Fluctuation modes in multi-gap superconductivity and theory of spontaneous symmetry breaking

Takashi Yanagisawa
National Institute of Advanced Industrial Science and Technology (AIST), Japan

Abstract:
We discuss the Nambu-Goldstone boson and the Ward-Takahashi identity in a system with spontaneous symmetry breaking. We give a formula for the Nambu-Goldstone boson for a general transformation group G. The Ward-Takahashi identity is modified in the presence of the Nambu-Goldstone boson. We apply this theory to examine low-excitation modes in superconductors. In a multi-gap superconductor, the multiple-phase invariance is partially or totally broken. The Nambu-Goldstone-Leggett modes, as well as Higgs modes, are important and will play an important role in superconductors. The properties of these modes are dependent upon inter-band couplings (Josephson couplings). Frustrated Josephson couplings induce many interesting phenomena in a multi-gap superconductor [1-4]. For example, new excitation modes appear in a phase with time-reversal symmetry breaking. The sine-Gordon model for the Leggett mode can be generalized to a nonabelian case [5].

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| 15:15 | B4-2(Keynote) | Novel superconductivity in multiband materials  
Mukunda Das  
Department of Theoretical Physics, Australian National University, Australia |

Abstract:
During the past decade there has been renewed interest in the physics of multiband superconductivity. Materials exhibiting multiband superconductivity possess multiband electronic structure. The inter-band coupling in these systems is the main cause of novel properties. Examples of such materials include MgB$_2$, Boro-carbides, Pnictides and Chalcogenides. In this talk we shall review novel features of multiband superconductivity and present two theoretical aspects: (i) an extended version of multiband Ginzburg Landau theory [1] and (ii) a generalization of multiband BCS theory [2]. In both approaches the interband couplings show several new features. In the former case the order parameters vs. temperature are investigated as the interband couplings vary. In the latter case Leggett (collective) modes and time reversal broken symmetry states are studied, which are novel in the multiband superconductors.


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| 15:45 | B4-3(Invited) | The driving force on vortices in superconductors  
Yusuke Kato  
University of Tokyo, Japan |
Abstract: The driving force on isolated vortex in type II superconductors have been subject to hot debates for last fifty years. Some authors claimed that the vortex motion is driven by Lorentz force (magnetic force) and other authors hydrodynamic force. A possible source of controversy is in the fact that earlier works have not considered the non-uniformity of the transport current; away from vortex, current density follows the London equation and thus current varies spatially over the scale of penetration depth. Earlier results correspond to the case with infinite We address [1] the nature of driving force for superconductors with finite on the basis of the time-dependent-Ginzburg-Landau(TDGL) theory and a generalized TDGL model. We show that neither Lorentz force nor hydrodynamic force accounts for the driving force on vortices in full magnitude. The sum of these force is physically meaningful as the driving force on vortices. The underlying physics of this result is in the fact that neither quantum circulation nor the magnetic flux is quantized but the London’s fluxoid is quantized around the isolated vortex.

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<td>16:30</td>
<td>B4-4(Invited)</td>
<td>Numerical method for transition temperature and vortex states in nano-sized superconductors using the Eliashberg equation and the finite element method</td>
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<td>Masaru Kato</td>
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<td>Osaka Prefecture University, Japan</td>
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<td>Abstract: In nano-sized superconductors, peculiar vortex structures and enhancement of transition temperature have been studied experimentally and theoretically. For the transition temperature enhancement, high-pressure torsion experiment showed that the superconducting transition temperature of nano-sized Nb becomes higher than that of bulk Nb [1]. Theoretical investigations were done using the Ginzburg-Landau equations or the Bogoliubov-de Gennes equations [2,3]. For this problem, we have developed a numerical method using the Eliashberg equation and the finite element method. In this method, we incorporate explicitly the phonon structures, which cause attractive interaction between electrons. Also we incorporate the impurity effects. Therefore we can investigate effects of phonon structures and impurities on the transition temperature enhancement in nano-size superconductors. Because we use the finite element method, we can investigate the shape dependence of superconducting transition temperature. We can also investigate the vortex structures in nano-size superconductors under an external field. In this talk we show details of our numerical method and numerical results for transition temperature enhancement and vortex structures. [1] T. Nishizaki, et al., Physica C, 493 (2013) 132. [2] L. F. Chibotaru, et al., Nature 408 (2000) 833. [3] H Suematsu, M Kato, T Ishida, J. of Phys.: Conf. Ser., 150 (2009) 052250.</td>
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<td>17:00</td>
<td>B4-5(Invited)</td>
<td>Ab-initio Eliashberg Approach for Superconductivity in Sulfur Hydrides</td>
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Takashi Koretsune
Institute of Physical and Chemical Research (RIKEN), Japan

Abstract:
We evaluate the superconducting transition temperature (Tc) of sulfur hydrides by solving the Eliashberg equation in the Green’s function representation. In this approach, we calculate all the quantities including the Coulomb interaction from first principles and consider several effects which are neglected in the conventional Migdal-Eliashberg approach; that is, energy dependence of the density of states, self-consistency of the Green’s function, the effect of zero-point motion on the band structure and anharmonicity of the phonon frequencies. We also estimate the effect of vertex correction. In H3S, we find that all of these show non-negligible effects on Tc since the phonon frequency and amplitude are significantly large and there is a Van Hove singularity around the Fermi level. Including all of these and the plasmon effect, we successfully reproduce the experimental Tc. This work is done in collaboration with Wataru Sano, Terumasa Tadano, Ryosuke Akashi and Ryotaro Arita.

Izumi Hase, Takashi Yanagisawa, Kenji Kawashima
National Institute of Advanced Industrial Science and Technology (AIST), Japan

Abstract:
In some superconductors the charge-density wave (CDW) state is adjacent to the superconducting state in the phase diagram. This CDW phase can be collapsed either by pressure or by chemical doping, depending on compounds. Among them, in so-called valence skip compounds, a large charge fluctuation with the large electron-phonon interaction is expected [1]. We performed a first-principles study and investigated how the CDW gap is collapsed by pressure for several valence-skip compounds, i.e. BaBiO3, SnX3 and RbTlX3 (X=F,Cl,Br). We found that the CDW gap is
rather robust for the isotropic volume change, and on the contrary, the magnitude of the CDW gap strongly depends on the position of the anion. This means that the electronic structure is strongly coupled with the optical phonon mode.

Session’s Title (Topological and Skyrmion)

**Thu – 19 Jan 2017 | 15:45 ~ 17:45 | Room 8**

Session Chair(s): Mukunda Das (Australian National University), Takashi Yanagisawa (AIST)

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<td>15:45</td>
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<td>Computational Modelling of Vortex and Skyrmion Lattices in Nanostructured Samples</td>
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<td>Charles M. Reichhardt</td>
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<td>Theoretical Division, Los Alamos National Laboratory, USA</td>
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**Abstract:**

Since the initial discovery of skyrmion lattices in chiral magnets, there has been tremendous growth in this field. As an increasing number of compounds, are now found to have extended regions of stable skyrmion lattices at room temperature. These systems have significant promise for applications due to their size scale and the ability to drive the skyrmions with an applied current. Another interesting aspect of skyrmions is that their dynamics is dominated by a non-dissipative term or a Magnus effect, which makes them unique in terms of collective driven dynamics compared to other systems such as vortex lattices in type-II superconductors, sliding charge density waves, or frictional systems. We use a combination of continuum and particle based computational techniques to examine the structure and dynamics of skyrmions and vortices interacting with random pinning, periodic substrate potentials, and ratchet potentials. In systems with random pinning we find a finite
depinning threshold and a strong dependence of the Hall angle on the disorder strength. As a function of disorder strength we observe a pinned skyrmion crystal, a skyrmion glass phase, a dynamical liquid state, and a moving crystal phase, and show that transitions between these states can be deduced from changes in the transport signatures, noise signal, and structure factor. When skyrmions are moving over a two-dimensional periodic substrate we show that the skyrmion Hall angle becomes quantized due to dynamical symmetry locking with the substrate. For skyrmions and vortices interacting with 1D symmetric and asymmetric substrates, we find a variety of Magnus-induced transport effects including phase locking, negative differential conductivity, ratchet effects, and even negative mobility in which the skyrmion moves in the direction opposite to the external drive. We also examine skyrmion ordering using a GPU-based continuum model which allows us to capture the internal modes of the skyrmion shape and dynamics. We find that a rich variety of skyrmion superlattice structures can be realized for systems with 2D and 1D periodic substrates, including a square skyrmion lattice, incommensurate phases, and composite lattices of multiple species of skyrmions. For skyrmions in a confined quasi-1D geometry we also show that there can be transitions from single skyrmion chains to a zig-zag state or multiple rows of skyrmions.
describing a circular Josephson junction made of a superconductor surrounded by another superconductor [2]. Then, multi-layered Josephson junction can be described as multiple domain walls in the multi-component system [3]. Both frustrated and unfrustrated Josephson junctions of three superconductors are discussed and in the former case frustrated/unfrustrated transition depending on the width of the middle superconductor was found. This model can be generalized to non-Abelian Josephson junction of two non-Abelian (color) superconductors [4,5]. In this case, a non-Abelian Josephson junction is described as a non-Abelian domain wall and non-Abelian Josephson vortices are described by non-Abelian sine-Gordon solitons [6,7].


16:45

B4-9(Invited)

Numerical Study for Searching the Majorana Bound States in Topological Superconductors

Takuto Kawakami
### National Institute of Materials Science (NIMS), Japan

**Abstract:**
Recently, the Majorana bound states (MBSs), which are zero-energy quasiparticle excitations in topological superconductors, attract much attention since they can realize the non-Abelian quantum statistics useful for achieving a decoherence-free quantum computation. As a platform of the topological superconductor, a heterostructure of s-wave superconductors and topological insulators was theoretically proposed sometime ago. Meanwhile, identifying MBSs conclusively in experiments remains challenging so far.

In this work, solving the Bogoliubov-de Gennes equation numerically, we investigate local density of states (LDOS) inside the vortex core in the heterostructure. As the result, we reveal that the spatial-energy distribution of the LDOS evolves from a V-shape to a Y-shape with emergence of the MBS [1], in nice agreement with a recent STM/STS experiment in Bi2Te3 thin layer on top of NbSe2 substrate [2]. Furthermore, we propose that the ratio of the LDOSs in spin-up and -down channels exhibits the checkerboard-type pattern [1]. It provides a clue toward distinguishing the MBS as a single quantized state in the whole spectrum by using spin-resolved STM/STS experiments [1,3].


### B4-10 (Invited)

**Ginzburg-Landau Equations in Superconducting Topological Insulator Cu-doped Bi2Se3**

Yukihiro Ohta, Yuki Nagai, Masahiko Machida

**Abstract:**
Studying topological superconductor is an attractive issue in condensed matter physics. Superconducting topological...
insulator, Cu-doped Bi2Se3, is a good candidate of bulk topological superconductors. Towards studying transport and vortex physics in this novel superconductor, we construct the Ginzburg-Landau (GL) theory from a two-orbital model with short-range density-density interaction proposed by Fu and Berg. Taking six kinds of the order parameters attainable from this model into account, the GL expansion of a superconducting free energy is performed in the vicinity of Tc systematically. The expansion coefficients are characterized well by both a normal-state property (i.e., mass in the Dirac-type normal-state dispersion relation) and a superconducting-state property (i.e., parity quantum number with respect to spatial inversion). To reveal unique features of the resultant GL equation, we mainly argue (i) the spatial distribution of supercurrent in the presence of point-node gaps (i.e., a kinetic-term aspect) and (ii) the discrepancy between a conventional s-wave state and a topological odd-parity state with respect to the penetration depth (i.e., a nonlinear-term aspect). Thus, the GL theory may lead to a useful approach of understanding superconducting properties in Cu-doped Bi2Se3 near Tc.