction between a single-band superconductor and a three-band time-reversal-symmetry-broken (TRSB) superconductor as shown in Figure 1. We study the Andreev spectra and Josephson currents with Bogoliubov-de Gennes (BdG) equations. Unequal critical currents in opposite directions as a consequence of broken TRS is obtained [3]. Then we explore the response of the junction to microwave irradiation, in which subharmonic Shapiro steps are revealed.

It is intriguing to notice that unequal critical currents and subharmonic Shapiro steps have already been observed in a Josephson junction between a single-band superconductor and an iron-based superconductor [4]. In the light of our present work [3], TRSB states might have already been realized in iron-based superconductors.

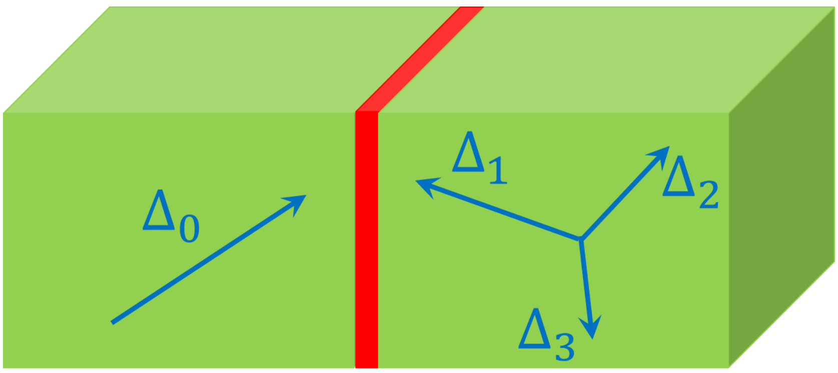

Figure 1: Schematic of Josephson junction between single-band and three-band TRSB superconductors.

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Transport through the topological superconductor wire with multiple Majorana states

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The topological superconductor (TS) wire is known to host Majorana fermions on its ends. Attaching the normal leads (N) to the ends of the wire one can perform the transport measurements observing the zero bias peak anomaly. The conductance through Majorana modes depends on the tunnelling amplitudes. The single Majorana fermion on one end of the wire implies the absence of the lead-wire interactions and the tunnelling coefficients remain unchanged. In the case of multiple Majorana fermions on one end the Kondo-like coupling can be realised. We considered the spinfull lead and the important particular case of three Majorana fermions coupled to this lead and demonstrated that a) the coupling strength and tunnelling amplitudes get renormalised; b) the six components of the lead to Majorana tunnelling coefficients can be classified according the the $SU(2)$ representations and can be separated into two groups each of which obeys to very different renormalisation rules. Thus, we showed that the different signs of the Kondo-like interaction coupling result in the forming of very different edge states on N-TS interface.

Excitonic superfluidity in electron-hole bilayers: current status and perspectives

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Excitonic superfluidity in electron-hole bilayers based on semiconductor nanostructures, graphene and topological insulators will be reviewed. Role of the hybridization will be analyzed.

Correlation effects, self consistent screening and BCS-BEC crossover will be discussed.

Drag effect and Cooper electron-hole pair fluctuations will be considered.
Fluctuational internal Josephson effect in the system is analyzed.

Larkin–Ovchinnikov–Fulde–Ferrell-like (LOFF) state at mismatch of the concentrations of e and above the critical value will be discussed. Possible phase-sensitive experiment based on the internal Josephson effect in the system for probing spatial structure of order parameter in a LOFF-like state will be discussed.

Instabilities in the system of dipole excitons (excitons with spatially separated electron and holes) will be analyzed.

Possible crystal and supersolid phases in dipole exciton systems will be discussed.

Toward Room Temperature Electron-Hole Pair Condensates

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Equilibrium electron systems sometimes have a type of order in which coherence is spontaneously established between two distinct groups of electrons. These spontaneous-phase-coherence ordered states can be viewed as equilibrium electron-hole pair (exciton) condensates or as XY pseudospin ferromagnets. When the two subsystems can be electrically contacted separately, spontaneous coherence leads to exotic transport properties related to superfluidity.

Equilibrium exciton condensation has so far been been extensively studied[1] only in double-layer two-dimensional electron gas systems, only in certain strong magnetic field limits, and only at temperatures below 1 K. I will briefly review some of the surprising superfluid transport effects that have already been observed in double-layer exciton condensates. Most of my lecture will focus on the possibility of realizing similar effects at room temperature either by enhancing the stability of exciton condensates using bilayer graphene[2] or transition metal dichalcogenide [3] as two-dimensional materials, or by designing ferromagnetic materials[4] with appropriate properties.

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Theoretical studies of Pauli paramagnetic effects in multiband superconductors

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Strongly correlated superconductors often exhibit exotic superconducting properties compared with conventional ones, such as power law behaviors in thermodynamic quantities, which are interpreted as a nodal gap structure, or strongly suppressed upper critical field H_{c2}, which ultimately leads to a first order phase transition at H_{c2} sometimes. Typical examples include heavy Fermion superconductors $CeCu_2Si_2$[1] and UBe_{13}[2], and extreme two-dimensional like layered superconductor Sr_2RuO_4[3]. The detailed pairing symmetries of those materials still remain mystery and the associated gap structures are not yet determined completely.

In this presentation, we investigate those three exotic superconductors through a coherent stand point of the Pauli paramagnetic effects and multiband effects. Our calculations are based on a microscopic theory by solving the quasi-classical Eilenberger equation. Namely, those superconductors can be viewed in common by having strong Pauli paramagnetic effects because of inherent strong correlation and are characterized by multiple bands whose different Fermi surfaces accommodate different gap values. This stand point allows us to re-interprete some of the seemingly mysterious exotic phenomena associated with those materials in terms of multi-bandness with Pauli paramagnetic effects. This reinterpretation is supported by our close collaborative works with several experimental groups [1,2,3].

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Multi-band Effects through the Dynamic Hubbard Model

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The importance of accounting for more than one band to properly describe superconductivity is increasingly becoming recognized in the present-day literature. In this talk we will explain how the Dynamic Hubbard model describes multi-band effects at the many-particle level. That is, a second set of orbitals comes into play only when particles interact one another, and not at the single particle level. This represents a more subtle manifestation of multi-band materials; we will present some results determined through DMFT and cluster calculations.

Fractional vortex states in multiband superconductors

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In this talk, I will report our recent findings on fractional vortex states and their dynamics in multiband superconductors. The main underlying mechanism for the previously observed vortex fractionalization in two-band mesoscopic samples is the difference in length-scales for the two coupled condensates [1] (which can become rather extreme in the vicinity of hidden criticality [2]), and hence different action of confinement on vortices in those condensates [3]. In 3+ multiband systems, an alternative mechanism for fractionalization arises due to possible intrinsic frustration of phase-differences between the band-condensates - the so called chiral superconductivity [4]. Besides the intriguing vortex states as a result of this fractionalization [5], the dynamics of vortex entry and motion in these systems under applied current is also novel and highly unusual [6], where band-fractions of a given vortex emulate particles on a spring, bound together by the elastic contour of fluxoid quantization. As a third source of fractionalization, I will also address the issue of interaction of the currents in the two condensates. This so-called 'drag' effect can act against the direct coupling between the condensates and cause breakup of vortices even if the relevant length-scales and interband phases are not in competition [6]. This is particularly the case in the dirty limit, characteristic of experimentally deposited thin film samples [7].

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Enhancement of electron-hole superfluidity in double few-layer graphene

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Currently there is a large experimental effort to try to generate electron-hole superfluidity in double sheets of graphene and in related nano-thin materials. A driving motivation is the expectation of very high transition temperatures.[1] This manuscript proposes a novel graphene nano-structure which is aimed at further boosting the transition temperature and the minimum density for superfluidity of electron-hole pairs in double sheets of graphene. It has been theoretically demonstrated that double bilayer sheets of graphene with carrier densities in a range accessible to experiments, can access the regime of strong pairing necessary for superfluidity.[2] What we propose here is to push this concept further to graphene sheets of three or four layers each. We show that this new structure enhances superfluidity transition temperatures by factors of up to three and enhances minimum carrier densities for superfluidity by factors of up to seven.

We include in our calculation realistic effects such as the opening of an energy band gap due to carrier doping. We include the screening of the Coulomb attraction between the electrons and holes in a self-consistent way,[3] having in previous work shown that this screening successfully reproduces existing Diffusion Quantum Monte Carlo results in related systems.[4, 5]

Our results strongly suggest that electron-hole superfluidity and counterflow superconductivity should be readily detectable in the proposed system of double sheets of few-layer graphene using current technologies. With this structure, we predict liquid nitrogen temperature electron-hole superfluidity at carrier densities as high as 10^{12} cm^{-2}. The nano-thick h-BN dielectric insulating barrier we propose for separating the two sheets has already been utilized in double bilayer graphene.[6] In fact, all the parameters for the experimental samples we are proposing have already been achieved in the laboratory.

In summary, we show that the use of trilayer and quadlayer graphene as sheets in these double sheet systems leads to a large enhancement in the minimum carrier densities and a large enhancement in the transition temperatures up to liquid nitrogen. Our work should materially assist the experimental efforts currently being undertaken to observe superfluidity in these graphene systems.

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Ginzburg-Landau formalism for multiband superconductors

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The Ginzburg-Landau (GL) formalism for a multiband superconductor from the microscopic BSC model was derived. The standard Gor'kov procedure with an additional truncation was employed in order to match accuracies of the obtained terms. The second truncation is meant to remove contributions to band gaps of orders higher than $\tau^{1/2}$ (where τ is the proximity to the critical temperature) that are not inherent to the GL domain and they only appear in the presence of multiple bands. In the obtained formalism there are only two possible and qualitatively different scenarios such as the solution with non-degenerated T_c and with a degenerated one. For the first scenario, we obtain the unique Landau order parameter in the system and the band gaps are proportional to this order parameter. The GL theory of a multiband superconductor maps effectively onto a single-component GL formalism in this case. For the degenerated solution, the number of relevant Landau order parameters of the system equals to the degeneracy factor. The last scenario is considered for a three-band system with strong interband couplings, which may be relevant for pnictides. In this case T_c is two-fold degenerated, thus there are two order parameters. We found that the ground state of such system develops a nontrivial phase difference between the band gaps, referred to as the state with the phase frustration or the chiral solution[1].

Another example of multiband superconductors is nanofilms with atomically uniform thickness. The single-particle energy spectrum in nanofilm is tightly bound in the perpendicular quantum-confined direction. This leads to the formation of a series of single -particle subbands. Here the system size perpendicular to the film is much smaller than the bulk Cooper-pair radius and the order parameter exhibits fast spatial variation in the direction perpendicular to the nanofilm. Therefore, the Gor'kov derivation of the three-dimensional GL formalism is not applicable. The GL formalism appropriate for nanofilms was derived and it was demonstrated that the presence of the size quantization leads to a multiband formalism. We start the derivation from the microscopic BCS theory first by integrating out the perpendicular coordinates in the gap equation. Afterwards, we deploy the Gor'kov truncation procedure and subsequent additional reconstruction in the similar way as in the derivation of the GL equations for the multiband superconductor. A unique coherence length and the 2D magnetic screening length for all subbands were obtained. In the limit when the number of subbands is large, the quantum-size effects are weakened. Then the magnetic screening length becomes inversely proportional to the film thickness which is the well-known Pearl result for superconducting films[2].

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Towards dipolar quantum many-body physics with ultracold polar molecules

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The long range dipolar interaction between polar molecules is expected to pave the way to the study of such intriguing phenomena as quantum magnetism, supersolids and novel anisotropic superfluids.
In this talk, I will review recent experimental progress in the preparation, manipulation and control of polar molecules and their dipolar interactions. In particular, I will present experimental progress towards the preparation of ultracold ground state NaK molecules with a large dipole moment of about 2,7 Debye.

Segregation of antiferromagnetism and superconductivity in $Ca_{1-x}La_xFe_2As_2$

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We report the effect of applied pressures on magnetic and superconducting order in single crystals of the aliovalent La-doped iron pnictide material $Ca_{1-x}La_xFe_2As_2$. Using electrical transport, elastic neutron scattering and resonant tunnel diode oscillator measurements on samples under both quasi-hydrostatic and hydrostatic pressure conditions, we report a series of phase diagrams spanning the range of substitution concentrations for both antiferromagnetic and superconducting ground states that include pressure-tuning through the antiferromagnetic (AFM) superconducting (SC) critical point. Our results indicate that the observed superconducting phase with maximum transition temperature of T_c=47 K is intrinsic to these materials, appearing only upon suppression of magnetic order by pressure tuning through the AFM critical point. The superconducting phase appears to exist only exclusively from the antiferromagnetic phase in a manner similar to the oxygen- and fluorine-based iron-pnictide superconductors with the highest transition temperatures reported to date. The unusual dichotomy between lower-T_c systems with coexistent superconductivity and magnetism and the tendency for the highest-T_c systems to show non-coexistence provides an important insight into the distinct transition temperature limits in different members of the iron-based superconductor family.

Systematic investigation of the effects of disorder at the lowest order throughout the BCS-BEC crossover

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A systematic investigation of the effects of disorder on the BCS-BEC crossover at the lowest order in the impurity potential is presented for the normal phase above the critical temperature T_c. Starting with the t-matrix approach for the clean system, by which pairing correlations between opposite-spin fermions evolve from the weak-coupling (BCS) to the strong-coupling (BEC) limits by increasing the strength of the attractive interparticle interaction, *all* possible diagrammatic processes are considered where the effects of a disordered potential are retained in the self-energy at the lowest order. An accurate numerical investigation is carried out for all these diagrammatic terms, to determine which of them are mostly important throughout the BCS-BEC crossover. Explicit calculations for the values of T_c, the chemical potential, and the Tan's contact are carried out. In addition, the effect of disorder on the single-particle spectral function is analyzed, and a correlation is found between an increase of T_c and a widening of the pseudogap energy at T_c on the BCS side of unitarity in the presence of disorder, while on the BEC side of unitarity the presence of disorder favors the collapse of the underlying Fermi surface. The present investigation is meant to orient future studies when the effects of disorder will be considered at higher orders, with the purpose of limiting the proliferation of diagrammatic terms in which interaction and disorder are considered simultaneously.

A bosonization method for many-body and relativistic field theories: The nilpotency expansion

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I present a method of bosonization that maps fermionic theories onto theories of composite bosons interacting among themselves and with fermionic quasiparticles. The expansion parameter is the inverse of the index of nilpotency of the composites, namely the number of fermionic states in their structure function.

The interaction among composites whose mixing is allowed by symmetries is strong, but a simple condensate (ground state built by a large number of composite bosons in one single particle state) cannot have a significant mixing with other composites. We determine the conditions of decoupling, study their effects and compare the results with the Random Phase Approximation and the BCS theory.

We discuss applications to atomic nuclei, graphene and QCD.

Influence of quantum confinement in nanoscale superconductors

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It is well known that when the dimensions of a superconductor are comparable to the Fermi wavelength, the superconducting properties will be strongly affected by quantum confinement. For example, shape resonances appear and manifest as oscillations of the critical temperature with the lateral dimension. By numerically solving the Bogolibov-de Gennes equations, we uncover several peculiar effects induced by quantum confinement. First we show that the vortex structure of a nanoscale superconducting square deviates from the conventional structure observed at mesoscopic scales, and is dependent on the ratio between superconducting coherence length and the Fermi wavelength[1]. We found a plethora of unconventional vortex ground states and the tendency of forming multi-vortex rather than giant-vortex configurations[2]. Next we present the effect of non-magnetic impurities and show that: 1) impurities strongly affect the superconducting properties, 2) the effect is impurity position-dependent, and 3) it exhibits opposite behavior for resonant and off-resonant wire widths [3].

* Work done in collaboration with L.F. Zhang, L. Covaci, G.R. Berdiyorov and M.V. Milosevic.

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Resonant Bose-Fermi Mixtures in the Condensed Phase

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We consider a Bose-Fermi mixture in the presence of a broad Feshbach resonance allowing to change continuously the attraction between bosons and fermions from weak to strong coupling. We set up a diagrammatic formalism which includes both the Bose-Fermi tunable attraction and a Bose-Bose repulsion at zero temperature. Remarkably, we find that for boson density smaller than or equal to the fermion density, the boson condensate fraction does not depend on the density imbalance across most of the resonance. In the limit of vanishing boson concentration, we find very good agreement with previous results for the polaron quasi-particle residue obtained in the context of strongly polarized Fermi-Fermi mixtures [1]. We calculate also the boson and fermion chemical potentials and momentum distribution functions and, when the condensate fraction vanishes, we recover the results of our previous works for the normal phase [2, 3]. In addition, we calculate the effective masses and Fermi steps for the unpaired and composite fermions. We find that the Fermi step of the unpaired fermions remains pinned to the value given by the Fermi radius of a free Fermi gas across most of the resonance, in agreement with the Luttinger's theorem [4], until molecules start to form. The formation of molecules is signaled by the appearance of a second pole in the boson-fermion propagator, which marks the access to a regime where bosons, fermions and molecules cohexist, and by the presence of a Fermi step for the composite fermions, which is related to the density of molecules. Finally, we find quite a good agreement between our results for the condensate fraction and Quantum Monte Carlo calculations [5].

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Ultracold atoms in optical lattices: beyond the Hubbard model

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Ultracold atomic gases trapped in optical lattices offer the possibility to study the intriguing properties of quantum many-body systems in an experimental setup where inter-particle interactions and external periodic potentials can be tuned essentially at will. In this work, we employ novel continuous-space quantum Monte Carlo techniques to address the regime of shallow optical lattices, where the conventional single-band (Hubbard) models are not reliable and multi-band effects play a fundamental role.
In the case of bosonic atoms, we show that, at a commensurate density, repulsive interactions cause a sharp increase of the superfluid transition temperature, before turning the system into a Mott insulator [1].
In the case of fermionic atoms, we study how a shallow optical lattice can be used to favor the ferromagnetic instability, thus providing a path to investigate itinerant ferromagnetism with atomic gases. We make comparison with previous results for the Hubbard model, highlighting the important role played by multi-band effects and interaction-induced hopping [2].

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Anomalous Coulomb drag resistivity in graphene/GaAs hybrid heterostructures

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Currently there is a great deal of interest in vertical heterostructures [1] combining different layered materials, since these may offer novel opportunities for applications and fundamental studies of collective behavior driven by inter-layer Coulomb coupling. In this talk I will report on heterostructures comprising a single-layer (or bilayer) graphene carrying a fluid of massless (massive) chiral *holes*, and a quantum well created in GaAs 31.5 nm below the surface, supporting a high-mobility two-dimensional electron gas [2, 3]. These are a new class of double-layer devices composed of spatially-separated electron and hole fluids. We have recently discovered [3] that the Coulomb drag resistivity in this hybrid graphene/GaAs heterostructures significantly increases for temperatures below 5-10 K, following a *logarithmic* law. We have interpreted this anomalous behavior as a signature of the onset of strong inter-layer correlations, compatible with the proximity to a condensate of permanent excitons [4].

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Interaction in Graphene Double Layers Structures

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Recent advances in the fabrication of heterostructures based on 2D atomic crystals have opened up several new directions in graphene research [1]. In particular, devices with two strongly interacting two-dimensional gases of Dirac fermions can now be readily assembled by alternative stacking of two graphene layers with several layers of hexagonal boron nitride (hBN) of nanometer thickness. Despite small separation, graphene films remain electrically isolated even when hBN spacer is as thin as 1 nm, while self-cleansing process ensures a nearly ideal interface between materials and very high carrier mobility [2, 3]. To study interaction we employ Coulomb drag and quantum capacitance measurements. The former directly depends on interlayer electron-electron scattering rate, while the latter is proportional to the density of states and may be used to probe many-body phenomena. In this presentation I will overview our recent results and experimental efforts in searching for interlayer excitons formed by electrons and holes in different graphene layers and discuss the possibility of the excitonic condensation.

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Study of superconducting properties in Nb/Pb/Nb multilayer: engineering of artificial multiband superconducting systems

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Multiple coupled superconducting layers are well-known due to their nontrivial properties. In particular, in Ta/Ge multilayers, the critical temperature is increased due to the proximity effect [1]. Flux pinning mechanism is observed in Nb/Al structures as well as in ferromagnetic and superconducting thin multilayers [2-3]. Also layered metallic superconductors have been studied because of their analogous structure to high T_c superconductors [4]. Recently, an interest in superconducting multilayers has been renewed owing to their clear link to multiband superconductivity [5]: a combination of multiple layers with different properties (e.g., type I and type II superconductors) can be a promising route to new artificial multiband materials with tailored properties.

In our work we have investigated layered structure Nb(5 nm)/Pb (500 nm)/Nb (50 nm). Each layer individually has also been analyzed. The samples were deposited via the magnetron sputtering using both the dc and rf sources on the glass substrate at pressure 3.7 mTorr Ar. The structure of the films has been controlled through the X-ray diffraction patterns. The superconducting parameters were studied via magnetic and transport measurements. The magnetization and resistivity have been analyzed as functions of the temperature and magnetic field by using the VSM magnetometer and Quantum Design PPMS. The measurements, were performed at $0 < H < 0.25$ T and 1.6 K $< T <$ 7.0 K. For both field setups, perpendicular and parallel to the layers, only one superconducting temperature $T_c = 7.2K$ was observed. The temperature dependence of the critical magnetic field (upper and lower) $H_c(T)$ showed unconventional behavior which, we believe, can reflect the multiband character of the system of interest.

This work was supported by the Brazilian science agencies CAPES, CNPq, and FACEPE, by the Research Foundation Flanders (FWO), and the CNPq-FWO cooperation program.

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Dynamics of blockaded Rydberg gases in low dimensions

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We discuss the quantum phases and dynamics of a gas of two-dimensional Bosonic particles with finite-range soft-core interactions. For low densities, the system is shown to form a solid in which superfluidity is provided by delocalized zero-point defects. This provides the first example of continuous-space supersolidity consistent with the Andreev-Lifshitz-Chester scenario. We further discuss the connection between quantum mechanical supersolid behaviour and a novel mechanism for glass formation in a gas of monodisperse, isotropic classical and quantum particles.

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Novel Features of p-wave Superfluidity in Fermi Systems with Species Imbalance

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We study p-wave pairing in a 2-component Fermi system with unequal population in BCS-BEC regimes. We find a rich spin triplet p-wave superfluid (SF) ground state structure with population imbalance. Under a phase stability condition, the "global" energy minimum is given by a multitude of "mixed" SF states formed of orbital angular momentum l = 1 sub-states. Except for the "pure" SF states, (l = 1; m = 1), others exhibit oscillation in energy with the relative phase between constituent gap amplitudes. We also find states with "local" energy minimum that can be stable at higher polarizations, suggesting a quantum phase transition between the "global" and local" states. These may be associated with Morse and non-Morse critical points. We also explore the possibility of "breached pairing" states on BEC and BCS regimes, and find these may form under certain conditions.

Control and enhancement of superconductivity by engineering materials at the nanoscale

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High temperature superconductors hold the promise of great efficiency as they can superconduct at temperatures in excess of the boiling point of liquid nitrogen, an economically favorable property. However to date their complex mechanical and chemical properties have prevented much practical application. Recently a new approach for increasing the superconducting transition temperature Tc in conventional metallic superconductors has been experimentally demonstrated. The crucial idea is due to artificial nano-structuring. Reducing the spatial dimensions of metals by confinement in atomically thin layers (2D-systems) or wires (1D-systems), a resulting geometric electron resonance effect can be exploited to significantly increase Tc. We are exploring the possibility of increasing Tc in metallic-like material nanostructures to get a Tc above liquid nitrogen. We plan to transfer into artificially constructed metallic structures two characteristics of the cuprate ceramics that are known to increase their Tc: their natural nano-structuring which induces the electron resonances and the multi-component nature of this superconductivity. In a joint theoretical and experimental effort, we plan to artificially copy within metallic-like materials these two characteristics to significantly increase Tc. Finally, the coherent properties of low dimensional superconducting systems have also been studied in the context of hybrid systems, in which a nano-sized metal or a semiconductor (e.g. Silicon/Germanium) is bridged to superconducting metallic contacts. The superconducting wave-function is able to penetrate into the normal-state bridge by the proximity effect. The properties of the superconducting wave-function, such as the leakage length and the order parameter profile with different materials and geometries, are being studied at both theoretical and experimental levels.

SDW-CDW fluctuations and complex organization in $La_{1.72}Sr_{0.28}NiO_4$

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The problem of charge-spin-lattice interaction in cuprates High Temperature Superconductors (HTS) and in strongly correlated systems is still on the center of a big discussion. Recently, new techniques like scanning micro X-ray diffraction (mXRD) and X-ray Photon Correlation Spectroscopy (XPCS) have been used to evidence high spatial inhomogeneous properties and the dynamics of these functional materials [1-7]. In this work we investigated the SDW and CDW stripes in $La_{1.72}Sr_{0.28}NiO_4$ at ALS (Berkeley) using resonant XPCS finding an interesting complex behavior in the SDW-CDW domains walls fluctuation. Moreover, using mXRD the SDW and CDW spatial inhomogeneity have been investigated showing multiscale phase separation and describing a complex superstripes scenario where multiple networks of CDW-SDW and lattice stripes coexist.

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Proximity Phenomena and Superconductivity in Pb/Si(111) monolayers

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Do novel phenomena emerge when one reduces the thickness of a metal or a superconductor down to the atomic limit? In 1964 V. L. Ginzburg predicted that new superconducting phases could appear in ultrathin films deposited on insulators. In order to get some insight on this fundamental question we studied single atomic layers of Lead deposited on atomically clean Silicon by scanning tunneling spectroscopy. The monolayers of Pb/Si(111) can be on-demand made amorphous or crystalline with various reconstructions.

The amorphous Pb monolayer is non-superconducting down to 0.3K but rather, it behaves like a bad metal with important electrons correlations. In order to apprehend how the superconducting pairing correlations evolve in such a material, we deposited on its top bulky superconducting islands of Pb (T_C=6.3K), and spatially probed the proximity effect in their vicinity. We found that the pairing correlations evolve on a global Altshuler-Aronov background, and described their spatial and spectral evolution [1].

Contrary to the amorphous Pb/Si(111), several reconstructed Pb-structures become superconducting below 2K. In these systems the proximity interface between superconducting islands and monolayers may formally be identified as S-S or as S-N, depending on temperature [2]. We found however, that even above T_C of monolayers, the finite superconductivity establishes there in the vicinity of islands.

The reconstructed Pb/Si(111) monolayers exhibit different kinds of local defects such as vacancies, adatoms, twin boundaries, stacking faults, and step edges. We discovered a surprising sensitivity of the superconducting phase to these non-magnetic defects, depending on specific reconstruction [3]. Precisely, the striped incommensurate structure does not present any perturbation of the superconducting condensate at step edges, while for the $\sqrt{3}\times\sqrt{7}$ monolayers the steps have a strong disruptive effect: The sample becomes a nanometer-scale network of atomic superconducting terraces weakly connected by native Josephson links at steps edges. We also found that inside terraces both structures present a strong sensitivity to atomic scale disorder. Precisely, short range superconducting fluctuations are observed at length scales much shorter than ξ, similar to the effect of magnetic impurities in bulk superconductors.

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Parity violating superfluidity in ultra-cold fermions under the influence of spin-orbit coupling, exchange and Zeeman fields

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I discuss the creation of parity violating Fermi superfluids in the presence of Abelian and non-Abelian gauge fields involving spin-orbit coupling and crossed Zeeman fields. I focus on spin-orbit coupling with equal Rashba and Dresselhaus (ERD) strengths [1] which has been realized experimentally in ultra-cold atoms, but I also discuss the case of arbitrary mixing of Rashba and Dresselhaus (RD) and of Rashba-only (RO) spin-orbit coupling. To illustrate the emergence of parity violation in the superfluid, I analyse first the excitation spectrum in the normal state for weak or zero attractive interactions and show that the generalized helicity bands do not have inversion symmetry in momentum space when crossed Zeeman fields are present [2]. This is also reflected in the superfluid phase, where the order parameter tensor in the generalized helicity basis violates parity. However, the pairing fields in singlet and triplet channels of the generalized helicity basis are still parity even and odd, respectively. Parity violation is further reflected on ground state properties such as the spin-resolved momentum distribution, and in excitation properties such as the spin-dependent spectral function and density of states [3]. Furthermore, the effects of parity violation are also dramatic on Feshbach molecules encountered in the normal state of Fermi superfluid in the limit of strong attractive interactions [4].

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Condensate fraction for a polarized three-dimensional Fermi gas

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We investigate a two-component polarized Fermi gas in three dimensions across the BCS-BEC crossover. We analyze the zero-temperature properties of this system at mean-field level both in the uniform case and in the presence of an external confinement treated in the local density approximation. We use the number and the gap equations to study the condensate fraction [1, 2] as a function of the interatomic strength and polarization. In the former case, we find that an enhancement of the population imbalance produces a suppression of the condensate fraction which is shown to decrease linearly in the deep BEC regime. In the latter study, we compare our results with experimental data [3] finding that our predictions are compatible with these data for sufficiently small polarizations. We study the phase separation between superfluid and normal phase regions [4, 5, 6, 7] and analyze the condensate and total density profiles in terms of spatial variations from the inner superfluid core to the normal region passing for the interface. Here a density jump is a clear manifestation of this phase-separated regime.

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Vortex states in a mixed superconducting stripe

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Although multiband superconductors have been proposed theoretically almost fifty years ago, it was only after the discovery of the MgB_2 when the interest on these systems reappeared producing many theoretically and experimental advances. For instance, vortex states with a short range repulsion and long range attraction were predicted theoretically [1]. These kind of interactions between vortices are originated in the competing length scales of the bands producing unusual vortex structures [2]. In principle it is possible to produce an artificial two-band superconductor putting together two superconducting layers, one Type-I and another Type-II. In these systems one expect that the repulsion of vortices in the Type-II layer will compete with the attraction of vortices in the Type-I leading to unusual vortex structures. Following this scenario, recently Komendová *et al.* [3] used Lawrence Doniach energy functional to study a I/II bilayer model and observed such structures.
In this work we solved numerically the time dependent Ginzburg-Landau equations to find vortex distribution profiles in a mixed superconducting stripe. Our sample consists in a stripe composed by two superconducting materials with finite width and infinity length and thickness. Each superconducting material occupies half of the stripe width. The sample is submitted to an applied magnetic field perpendicular to its width and to a current parallel to the interface between the two superconducting materials. For this configuration, the applied current induces a favorable direction for the movement of the vortices. We studied the cases when the first superconductor is a Type-I (Pb) or a Type-II superconductor (V) maintaining the second one as a Type-II superconductor (Nb). As results, we found a different behavior of the density superconducting carriers depending on the direction of the current in the system Pb/Nb inducing the formation of normal regions in the Pb side when the vortices income from the Nb half. For the V/Nb system a triangular lattice is found, the shape of this one is studied as a function of the characteristic lengths.

Work supported by CAPES, CNPq, FACEPE.

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Quartet condensation in attractive four fermion systems.

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A microscopic approach for quartet condensation in attractive four component Fermi systems is presented. It follows on similar lines as the Gorkov equations for standard pairing. It will be shown that there exists a strong qualitative difference between the quartet and the usual pairing case. Condensation of quartets only exists on the BEC side, i.e., as long as the chemical potential is negative what means binding. The BCS theory allows non-vanishing order parameters for negative *and* positive values of the chemical potential with a smooth transition between both regimes. For the quartet case the order parameter goes to zero for positive chemical potential. A detailed analysis of this behavior will be given. A strong candidate for quartet condensation is the α particle in nuclear physics. Bi-excitons in semi-conductors may be another exemple. Eventually in the future one may trap four different fermions in magneto-optical traps where bound quartes may be created with the help of Feshbach resonances. In this contribution, we will give examples for nuclear systems but the presentation will remain general.

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Effects of intralayer interactions on the mean-field excitonic condensation in a symmetric e-h bilayer.

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We first analyze the existing QMC simulations results for the electron-hole symmetric bilayer at $T = 0$, comparing our own findings [1] with those of a very recent investigation [2] that, thanks to the availability of much reacher computational resources, projects from a more flexible trial function, allowing for biexciton formation.

We then investigate the predictions of a mean field treatment of excitonic condensation in the symmetric electron-hole bilayer, employing (i) either unscreened or statically screened interactions and (ii) either including or neglecting the intralayer interactions. We compare our predictions with those of recent studies neglecting the intralayer interactions [3, 4].

The present admittedly oversimplified model (the symmetric electron-hole bilayer) has been argued [5] to be relevant to the physics of coupled bilayer graphene sheets in the quadratic dispersion regime.

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Multiband coherent systems: interband pairing causes exotic gapless states

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In the presence of multiple bands (components), the aggregate condensate becomes the coherent mixture of different partial condensates with radically different properties, which brings new physics based on constructive and destructive interference [1]. Typically, there are no pronounced pairing effects of fermions between different available bands. However, multiband systems with shallow bands can be an important exclusion (shallow Fermi pockets in $FeSe_xTe_{1-x}$ [2], double-bilayer graphene [3] etc.). Here, when the pairing energy is of order of or larger than the energy spacing between different bands, the interband pairing cannot be neglected any more. Trivially, one can expect some enhancement of superconducting characteristics, when including interband scattering effects. Our study indeed confirms this expectation reported earlier. However, we find also a nontrivial qualitative feature overlooked previously: the interband pairing results in the formation of rather unusual gapless states which, counterintuitively, enhance the system coherence.

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True and nearly multi-component superconductors

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Unconventional superconductors with intrinsic multi-component order parameters present a stage for a large variety of exotic properties unknown in standard superconductors. These encompass multiple superconducting phases and phase transitions, a variety of topological defects and the interplay between different ordered phases. In this talk I will use two examples of unconventional superconductors: (1) Sr_2RuO_4 and (2) $CePt_3Si$ to discuss features of the multi-component nature of their superconducting condensates. (1) Sr_2RuO_4 is widely believed to be a multi-component superconductor forming a chiral p-wave phase. The implications of possible chiral domain formation and the inhomogeneous nucleation of this superconducting phase in eutectic-Ru-Sr_2RuO_4 systems yielding the so-called 3-Kelvin phase will analyzed in view of recent experiments. (2) $CePt_3Si$ is a non-centrosymmetric superconductor with a "single-component" mixed-parity pairing. The nature of spin-orbit coupling, essential for these systems, can introduce novel multi-component states at crystal defects such as twin boundaries, where superconductivity can also combine with magnetism. Both types of superconducting phases represent also topological superconducting states.

Equation for the superfluid gap obtained by coarse graining the Bogoliubov-de Gennes equations throughout the BCS-BEC crossover

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We derive a nonlinear differential equation for the gap parameter of a superfluid Fermi system by performing a suitable coarse graining of the Bogoliubovde Gennes (BdG) equations throughout the BCS-BEC crossover, with the aim of replacing the time-consuming solution of the original BdG equations by the simpler solution of this novel equation. We perform a favorable numerical test on the validity of this new equation over most of the temperature-coupling phase diagram, by an explicit comparison with the full solution of the original BdG equations for an isolated vortex. We also show that the new equation reduces both to the Ginzburg-Landau equation for Cooper pairs in weak coupling close to the critical temperature and to the Gross-Pitaevskii equation for composite bosons in strong coupling at low temperature.

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Conference Topics: Multi-component ultracold atoms and molecules.

Preference: Poster.

Les trois longueurs de la supraconductivité - Vingt ans après

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We calculate the pair correlation function and the order parameter correlation function, which probe, respectively, the intra-pair and inter-pair correlations of a Fermi gas with attractive inter-particle interaction, in terms of a diagrammatic approach as a function of coupling throughout the BCS-BEC crossover and of temperature, both in the superfluid and normal phase across the critical temperature T_c. Several physical quantities are obtained from this calculation, including the pair coherence and healing lengths, the Tan's contact, the crossover temperature T^* below which inter-pair correlations begin to built up in the normal phase, and the signature for the disappearance of the underlying Fermi surface which tends to survive in spite of pairing correlations. A connection is also made with recent experimental data on the temperature dependence of the normal coherence length as extracted from the proximity effect measured in high-temperature (cuprate) superconductors.

Density-wave instability, collective excitations, and drag effect in double-layer dipolar bosons

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We study the ground-state and dynamical properties of a double-layer structure of strongly interacting dipolar bosons. Our system consists of two identical two- dimensional layers and each layer is loaded with dipolar bosons. Dipoles are aligned perpendicular to the plane and no tunnelling between the layers is permitted. Using the results from a recent hypernetted-chain [1] approximation calculation for the ground-state properties of isolated layers we obtain the intra-layer correlations. For the inter-layer correlations, we use bare interactions or screened interactions within the random-phase approximation (RPA). We investigate the instability of the double-layer system towards the formation of density-waves from the static density-density response function. Similar to the double-layer systems of electrons [2] and charged bosons [3], we observe that dipolar double-layers become unstable at small layer spacings. Furthermore, we study the in-phase and out-of-phase collective modes of these bilayers from the dynamical density- density response functions. Finally, drag effect between these layers in the presence of background velocities is discussed.

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Multiband Fermi superfluids beyond the local density approximation

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The present work is devoted to a development of an effective method for the description of the macroscopic wave function of a fermionic superfluid system. The treatment is mainly focused to the atomic Fermi gases in the BCS-BEC crossover regime. At present, the reliable theories for an inhomogeneous superfluid phase in Fermi gases exploit the Bogoliubov – de Gennes (BdG) equations. The other technique, based on the Ginzburg – Landau (GL) theory, is restricted to a close vicinity of the critical temperature T_c.

We have extended the Ginzburg – Landau (GL) formalism to the whole temperature range below T_c for a two-band superfluid Fermi gas [1]. In the limit $T \to T_c$, we retrieve the theory of Ref. [2]. The developed method has been applied to variationally describe vortices in a two-band Fermi gas in the BEC-BCS crossover regime. The healing lengths determined from the variational vortex wave function are shown to exhibit hidden criticality well below T_c. The present method can find a wide spectrum of applications. The present theory explains the deformation of the density profiles of superfluid Fermi gases in strongly anisotropic traps and the behavior of vortices and vortex pairs in a finite-temperature Fermi gas. For dark solitons in an ultracold fermion system, the spatial profile of the pair field and for the parameters of state for the soliton are analytically determined. In the strong-coupling regime, the obtained analytic solutions match well the numeric BdG results.

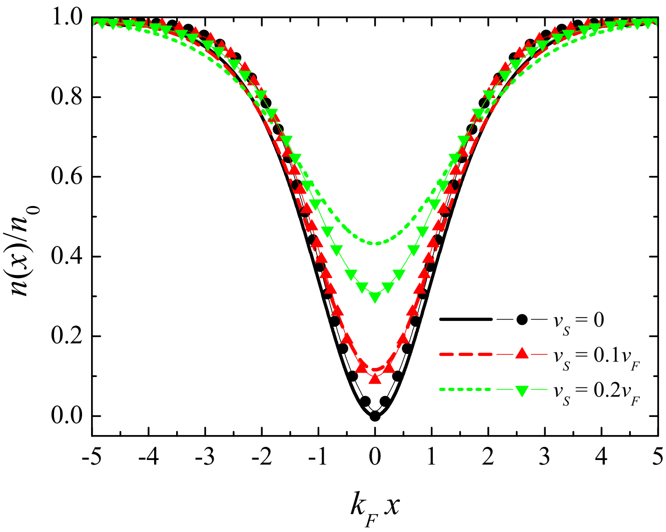

Figure 1: Density profile at different velocities v_S (in units of the Fermi velocity v_F) for a dark soliton with the inverse scattering length $1/(k_F a_S) = 1$. The curves are the results of the extended GL approach. The symbols show the BdG data [3].

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Superfluid correlations in low-dimensional ultracold gases

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A balanced two-component Fermi gas in one dimension is perturbed with a moving potential well or barrier that sweeps across the lattice [1]. Different velocities and strengths of the perturbation are studied using the time-evolving block decimation (TEBD) method, and two velocity regimes are distinguished based on features in the particle densities and in the pair correlation function. In the slow velocity regime, the densities deform as particles are either attracted by the potential well or repelled by the barrier, and a wave front of hole or particle excitations propagates at the maximum group velocity. The pair correlations show that the initial superfluid state is broken: coherence over different sites is lost after the potential has passed a point in the chain. In the fast regime, the densities are not considerably deformed and the pair correlations are preserved. This is in contrast with the concept of a superfluid critical velocity in higher dimensions.

We study the superfluid properties of two-dimensional spin-population-imbalanced Fermi gases to explore the interplay between the Berezinskii-Kosterlitz-Thouless (BKT) phase transition and the possible instability towards the Fulde-Ferrell (FF) state [2]. By the mean-field approximation together with quantum fluctuations, we obtain phase diagrams as functions of temperature, chemical potential imbalance and binding energy. We find that the fluctuations change the mean-field phase diagram significantly. We also address possible effects of the phase separation and/or the anisotropic FF phase to the BKT mechanism. The superfluid density tensor of the FF state is obtained, and its transverse component is found always vanishing. This causes divergent fluctuations and possibly precludes the existence of the FF state at any non-zero temperature in 2D.

Fermionic superfluidity in strongly anisotropic optical lattices with attractive interactions is studied utilizing cluster DMFT and real-space DMFT methods and focusing in particular on the role of non-local quantum fluctuations [3]. We show that non-local quantum fluctuations impact the BCS superfluid transition dramatically. Moreover, we show that exotic superfluid states with delicate order parameter structure, such as the Fulde-Ferrell-Larkin-Ovchinnikov phase driven by spin population imbalance, can emerge even in the presence of such strong fluctuations.

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Extended Ginzburg-Landau theory and critical superconductors

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Multi-band superconductors often reveal untypical vortex configurations that are not found in common superconducting materials [1]. The origin of such vortex states is yet not clear and is being highly debated. Of particular interest is whether multi-band superconductors fall into one of the standard superconductor types or this classification needs be amended. We consider another dimension to this problem by studying superconductivity in vicinity of a critical Bogomolny point [2], where superconductivity exhibits properties notably different from the two standard types. In the analysis the extended version of the Ginzburg-Landau theory is used.

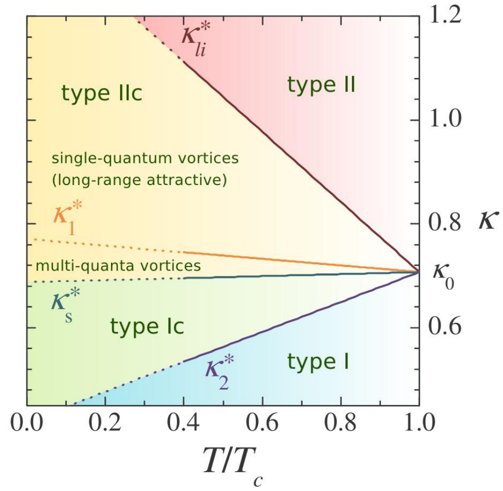

FIG. 1. Domain of critical superconductors for single-band materials as follows from the extended Ginzburg-Landau theory.

The conventional Ginzburg-Landau theory is arguably the most convenient and frequently employed tool in studying inhomogeneous condensate states. However, its multi-band generalization has encountered serious inconsistencies. We derive the extended theory in the form of the perturbation expansion of the microscopic free-energy functional and the gap equation using the proximity to the critical temperature as the small parameter [3-5]. The two lowest orders of this expansion yield the standard Ginzburg-Landau theory and the higher orders are its corrections. A particular advantage of this approach is that in many situations if offers the results in the form of easily tractable analytical and semi-analytical expressions.

Properties of the vortex states are investigated in the vicinity of the Bogomolnyi critical point. Originally introduced in string theories this point is also fundamental to superconductivity, where at T_c it marks the border between ideally diamagnetic bulk type-I superconductors and type-II ones that can host vortices. At this point distributions of magnetic flux the system can harbor is infinitely degenerate. We show that below T_c the physics of the Bogomolnyi point projects onto a wider range of microscopic parameters, even extremely wide for multi-band superconductors. In this domain the degeneracy of the superconducting state at T_c d into a sequence of novel topological equilibria and the customary understanding of superconducting phenomena does not suffice. As a radical departure from traditional views, we introduce the paradigm of *critical superconductors*, discuss their magnetic properties, advocate their subdivision in terms of possible intermediate states, and demonstrate the relevance of this paradigm to superconducting materials of interest today.

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Strongly interacting Fermi gases in 2 and 3 dimensions

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We present our recent progress on studies of ultracold Fermi gases tuned to the strongly interacting regime in two and three dimensions. We have measured the local (homogeneous) density-density response function of a 3D Fermi gas at unitarity using spatially resolved Bragg spectroscopy. By analyzing the Bragg response across one axis of the cloud we extract the response function for a uniform gas which shows a clear signature of the Bose-Einstein condensation of pairs of fermions when the local temperature drops below the superfluid transition temperature [1]. The method we use for local measurement generalizes a scheme for obtaining the local pressure in a harmonically trapped cloud from the line density and can be adapted to provide any homogeneous parameter satisfying the local density approximation.

We have also prepared Fermi gases in a single highly oblate 2D trapping potential with an aspect ratio exceeding 200. This allows us to produce much larger clouds of fermions in the 2D and quasi-2D regimes compared to our previous work [2]. Interactions between atoms are controlled via a broad Feshbach resonance providing access to the BCS-BEC crossover in 2D and quasi-2D. We will present our progress towards measurements of the thermodynamic equation of state [3, 4] throughout the crossover.

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Quartets of Order Parameters and Patterns of Condensates in Domes Preventing Quantum Critical Points and in Correlated Nanostructures

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A multitude of quantum ordered states is accessible in correlated systems. For example, if we consider the possibility of coexistence and competition of Density Waves with Superconductivity, we may construct an eight-dimensional spinor theory that defines 63 different accessible order parameters, among which 31 are particle-hole condensates from which the 26 have a magnetic character [1]. We have demonstrated a general *rule* [1] that predicts hidden symmetries and induced order parameters. We identify a universal interaction between the order parameters that have tendency to aggregate into *quartets* of order parameters. We have verified the relevance of the rule on dozens of examples, and we conclude that the quartets of order parameters constitute the building blocks of quantum complexity through overlapping quartets that form closed patterns of condensates.

The quartets may be in the *hierarchy* regime where usually one order parameter dominates, or in the *equity* regime where all members fully develop. The *equity* regime defines *domes* preventing the expected quantum critical points of dominating orders and we argue that such *domes* seen in various materials, in some cases delimited by first order double step *metamagnetic* transitions, have a common characteristics, reflecting in fact the transition from the hierarchy regime to the equity regime [1]. In the equity *dome* regime we observe exotic states and exotic phase transitions. We have shown long ago that a competition of conventional CDW and SDW of similar magnitude when they coexist in a quartet with Ferromagnetism and particle-hole asymmetry may explain the CMR phenomenon [2]. The high field exotic Q-phase in the superconducting state of $CeCoIn_5$ involves another quartet: d-wave SC + π-triplet SC +SDW + particle-hole asymmetry [3].

However, quartets are not only relevant in the *dome* areas of materials phase diagrams. Our quartets can be *engineered* at interfaces and in nanostructures producing extraordinary new phenomena of great interest for technologic applications. We will discuss some characteristic examples of engineered quartets, proposing a novel picture of the phenomenology of $LaAlO_3/SrTiO_3$ and other oxides interfaces. The potential implications of our engineered quartets range from the field of topological error-free quantum computation to topologically protected spin current devices and other spintronics applications.

[1] G. Varelogiannis, arXiv:1305.2976
[2] G. Varelogiannis, Physical Review Letters **85**, 4172 (2000).
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Fluctuations in Two-Band Superconductors

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A theory of fluctuations in two-band superconductor is developed. Since the standard Ginzburg-Landau approach fails in description of its properties, we generalize it based on the microscopic theory of a two-band superconductor [1]. Calculating the microscopic fluctuation propagator, we build up the nonlocal two-band GL functional and derive the corresponding time-dependent GL equations. Especial attention is devoted to the MgB_2 superconductor, where the pairing in σ and π bands differs strongly. We find parametrically narrow range of temperatures where the standard GL theory of fluctuations is still applicable. Beyond it fluctuations become non-local and we propose corresponding generalization of the GL approach. This allows us to calculate the main fluctuation observables such as fluctuation specific heat and conductivity, find the critical exponents in different regimes and explain the specifics of the available experimental findings [2].

The second part of presentation is devoted to the recently observed striking contrast in the shapes of superconductive transitions in magnetic field studied simultaneously by the heat capacity and resistivity measurements on P-doped 122 iron pnictides [3]. With increasing magnetic field the heat capacity transition shifts away from the resistive transition to higher temperatures. We study theoretically the fluctuation corrections to both of these characteristics in magnetic field close to the $H_{c2}(T)$ line and attribute the observed anomaly to the dissimilar parameters of the electron and hole bands leading to different partial contributions of these bands to fluctuating thermodynamics and transport properties.

[1] A. E. Koshelev, A. A. Varlamov, and V. M. Vinokur, Physical Review **B 72**, 064523 (2005).
[2] V. Ferrando, I. Pallecchi, A. Malagoli, M. Putti, X.X. Xi, A.A. Varlamov, A.E. Koshelev, C. Ferdeghini, Physica **C 460-462**, 608 (2007).
[3] U.Welp, C. Marcenat, unpublished.

MULTISUPER-2014 TIMETABLE

Tuesday

Time		
8:30	Opening	
9:00	Varlamov Plenary	
9:45	Vagov	
10:15	Babaev	
10:45	Presentation (Leiden Cryogenics)	
11:00	Coffee	
11:30	Benfatto	Palumbo
12:00	Milosevic	Varelogiannis
12:30	Marsiglio	Kashuba
13:15	LUNCH Cortile dei Governatori	
15:00	Borisenko Plenary	
15:45	Bianconi	
16:15	Paglione	
16:45	Coffee	
17:15	Daghero	
17:45	Capone	
18:15	Doria	
18:45	Close	

Wednesday

Time		
9:00	Vale Plenary	
9:45	Strinati	
10:15	Ospelkaus	
10:45	Coffee	
11:15	Ricci	Barbiero
11:45	Glatz	De Palo
12:15	Barci	Fratini
12:45	Croitoru	Quader
13:15	LUNCH Cortile dei Governatori	
15:00	Sa de Melo	
15:30	Fetter	
16:00	Baym	
16:30	Törmä	
17:00	Tempere	
17:30	Posters & Gelato	
	Bertaina	Corredor
	Da Silva	De Leo
	Dolce	Guidini
	Huang	Orlova
	Palestini	Pieri
	Portela	Rezvani
	Sanchez-Loreto	Simonucci
19:30	Close	

Thursday

Time		
9:00	Lozovik Plenary	
9:45	Hamilton	
10:15	MacDonald	
10:45	Polini	
11:15	Coffee	
11:45	Astrakharchik	Salasnich
12:15	Neilson	Pilati
12:45	Tanatar	Pupillo
13:15	LUNCH Cortile dei Governatori	
15:00	Giorgini	
15:30	Schuck	
16:00	Boronat	
16:30	Coffee	
17:00	Ponomarenko	
17:30	Shanenko	
18:00	Senatore	
18:30	Close	
20:00	Conference Dinner	

Friday

Time	
9:00	Sigrist Plenary
9:45	Machida
10:15	Caprara
10:45	Garcia-Garcia
11:15	Peeters
11:45	Coffee
12:15	Roditchev
12:45	Hasegawa
13:15	Aguiar
13:45	Bose
14:15	LUNCH Cortile dei Governatori
15:30	

Legend
Bulk multiband superconductors
Multiband and multicomponent superfluidity in ultracold atoms
Electron-hole superfluidity
Unconventional multicomponent superconductivity