T01

Amplitude modes in cold atoms

S.D. Huber,
Institute for Theoretical Physics, ETH Zurich
E-mail address: sebastian.huber@phys.ethz.ch

The Bose Hubbard model exhibits a quantum phase transition between an insulating Mott state and a superfluid. We aim at the determination of the excitation spectrum of the superfluid phase, in particular its evolution from the vicinity of the Mott phase towards the weakly interacting regime. Furthermore, we discuss a method allowing to observe our findings in an experiment. We make the link between our microscopic findings and the notion of a "Higgs" mode. Specifically, we highlight the role of emergent symmetries. Recent developments in the description of amplitude modes in exotic chiral Mott insulators will be mentioned.

[1] S.D. Huber, E. Altman, H.P. Büchler, and G. Blatter, Phys. Rev. B, **75** 085106 (2007)
[2] S.D. Huber, B. Theiler, E. Altman, G. Blatter, Phys. Rev. Lett., **100** 050404 (2008)
[3] S.D. Huber and N.H. Lindner, Proc. Natl. Acad. Sci. USA, **108** 19925 (2011)

T02

Higgs mode and universal dynamics near quantum criticality

D. Podolsky
Department of Physics, Technion – Israel Institute of Technology, Haifa 32000, Israel
E-mail address: podolsky@physics.technion.ac.il

The Higgs mode is a ubiquitous collective excitation in condensed matter systems with broken continuous symmetry. Its detection is a valuable test of the corresponding field theory, and its mass gap measures the proximity to a quantum critical point. However, since the Higgs mode can decay into low energy Goldstone modes, its experimental visibility has been questioned. In this talk, I will show that the visibility of the Higgs mode depends on the symmetry of the measured susceptibility. I will also present an analysis of the evolution of the Higgs mode upon approach to the Wilson-Fisher fixed point in 2+1 dimensions and demonstrate that the Higgs mode survives as a universal resonance in the scalar susceptibility arbitrarily close to the quantum critical point. I will discuss the implications of these results for experiments on lattice Bose condensates near the Mott insulator to superfluid transition.

[1] D. Podolsky, A. Auerbach, and D. P. Arovas, *Phys. Rev. B* **84**, 174522 (2011)
[2] D. Podolsky and S. Sachdev, *Phys. Rev. B* **86**, 054508 (2012)
[3] S. Gazit, D. Podolsky, and A. Auerbach, *Phys. Rev. Lett.* **110**, 140401 (2013).
[4] S. Gazit, D. Podolsky, A. Auerbach, and D.P. Arovas, Phys. Rev. B **88**, 235108 (2013).

T03

Observation of the Higgs amplitudemode in a two-dimensional superfluid

T. Fukuhara[1], M. Endres[1], M. Cheneau[1], P. Schauß[1], C. Gross[1], S. Kuhr[1,2], and I. Bloch[1,3]
[1] Max-Planck-Institut für Quantenoptik, 85748 Garching, Germany
[2] University of Strathclyde, SUPA, Glasgow G4 0NG, United Kingdom
[3] Ludwig-Maximilians-Universität, 80799 München, Germany
E-mail address: takeshi.fukuhara@mpq.mpg.de

Ultracold bosonic atoms in optical lattices offer unique opportunities to study quantum phase transitions in systems with reduced dimensionality. These systems are nearly ideal realizations of the Bose-Hubbard model, which is parameterized by a tunneling amplitude J and an on-site interaction energy U. The ratio between them is easily tunable via the lattice depth, and the dimensionality of the system can be reduced by suppressing tunneling in a certain direction. At a critical parameter J/U and commensurate filling, the systems undergo a quantum phase transition from a superfluid (ordered) to a Mott insulating (disordered) phase. Close to the transition point, they are described by an O(2) relativistic field theory, which constitutes a minimal model for spontaneous breaking of a continuous symmetry. Using such systems, here we experimentally find and study a Higgs amplitude mode in a two-dimensional superfluid. We identify the mode by observing the expected reduction in frequency of the onset of spectral response when approaching the transition point [1]. In our system, all microscopic parameters are known from first principles and the resolution of our measurement allows us to detect excited states of the many-body system at the level of individual quasiparticles. This allows for an in-depth study of Higgs excitations that also addresses the consequences of the reduced dimensionality and confinement of the system.

[1] M. Endres, T. Fukuhara, D. Pekker, M. Cheneau, P. Schauß, C. Gross, E. Demler, S. Kuhr, and I. Bloch, Nature **487**, 454 (2012).

T04

Universal quantum critical dynamics at the two-dimensional Superfluid-to-Insulator transition

Kun Chen[1,2], Longxiang Liu[1,2], Lode Pollet[3], Nikolay Prokof'ev[2,4]
[1] National Laboratory for Physical Sciences at Microscale and Department of Modern Physics, University of Science and Technology of China, Hefei, Anhui 230026, China
[2] Department of Physics, University of Massachusetts, Amherst, Massachusetts 01003, USA
[3] Department of Physics and Arnold Sommerfeld Center for Theoretical Physics, Ludwig-Maximilians-Universität München, D-80333 München, Germany
[4] Russian Research Center "Kurchatov Institute", 123182 Moscow, Russia
E-mail address: chenkun@mail.ustc.edu.cn

We study universal quantum critical dynamics of the (2+1)-dimensional XY universality class, which is realized in the cold atomic system at the superfluid (SF) and Mott insulator (MI) transition. Using large-scale Monte Carlo simulations and numerical analytical continuation we find that despite strong decay into massless Goldstone modes the Higgs (massive Goldstone) boson survives as a well-defined resonance. We construct universal spectral functions for scalar response both for SF and MI phases and reveal that they share similar properties: a resonant peak followed by a broader secondary peak before saturating to the critical plateau behavior at higher frequencies. Our simulations of a trapped system of ultra-cold ^{87}Rb atoms explain recent experimental data and how the signal is modified by tight confinement. We also compute the universal optical conductivity and precisely determine the conductivity on the quantum critical plateau, $\sigma(\infty) = 0.359(4)\sigma_Q$ with σ_Q the conductivity quantum. The universal conductivity curve is the textbook example of where the AdS/CFT correspondence from string theory can be tested and made to use. For the first time, the shape of the $\sigma(i\omega_n) - \sigma(\infty)$ function in the Matsubara representation is accurate enough for a conclusive comparison and establishes the particle-like nature of charge transport.We find that the holographic gauge/gravity duality theory for transport properties can be made compatible with the data only if temperature of the horizon of the black brane is different from the temperature of the conformal field theory.

T05

Fate of the amplitude mode in the vicinity of a quantum critical point

A. Rançon[1], N. Dupuis[2]
[1] James Franck Institute and Department of Physics, University of Chicago, Chicago, Illinois 60637, USA;
[2] Laboratoire de Physique Théorique de la Matière Condensée, CNRS UMR 7600, Université Pierre et Marie Curie, 4 Place Jussieu, 75252 Paris Cedex 05, France
E-mail address: rancon@jfi.uchicago.edu

The quantum $O(N)$ model is ubiquitous in condensed matter and cold atoms and describes the behavior of a number of systems close to a quantum phase transition. In the ordered (broken-symmetry) phase far from the critical point, there are N-1 Goldstone modes and a gapped amplitude mode. In low dimensions, the system is strongly coupled close to the critical point, and the existence of the amplitude mode is not guaranteed. We discuss the fate of the amplitude mode for $N \geq 2$ at zero and finite temperature using a non-perturbative renormalization group approach. For $N = 2$, we find a well-defined resonance, in agreement with recent Monte-Carlo simulations. The resonance persists at finite temperature below the Kosterlitz-Thouless transition temperature. We show that even if a resonance does exist in the disordered phase, its existence is not related to the physics of the amplitude mode. Furthermore, we show that the resonance in the ordered phase is strongly suppressed for $N \geq 3$, in agreement with the large N limit.

T06

Higgs particle properties from High-Energy experiment

M. Ishino[1],
[1] Kyoto University, Kyoto, 606-8502, Japan;
E-mail address: masaya.ishino@cern.ch

A new particle of mass about 125GeV has been discovered in July 2012 by ATLAS and CMS collaborations. Based on the datasets recorded by ATLAS experiment at the CERN Large Hadron Collider at center-of-mass energies of $\sqrt{s}$ = 7TeV and $\sqrt{s}$ = 8TeV, corresponding to an integrated luminosity of 25fb^{-1}, various properties of the new particle have been measured.

In the framework of the Standard-Model in elementary particle physics, if the new particle is a Higgs boson, its spin and parity should be $J^P = 0^+$. Using decay modes of the new particle to $H \to \gamma\gamma$, $H \to ZZ^* \to 4l$, $H \to WW \to l\nu l\nu$, it is confirmed that J^P=0$^+$ is strongly preferred and alternative possibilities $J^P = 0^-, 1^+, 1^-, 2^+$ are excluded at confidence levels above 97.8$\%$.
Another important point to characterize the new particle is the coupling strength to bosons and fermions. Since the mass of the new particle is around 125GeV, it decays to $ZZ, WW, \tau\tau, b\bar{b}$ and $\gamma\gamma$ via loop, also to other rare decay modes. The strength of Yukawa-couplings to fermions, of gauge-couplings to weak bosons are calculated in the framework of the Standard-Model. It is important to check consistencies between data and theoretical prediction. So far, the results tell that the new particle is consistent with the Standard-Model Higgs boson within errors. Finally the mass of the Higgs boson has been precisely determined by improving detector calibrations, the up-to-date result is presented.

[1] Physics Letters B 716 (2012) 1 - 29
[2] Physics Letters B 726 (2013) 88 - 119
[3] Physics Letters B 726 (2013) 120 - 144
[4] ATLAS-CONF-2014-009
(https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2014-009/)

T07

Supersymmetry after Higgs discovery

K. Hamaguchi[1],
[1] Department of Physics, University of Tokyo, Tokyo 113-0033, Japan
E-mail address: hama@hep-th.phys.s.u-tokyo.ac.jp

We discuss implications of the discovered Higgs boson mass, 126 GeV, for the physics beyond the Standard Model, in particular for the supersymmetic models.

T08

Possible compositeness of the 125 GeV Higgs boson

M.A. Zubkov[1],[2]
[1] University of Western Ontario, London, ON, Canada N6A 5B7;
[2] ITEP, B.Cheremushkinskaya 25, Moscow, 117259, Russia
E-mail address: zubkov@itep.ru

We suggest the hypothesis, that the 125 GeV Higgs boson is composed of the Standard Model fermions, and at the distances of the order of $\sim 1/100$ GeV its interaction with the fermions is $U(12) \otimes O(4)$ symmetric, so that all Standard Model fermions enter it in an equal way. According to the suggested scenario at the distances $\gg 1/100$ GeV the mentioned symmetry is broken, and the interaction term dominates that provides the nonzero mass of the top quark (the other SM fermions remain massless on this level of understanding). In the suggested model the symmetry $U(12) \otimes O(4)$ is responsible for the relation between the Higgs boson mass and the top quark mass $M_H^2 = m_t^2/2$.

[1] M. A. Zubkov, “Strong dynamics behind the formation of the 125 GeV Higgs boson,” arXiv:1401.3311 [hep-ph], Phys. Rev. D 89 (2014), 075012
[2] M. A. Zubkov, “Modified model of top quark condensation”, arXiv:1405.4067 [hep-ph]

T09

Higgs mode in quantum spin systems

M. Matsumoto[1]
[1] Department of Physics, Shizuoka University, Shizuoka 422-8529, Japan
E-mail address: spmmatu@ipc.shizuoka.ac.jp

Since the discovery of the Higgs boson in high-energy physics, searching for a similar exited particle (Higgs mode) has attracted much interest in condensed matter physics. In quantum spin systems, the Higgs mode is an excitation of the amplitude-fluctuation of the ordered moment. In conventional spin systems, spin-wave excitations of the direction-fluctuation of the moment (Nambu-Goldstone mode) can be observed, however, the Higgs mode is hard to detect. To have the Higgs mode, it is necessary that the ordered moment must be shrunk by quantum effects. Low-dimensionality is one example as in quasi one-dimensional systems[1]. Another example is a spin dimer system, where a paramagnetic phase is stabilized at the ambient pressure owing to the strong antiferromagnetic intradimer interaction. In case of $TlCuCl_3$, applying pressure can induce a quantum phase transition into a magnetically ordered phase[2,3]. Here, Sachdev and Keimer pointed out that the Higgs mode was observed by inelastic neutron scattering measurements[3] in the vicinity of the quantum critical point[4]. To describe the Higgs mode, it is useful to adopt the bond-operator formulation[5-8]. We explain this formulation and the experimental results[3] including at finite temperatures[9]. The Higgs mode is also detectable by optical measurements[10,11]. We discuss this point in connection with related $S = 1$ systems with a strong easy-plane type single-ion anisotropy[12].

[1] I. Affleck and G. F. Wellman, Phys. Rev. B **46**, 8934 (1992).
[2] A. Oosawa *et al*. J. Phys. Soc. Jpn. **72** 1026 (2003).
[3] Ch. Rüegg *et al*., Phys. Rev. Lett. **100**, 205701 (2008).
[4] S. Sachdev and B. Keimer, Phys. Today **64**(2), 29 (2011).
[5] S. Sachdev and R. N. Bhatt, Phys. Rev. B **41**, 9323 (1990).
[6] A. V. Chubukov and D. K. Morr, Phys. Rev.B **52**, 3521 (1995).
[7] T. Sommer, M. Vojta, and K. W. Becker, Eur. Phys. J. B **23**, 329 (2001).
[8] M. Matsumoto *et al*., Phys. Rev. B **69**, 054423 (2004).
[9] P. Merchant *et al*., Nat. Phys. **10**, 373 (2014).
[10] H. Kuroe *et al*., J. Phys.: Conf. Ser. **400**, 032042 (2012).
[11] M. Matsumoto *et al*., J. Phys. Soc. Jpn. **77**, 033702 (2008).
[12] M. Matsumoto *et al*., J. Phys. Soc. Jpn. **82**, 093703 (2013).

T10

First-Order Magnetic Raman Scattering from Pressure-Induced Higgs Mode through Second-Order Magnetic Raman Process

H. Kuroe[1] and T. Sekine[1]
[1] Physics Division, Sophia University, Chiyoda-ku, Tokyo 102-8554, Japan
E-mail address: kuroe@sophia.ac.jp

Inelastic light scattering (Raman scattering) from the pressure-induced Anderson-Higgs mode in the spin dimer system $KCuCl_3$ is discussed. According to the bond-operator theory [1], the triplet excited states, namely the trliprons, can hop between the neighboring spin dimers in a crystal. This causes the dispersive magnetic excitations and the spin gap with the energy much smaller than the one expected from the strength of the exchange interaction forming the spin dimers. Application of high pressures can control the hopping integral, i.e., the band width in the magnon dispersion curve. At the critical pressure P_c, all of the magnon branches touch on the nonmagnetic ground state. This leads the property distinguished from the Anderson-Higgs and the Goldstone modes under magnetic fields. Neglecting magnetic anisotropy, a typical Mexican-hat shape (or a bottom-of-wine-bottle shape) potential curve is obtained, i.e, well defined Anderson-Higgs and Goldstone modes appear above P_c.

We have reported the first-order magnetic Raman scattering (one-magnon Raman scattering) from the singlet-triplet mixed ground state to the Anderson-Higgs mode under isotropic pressures [2,3]. Based on the results in these papers, we present the pressure dependence of the Raman spectrum including the magnetic Raman peak due to the Anderson-Higgs mode above P_c and the quantitative spectrum parameters of it. Especially, we focus on the lifetime of the Anderson-Higgs mode which is inversely proportional to its energy. The origin of this effect is discussed based on the anharmonicity caused by the decay channel from one Anderson-Higgs mode to two Goldstone modes. We compare our results with the recent ones obtained from the inelastic neutron scattering in $TlCuCl_3$ under high pressures [4].

This work was supported in part by a Grant-in-Aid for Scientific Research (C) (No. 22540350).

[1] M. Matsumoto *et al.*, Phys. Rev. B **69** (2004) 054423.
[2] H. Kuroe *et al.*, J. Phys.: Conf. Ser. **400** (2012) 032042.
[3] M. Matsumoto *et al.*, J. Phys. Soc. Jpn. **77** (2008) 033702.
[4] P. Merchant *et al.*, Nature Phys. **10** (2014) 373.

T11

Amplitude / Higgs Modes in Condensed Matter Physics

Chandra Varma
University of California, Riverside, CA. 92521, USA
E-mail address: chandra.varma@ucr.edu

The order parameter and its variations in space and time in many different states in condensed matter physics at low temperatures are described by a complex function $\Psi(\mathbf{r}, t)$. These states include superfluids, superconductors, and a sub-class of anti-ferromagnets and charge-density waves. The collective fluctuations in the ordered state may then be categorized as oscillations of phase and those of amplitude of $\Psi(\mathbf{r}, t)$. The phase oscillations are the *Goldstone* modes of the broken continuous symmetry. The amplitude modes, even at long wave-lengths, are well defined and de-coupled from the phase oscillations only at particle-hole symmetry, where the equations of motion have an effective Lorentz symmetry as in particle physics. They bear close correspondence with the so-called *Higgs* modes in particle physics, whose prediction and discovery is very important for the standard model of particle physics. In this review, I discuss the theory and the observation of the amplitude or Higgs modes in condensed matter physics - in superconductors, cold-atoms in periodic lattices, and in uni-axial anti-ferromagnets. Emphasis is placed on the necessity for at least approximate particle-hole symmetry as well as the special conditions required to couple to such modes.

T12

Observation of Higgs mode in s-wave superconductors

Ryo Shimano
Cryogenic Research Center, The University of Tokyo, Tokyo, 113-0032, Japan
Department of Physics, The University of Tokyo, Tokyo, 113-0033, Japan
E-mail address: shimano@phys.s.u-tokyo.ac.jp

Ultrafast photo-control of superconductivity is a fascinating subject, whereas various questions remain unresolved: how fast does the order parameter respond to the external perturbation? Is it possible to manipulate the order parameter by optical means? How does the collective mode in superconductors emerge in the photo-response? Theoretically, dynamics of amplitude mode in superconductors, recently referred to as the Higgs mode, has been intensively studied as a quench problem [1-6]. In contrast, the experimental investigation of the Higgs mode in superconductors has long been remained elusive, since the Higgs mode does not couple directly to the electromagnetic field. In this presentation, we report on our recent observation of the Higgs mode in s-wave superconductors, $Nb_{1-x}Ti_xN$ films [7] by using terahertz (THz)-pump and THz-probe spectroscopy technique [8]. In order to excite the Higgs mode, we irradiated the sample by an intense monocycle THz pulse whose center frequency was tuned to the superconducting gap energy. In the non-adiabatic excitation regime, a damped oscillation was observed in the transmission of the THz probe pulse as a function of pump-probe delay. The oscillation frequency coincides with the value of asymptotic gap energy after the THz pulse excitation, manifesting the character of Higgs mode. In this presentation, we will report on the ultrafast dynamics of Higgs mode and the coherent nonlinear interplay between light and the Anderson pseudo-spins. This work was done in collaboration with R. Matsunaga, Y. I. Hamada, A. Sugioka, H. Fujita, K. Makise, Y. Uzawa, H. Terai, Z. Wang, N. Tsuji, and H. Aoki.

[1] A. F. Volkov and S. M. Kogan, Zh. Eksp. Teor. Fiz. **65**, 2038 (1973) [Sov. Phys. JETP 38, 1018 (1974)].
[2] R. A. Barankov and L. S. Levitov, Phys. Rev. Lett. **96**, 230403 (2006).
[3] E. A. Yuzbashyan and M. Dzero, Phys. Rev. Lett. **96**, 230404 (2006).
[4] T. Papenkort, T. Kuhn, and V. M. Axt, Phys. Rev. B **78**,132505 (2008).
[5] N. Tsuji, M. Eckstein, and P.Werner, Phys. Rev. Lett. **110**,136404 (2013).
[6] Y. Barlas and C. M. Varma, Phys. Rev. B **87**, 054503(2013).
[7] R. Matsunaga, et al., Phys. Rev. Lett.**111**, 057002 (2013).
[8] R. Matsunaga and R. Shimano, Phys. Rev. Lett. **109**, 187002(2012).

T13

Far from Equilibrium Phases of Superconducting Matter

E. Yuzbashyan[1], V. Kuznetsov,[2] B. Altshuler,[3] M. Dzero,[4] O. Tsyplyatyev,[5] M. S. Foster,[6] V. Gurarie[7]

[1] Center for Materials Theory, Department of Physics and Astronomy, Rutgers University, Piscataway, New Jersey 08854, USA;

[2] Department of Applied Mathematics, University of Leeds, Leeds, LS2 9JT, UK

[3] Physics Department, Columbia University, New York, New York 10027, USA

[4] Department of Physics, Kent State University, Kent, Ohio 44242, USA

[5] Physics Department, Lancaster University, Lancaster LA1 4YB, UK

[6] Department of Physics and Astronomy, Rice University, Houston, Texas 77005, USA

[7] Department of Physics, University of Colorado, Boulder, CO 80309, USA

E-mail address: eyuzbash@physics.rutgers.edu

Coherent dynamics of many-body interacting systems became a major new field of study with a development of new systems and tools, such as ultracold gases, nanoscale devices and terahertz technology. Here steady states of matter with properties unseen in equilibrium can emerge. In this talk, I address the response of s and p-wave superconductors to fast perturbations [1,2,5]. Three far from equilibrium phases occur depending on the perturbation: gapless, gapped, and oscillating. Other interesting phenomena include weak turbulence [3], temporal solitons [4], and quantum quench-induced topological Floquet superfluids [6].

1. E. A. Yuzbashyan, O. Tsyplyatyev, B. L. Altshuler, Phys. Rev. Lett. **96**, 097005 (2006); Erratum: Phys. Rev. Lett. **96**, 179905 (2006).

2. E. A. Yuzbashyan and M. Dzero, Phys. Rev. Lett. **96**, 230404 (2006).

3. M. Dzero, E. A. Yuzbashyan, B. L. Altshuler, Eur. Phys. Lett. **85**, 20004 (2009).

4. E. A. Yuzbashyan, Phys. Rev. B **78**, 184507 (2008)

5. M. S. Foster, M. Dzero, V. Gurarie, E. A. Yuzbashyan, Phys. Rev. B **88**, 104511 (2013).

6. M. S. Foster, V. Gurarie, M. Dzero, E. A. Yuzbashyan, arXiv:1307.2256

T14

Density Matrix Theory for superconductors in non-equilibrium: Higgs mode and Pairing glue

Dirk Manske
Max Planck Institute for Solid State Research, D-70569 Stuttgart, Germany;
E-mail address: d.manske@fkf.mpg.de

We study the ultrafast dynamics of unconventional superconductors from a microscopic viewpoint employing density-matrix theory [1]. In particular, we derive and solve numerically equations of motions which allow calculating the resulting Higgs mode of the amplitude of the superconducting order parameter exactly. In a next step we study the role of phonons in the non-equilibrium state. The dynamics of coherent phonons after excitation with a short intense pump pulse can be treated at a fully quantum kinetic level [2]. We find that in the nonadiabatic regime the generation of coherent phonons is resonantly enhanced when the frequency of the order parameter oscillations is tuned to the phonon energy which can be achieved by changing the pump pulse intensity. In the case of incoherent phonons we use a bath approximation and calculate the 2-color time-resolved Raman signal and compare with data on the high-Tc compound Bi2212 [3]. Our theory can also be used to calculate the optical conductivity [4] and calculations of the pairing glue in cuprates are discussed in view of recent experiments. Finally, applications to MgB_2 and Fe-pnictide superconductors are addressed [5].

[1] J. Unterhinninghofen, D. Manske, and A. Knorr, PRB **77**, 180509(R) (2008).
[2] A. Schnyder, D. Manske, and A. Avella, PRB **84**, 214513 (2011).
[3] R.P. Saichu *et al.*, PRL **102**, 177004 (2009).
[4] H. Krull, G. Uhrig, A. Schnyder, and D. Manske, arXiv 1309.7318.
[5] A. Akbari, A. Schnyder, D. Manske, and I. Eremin, EPL **101**, 17002 (2013).

T15

Higgs mode and Anderson pseudospin resonance in superconductors

Naoto Tsuji[1]
[1] Department of Physics, University of Tokyo, Hongo, Tokyo 113-0033, Japan
E-mail address: tsuji@cms.phys.s.u-tokyo.ac.jp

Higgs mode in superconductors can be microscopically represented by a collective precession of Anderson's pseudospins, which does not directly couple to electromagnetic fields. In this talk, I will show that an s-wave superconductor irradiated by an ac electric field with frequency Ω induces a coherent precession of Anderson's pseudospins, and hence a coherent oscillation of the order parameter with a doubled frequency 2Ω through the nonlinear light-matter coupling [1]. It turns out that the induced precession of the pseudospins "resonates" with the Higgs mode (Anderson pseusospin resonance) at $2\Omega = 2\Delta$ with 2Δ the superconducting gap. In the BCS approximation, the resonance shape is characterized by a universal function of Ω/Δ. For strongly coupled superconductors, the nonequilibrium dynamical mean-field theory [2] is used to show that the resonance acquires a finite width, which corresponds to the lifetime of the Higgs mode.

[1] N. Tsuji and H. Aoki, arXiv:1404.2711.
[2] H. Aoki, N. Tsuji, M. Eckstein, M. Kollar, T. Oka, and P. Werner, to be published in Rev. Mod. Phys. (arXiv:1310.5329).

T16

Higgs mode in a superfluid of Dirac fermions

S. Tsuchiya[1,3], R. Ganesh[2] ,T. Nikuni[3]
[1] Tohoku Institute of Technology, 35-1 YagiyamaKasumi-cho, Taihaku-ku, Sendai 162-8601, Japan
[2] Institute for Theoretical Solid State Physics, IFW Dresden, PF 270116, 01171 Dresden, Germany
[3] Department of Physics, Faculty of Science, Tokyo University of Science, 1-3 Kagurazaka, Shinjuku-ku, Tokyo 162-8601, Japan
E-mail address: tsuchiya@tohtech.ac.jp

Motivated by recent developments of the study on Higgs mode in Bose condensates in optical lattices[1] and superconductors[2], we study the Higgs mode in a s-wave superfluid on a honeycomb optical lattice[3]. The attractive Hubbard model on the honeycomb lattice that describes the system was found to exhibit a quantum phase transition between the semi-metal and s-wave superfluid phases[4]. We find evidence for a stable Higgs amplitude mode below the two-particle continuum together with a gapless Anderson-Bogoliubov (AB) mode in the vicinity of the quantum critical point. We also find stable collective modes which have "Cooperon" and exciton character in the semi-metal phase. These collective modes are accommodated within a window in the two-particle continuum, which arises as a consequence of the linear Dirac dispersion on the honeycomb lattice. Cooperon and exciton smoothly evolve across the quantum critical point and hybridize into the Higgs mode and the AB mode following Cooperon condensation. We discuss possibility of observing the Higgs mode by Bragg spectroscopy measurements.

[1]M. Endres, *et al.*, Nature (London) **487**, 454 (2012).
[2]R. Matsunaga, *et al.*, Phys. Rev. Lett. **111**, 057002 (2013).
[3]S. Tsuchiya, *et al.*, Phys. Rev. B **88**, 014527 (2013).
[4]E. Zhao and A. Paramekanti, Phys. Rev. Lett. **97**, 230404 (2006).

T17

Polariton Condensation and Dynamics

P.B. Littlewood[1],
[1] Argonne National Laboratory and University of Chicago, Illinois, USA.
E-mail address: h-yukawa@yukawa.kyoto-u.ac.jp

The engineering of semiconductor optical microcavities allow us to hybridize electronic excitations with photons to create a composite boson called a polariton that has a very light mass, and recent experiments provide good evidence for a high-temperature Bose condensate. Polariton systems also offer an opportunity to use optical pumping to study quantum dynamics of a many body system outside equilibrium, in a new kind of cold atom laboratory. Polaritons are a composite particle formed from the superposition of a photon and an electron-hole pair, and the photon mediated interactions are long-range. Consequently the collective non-linear dynamics of the amplitude mode is visible as a well-defined optical excitation, and I will discuss the predicted nonlinear oscillations and pattern formation following a prepared quantum quench.
A similar physical model is generated by placing atoms excited into Rydberg states in an optical cavity, and here it is in principle possible to study the interplay between charge density wave instabilities and superfluidity. In these systems the interaction between the density and superfluid channels exhibits some similarities to solid state systems such as NbSe2, where this interchannel coupling long ago provided the evidence for ‘Higgs-like’ amplitude superconducting modes.

T18

Nambu-Goldstone modes in exciton-polariton condensates

Y. Yamamoto[1,2], S. Utsunomiya[2], M. Fraser[1]
[1] CEMS, RIKEN, 2-1 Hirosawa, Wako-shi, Saitama 351-0198, Japan;
[2]National Institute of Informatics, 2-1-2 Hitotsubashi, Chiyoda-ku, Tokyo 101-8430, Japan
E-mail address: yyamamoto@stanford.edu

An exciton-polariton is an elementary excitation consisting of quantum well excitons and microcavity photons. In this talk we will describe the measurements of the Bogoliubov excitation spectrum and the sound velocity in exciton-polariton condensates.
The effects of a high dissipation rate and existence of reservoir excitons will be discussed.

Higgs type excitations in cold atoms and cavity

Wu-Ming LIU
Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China
Email: wmliu@iphy.ac.cn

Higgs type excitations are the excitations which give mass to particles. The Higgs type excitations have a critical role both in particle physics and condensed matter physics. In particle physics, the suspected Higgs boson has been found by the Large Hadron Collider (LHC) in 2012. In condensed matter physics, the Higgs type excitations relate to order phase of the system. In this review, we present an overview of recent studies on the Higgs type excitations both cold atom systems and cavity. First, in non-interacting cold atom system, by synthesizing artificial non-Abelian gauge potential, we demonstrate that when a non-Abelian gauge potential is reduced to Abelian potential, the Abelian part constructs spin-orbit coupling, and the non-Abelian part emerges Higgs excitations. Secondly, the Higgs excitations which are the reputed Higgs amplitude mode in interacting cold atom system are discussed. We review the theoretical model and the experimental detection of Higgs amplitude mode in two dimensional superfluids. The observation of both Higgs type excitations in real experiments is also discussed [1, 2]. We demonstrate that the Higgs mode can also be observed in optical systems with only a few (artificial) atoms inside a cavity. We establish this connection by studying the U(1)/Z2 Dicke model where N qubits (atoms) coupled to a single photon mode. We determine the Goldstone and Higgs modes inside the super-radiant phase and their corresponding spectral weights by performing both 1/J = 2/N expansion and exact diagonalization study at a finite N. We find nearly perfect agreements between the results achieved by the two approaches when N gets down even to N = 2. The quantum finite size effects at a few qubits make the two modes quite robust against an effectively small counter-rotating wave term. We present a few schemes to reduce the critical coupling strength, so the two modes can be observed in several current available experimental systems by just conventional optical measurements [3].

References

[1] F. J. Huang, Q. H. Chen, W. M. Liu, Impact of scalar potentials on cold atoms with spin-orbit coupling, Phys. Rev. A 89, 033624 (2014).

[2] F. J. Huang, Q. H. Chen, W. M. Liu, Higgs type excitations in cold atom systems, Science China 56, 2272 (2013).

[3] Y. X. Yu, J. W. Ye, **W. M. Liu,** Goldstone and Higgs modes of photons inside a cavity, Scientific Reports 3, 3476 (2013).

T20

Peculiar phenomena in the time-dynamics of condensed matter systems undergoing symmetry-breaking transitions.

D. Mihailovic[1],
[1] Dept. of Complex Matter, Jozef Stefan Institute, SI-1000 Ljubljana, Slovenia
E-mail address: dragan.mihailovic@ijs.si

A unique insight into the dynamics of symmetry breaking (SB) can be obtained from real-time experiments on "freely evolving" phase transitions in condensed matter systems. Such experiments offer analogies with other time-evolving systems in cosmology and elementary particle collisions, and even in collective social phenomena. Charge ordered materials and superconductors are two examples where different symmetries are broken on femtosecond timescales which can be investigated with femtosecond laser spectroscopy techniques. The trajectories through the transition can be investigated via the response of single particle (fermionic) and collective (bosonic) excitations with very high temporal resolution. This enables us to observe new phenomena, such as coherent oscillations of the order parameter through the transition [1] and dispersive Higgs-like particle emission resulting from domain wall annihilation [1,2]. Weakly interacting massive particles (phonons) which interact with the order parameter offer analogies with dark matter existing prior to the transition [3]. Beyond standard theory, non-equilibrium trajectories to hidden states of matter are also observed under conditions where the fermionic and bosonic excitations are far out of equilibrium, reaching states which are unreachable under adiabatic conditions [4].

[1] Yusupov, R. et al. Coherent dynamics of macroscopic electronic order through a symmetry breaking transition. *Nat. Phys.* **6**, 681-684 (2010).
[2] Mihailovic, D., Mertelj, T., Kabanov, V. V. and Brazovskii, S. Coherent topological defect dynamics and collective modes in superconductors and electronic crystals. *J Phys-Condens Mat* **25**, 404206 (2013).
[3] Yusupov, R. et al. Femtosecond Coherent Non-equilibrium Electronic Ordering andDynamics of Topological Defect in Charge Density Waves. *J Supercond Nov Magn* **24**, 1191 (2010).
[4] Stojchevska, L. et al. Ultrafast switching to a stable hidden topologically protected quantum state in an electronic crystal. *Science* **344**, 177 (2014)

T21

Fluctuating Charge Density Waves in a Cuprate Superconductor

F. Mahmood[1], D.H. Torchinsky[1], A.T. Bollinger[2], I. Bozovic[2], N. Gedik[1],
[1] Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts, 02139, USA;
[2] Brookhaven National Laboratory, Upton, New York 11973, USA
E-mail address: fahad@mit.edu

Cuprate materials hosting high-temperature superconductivity (HTS) also exhibit various forms of charge and/or spin ordering whose significance is not fully understood. To date, static charge-density waves (CDWs) have been detected by diffraction probes only at special doping or in an applied external field. However, dynamic CDWs may also be present more broadly and their detection, characterization and relationship with HTS remain open problems. Here, we present a new method, based on ultrafast spectroscopy, to detect the presence and measure the lifetimes of CDW fluctuations in cuprates. In an underdoped $La_{1.9}Sr_{0.1}CuO_4$ film (Tc = 26 K), we observe collective excitations of CDW that persist up to 100 K. This dynamic CDW fluctuates with a characteristic lifetime of 2 ps at T = 5 K which decreases to 0.5 ps at T = 100 K. In contrast, in an optimally doped $La_{1.84}Sr_{0.16}CuO_4$ film (Tc = 38.5 K), we detect no signatures of fluctuating CDWs at any temperature, favoring the competition scenario. This work forges a path for studying fluctuating order parameters in various superconductors and other materials.

T22

Dispersion relation of Nambu-Goldstone modes at finite temperature and density

Y. Hidaka
Theoretical Research Division, Nishina Center, RIKEN, Wako 351-0198, Japan
E-mail address: hidaka@riken.jp

We discuss the dispersion relation of Nambu-Goldstone (NG) modes associated with spontaneous breaking of internal symmetries at finite temperature and density. It is known that the NG modes can be classified into two types: the type-B NG modes characterized by the expectation value of commutation relation between charges, and the other (type-A NG modes). Taking into account dissipation effects, we show that the dispersion relations of type-A and type-B NG modes are linear and quadratic in momentum, whose imaginary parts are quadratic and quartic, respectively. We also discuss mass formula for type-A and type-B NG modes when a small explicit breaking term is added into the Hamiltonian.

T23

Interaction among Nambu-Goldstone bosons and other low-energy degrees of freedom

Haruki Watanabe [1],
[1] Department of Physics, University of California, Berkeley, California 94720, USA
E-mail address: hwatanabe@berkeley.edu

Low-energy effective Lagrangians provide us a very useful basis to discuss the properties of Nambu-Goldstone bosons (NGBs) generally and systematically, including interaction effects to other low-energy degrees of freedom. Based on the pioneering work by Leutwyler [1], we have further developed and examined the structure of the effective Lagrangian without assuming the Lorentz invariance [2,3].

In this talk, we will first review the counting rule and the dispersion relations of NGBs [2]. We also discuss the scaling rule of interactions among NGBs to verify that continuous symmetries can, in fact, be broken in $1+1$ dimensions in the case with type-B NGBs, contrary to the widespread belief in high-energy community [3].

We will then switch gear to explore more interesting physics of NGBs by coupling them to other gapless degrees of freedom. Specifically, we will discuss the following two examples:
(i) A ripple fluctuation of a domain wall in superfluid-superfluid interface has a peculiar fractional-power dispersion relation due to its interaction to bulk NGBs, forming a close analogy to the plasma oscillation of Wigner crystals in $2+1$ dimensions [4].
(ii) When NGBs originate from space-time symmetries that do not commute with the conserved momentum operator, such as spatial rotations and magnetic translations, their interactions to a Fermi surface may be nontrivial and result in over-damping of NGBs and non-Fermi liquids behavior of electrons [5].

[1] H. Leutwyler, Phys. Rev. D 49, 3033 (1994).
[2] H. Watanabe and H. Murayama, Phys. Rev. Lett. 108, 251602 (2012).
[3] H. Watanabe and H. Murayama, arXiv:1402.7066.
[4] H. Watanabe and H. Murayama, Phys. Rev. D 89 101701 (R) (2014).
[5] H. Watanabe and A. Vishwanath, arXiv:1404.3728.

T24

Nambu-Goldstone modes localized around vortices and solitons

M. Nitta[1,2], M. Kobayashi[3] D. A. Takahashi[4,2]
[1] Department of Physics, Keio University, Hiyoshi 4-1-1, Yokohama, Kanagawa 223-8521, Japan;
[2] Research and Education Center for Natural Sciences, Keio University, Hiyoshi 4-1-1, Yokohama, Kanagawa 223-8521, Japan;
[3] Department of Physics, Kyoto University, Oiwake-cho, Kitashirakawa, Sakyo-ku, Kyoto 606-8502, Japan;
[4] RIKEN Center for Emergent Matter Science (CEMS), Wako, Saitama 351-0198, Japan
E-mail address: nitta@phys-h.keio.ac.jp

Two kinds of gapless Nambu-Goldstone (NG) modes appear when a continuous symmetry is spontaneously broken; type-I NG modes with linear dispersion relation and type-II NG modes with quadratic dispersion relation. The counting rule was derived for internal symmetry breaking by Watanabe and Murayama and Hidaka independently, but it is not yet for space-time symmetry.
Here, I discuss NG modes for space-time symmetry breaking in the presence of quantized vortices in superfluids [1], a domain wall in anisotropic ferromagnets [2], a skyrmion line in isotropic ferromagnets [3], and a domain wall in two-component Bose-Einstein condensates (BECs) [4]. They all have gapless modes associated with translational symmetry breaking; a Kelvin mode or Kelvon for a quantized vortex [1] and skyrmion line, a ripple mode or ripplon for domain walls in anisotropic ferromagnets [2] and two-component BECs [4]. In addition, some of them accompany additional gapless modes associated with internal symmetry and/or scale symmetry breaking.
I also discuss quantum effects on NG modes, with an example of non-Abelian NG modes localized in a non-Abelian vortex core in multi-component BECs [5].

[1] M.Kobayashi and M.Nitta, Prog.Theor.Exp.Phys.:021B01,2014 [arXiv:1307.6632 [hep-th]].
[2] M.Kobayashi and M.Nitta, arXiv:1402.6826 [hep-th].
[3] M.Kobayashi and M.Nitta, arXiv:1403.4031 [hep-th].
[4] D.A.Takahashi, M.Nitta, arXiv:1404.7696 [cond-mat.quant-gas]
[5] M.Nitta, S.Uchino and W.Vinci, arXiv:1311.5408 [hep-th].

T25

Transmission and scattering properties of Nambu-Goldstone modes

Y. Kato[1], S. Watabe[2] Y. Ohashi[3]
[1] Department of Basic Science, The University of Tokyo, Tokyo 153-8902;
[2] Department of Physics, The Universty of Tokyo, Tokyo 113-0077;
[3] Department of Physics, Keio University,Yokohama 223-8522.
E-mail address: yusuke@phys.c.u-tokyo.ac.jp

For the last decade, the understanding of tunneling properties of collective excitations in Bose-Einstein condensates (BEC) has been greatly advanced. It has been found that the Bogoliubov excitations in a scalar BEC (BEC without internal degrees of freedom) tunnel through a potential barrier without reflection in the low-energy limit[1-9]. This perfect transmission in the BEC was referred to as "anomalous tunneling" in a literature [2]. Recently we have reported that Bogoliubov excitations and spin waves in a spinor BEC (BEC with spin degrees of freedom) also exhibit this anomalous tunneling phenomenon [10-12]. Further we show that anomalous tunneling occurs also in classical spin waves in the ferromagnetic/antiferromagnetic Heisenberg magnets. Our result suggests that the anomalous tunneling phenomenon is not specific to BEC but generic to Nambu-Goldstone (NG) modes in spontaneously symmetry-breaking states. Existence of the Noether currents is crucial for the NG modes to transmit through the barrier without reflection.

[1] D. L. Kovrizhin, Phys. Lett. A **287**, 392 (2001).
[2] Yu. Kagan, D. L. Kovrizhin and L. A. Maksimov, Phys. Rev. Lett. **90**, 130402 (2003).
[3] I. Danshita, N. Yokoshi and S. Kurihara, New J. Phys. **8**, 44 (2006).
[4] YK, H. Nishiwaki, and A. Fujita, J. Phys. Soc. Jpn. **77**, 013602 (2008).
[5] S. Tsuchiya and YO, Phys. Rev. A **78**, 013628 (2008).
[6] YO and S. Tsuchiya, Phys. Rev. A **78**, 043601 (2008).
[7] SW and YK, Phys. Rev. A **78**, 063611 (2008).
[8] D. Takahashi and YK, J. Phys. Soc. Jpn. **78**, 023001 (2009).
[9] S. Tsuchiya and YO, Phys. Rev. A **79**, 063619 (2009).
[10] SW and YK, Phys Rev A **83** (2011) 053624.
[11] SW, YK and YO, Phys Rev A **83** (2011) 033627.
[12] SW, YK and YO, Phys. Rev. A **84** (2011) 013616.

T26

Higgs and Goldstone bosons with and without Lorentz invariance

Hitoshi Murayama[1,2,3]
[1] Department of Physics, University of California, Berkeley, California 94720, USA
[2] Theoretical Physics Group, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA
[3] Kavli Institute for the Physics and Mathematics of the Universe (WPI), Todai Institute for Advanced Study, University of Tokyo, Kashiwa 277-8583, Japan
E-mail address: hitoshi@berkeley.edu, hitoshi.murayama@ipmu.jp

The concept of the Higgs boson originated from the superconductivity and was adopted in particle physics, while the Goldstone bosons had influence from the Nambu’s theory onto condensed matter physics. While conceptually similar, details differ, due to the presence/lack of Lorentz invariance. I review the essential differences between the two cases. Then I discuss an apparent paradox with the Higgs bosons without Lorentz invariance, whose resolution requires a spontaneous breaking of Lorentz invariance. In addition, I discuss that the improved understanding in the absence of Lorentz invariance demonstrates fascinating behavior of topological solitons.

[1] Englert-Brout-Higgs Mechanism in Nonrelativistic Systems, Haruki Watanabe and Hitoshi Murayama, arXiv:1405.0997
[2] The effective Lagrangian for non relativistic systems, Haruki Watanabe and Hitoshi Murayama, arXiv:1402.7066
[3] Noncommuting Momenta of Topological Solitons, Haruki Watanabe and Hitoshi Murayama, Phys.Rev.Lett. 112 (2014) 191804
[4] Massive Nambu-Goldstone Bosons, Haruki Watanabe, Tom Brauner, and Hitoshi Murayama, Phys.Rev.Lett. 111 (2013) 2, 021601
[5] A Natural Higgs Mass in Supersymmetry from Non-Decoupling Effects, Xiaochuan Lu, Hitoshi Murayama Joshua T. Ruderman, Kohsaku Tobioka, Phys.Rev.Lett. 112 (2014) 191803

P01

Broken translational symmetry in superfluid ^{3}He confined in narrow cylinders

K. Aoyama[1,2],
[1] The Hakubi Center for Advanced Research, Kyoto University, Sakyo-ku, Kyoto 606-8501, Japan;
[2] Department of Physics, Kyoto University, Sakyo-ku, Kyoto 606-8502, Japan
E-mail address: bonn@kyoto-u.ac.jp

The superfluid phases of liquid ^{3}He are in spin-triplet p-wave Cooper pairing states. Although the liquid ^{3}He can potentially host various types of pairing states owning to the internal degrees of freedom, only two superfluid phases are realized in the bulk, A and B phases [1]. Recently, it has been theoretically suggested that in thin films of unconventional superconductors and superfluids, surface scattering effects trigger instability of uniform phases against spatially inhomogeneous ones [2,3].
In this study, we theoretically investigate pairing states of superfluid ^{3}He confined in narrow cylinders. The surface-induced distortion and the multiple internal degrees of freedom of the order parameter lead to the occurrence of a stripe structure along the cylinder axis in the B phase. We show that in sufficiently small cylinders with an anisotropic surface scattering, the stripe order with broken translational symmetry, which has no analog in bulk ^{3}He, may be stabilized as the lowest energy state [4].

[1] D. Volhardt and P. Wolfle, The Superfluid Phases of Helium 3 (Taylor and Fransis, London, 1990).
[2] A. B. Vorontsov and J. A. Sauls, Phys. Rev. B **68**, 064508 (2003).
[3] M. Hachiya, K. Aoyama, and R. Ikeda, Phys. Rev. B **88**, 064519 (2013).
[4] K. Aoyama, Phys. Rev. B **89**, 140502(R) (2014).

P03

Precursor of the Nambu-Goldstone mode in a non-equilibrium strongly interacting Fermi gas

R. Hanai[1], P. B. Littlewood[2], Y. Ohashi [1]
[1] Department of Physics, Keio University, 3-14-1 Hiyoshi, Kohoku-ku, Yokohama 223-8522, Japan;
[2] James Frank Institute and Department of Physics, University of Chicago, Chicago, Illinois 60637, USA
E-mail address: rhanai@rk.phys.keio.ac.jp

We investigate Bose excitations in a strongly interacting pumped decaying Fermi gas. For a model non-equilibrium Fermi gas where fermions are continuously pumped in from a bath (with pumping rate γ) and decay to the vacuum (with decay rate κ), we calculate excitation spectra in the Cooper channel, extending the strong-coupling T-matrix theory developed for the equilibrium system to the non-equilibrium case. Using these, we discuss how the precursor of the Nambu-Goldstone mode is seen in the pair-excitation spectra in a non-equilibrium Fermi gas. We find that the dispersion of low-energy Bose excitations describing the precursor of the Goldstone mode is remarkably modified in the non-equilibrium case, as shown in Fig. 1. Since non-equilibrium effects on a Fermi condensate has recently attracted much attention in various strongly-correlated systems, such as exciton gases, exciton-polariton condensates, as well as ultracold Fermi gases, our results would be useful for the development of physics of strongly-correlated fermions in the presence of non-equilibrium.

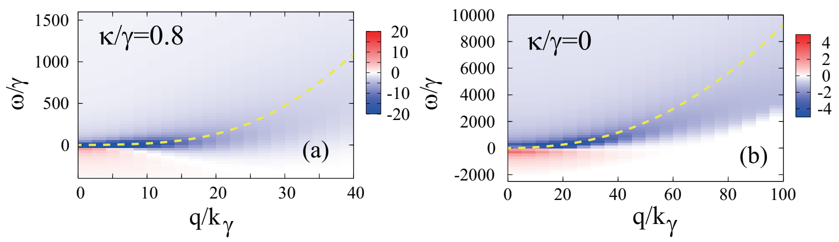

Figure 1: (a) Calculated pair-excitation spectrum in a non-equilibrium unitary Fermi gas ($(k_{\rm F}a_s)^{-1} = 0$) at the at the superfluid phase transition temperature $T_{\rm c}^{\rm Bath}$. We take $\kappa/\gamma = 0.8$ and bath chemical potential $\mu_{\rm Bath}/\gamma = 1000$. The dashed line shows the dispersion of a Cooper-pair molecule. For comparison, we also show result in the equilibrium case ($\kappa/\gamma = 0$) in panel (b).

P04

Direct Detection of Chirality in Superfluid ^{3}He-A

H. Ikegami[1, 2], Y. Tsutsumi,[3] and K. Kono[1, 2]
[1] Low Temperature Physics Laboratory, RIKEN, Wako, Saitama 351-0198, Japan;
[2] The Center for Emergent Matter Science, RIKEN, Wako, Saitama 351-0198, Japan;
[3] Condensed Matter Theory Laboratory, RIKEN, Wako, Saitama 351-0198, Japan
E-mail address: hikegami@riken.jp

The superfluid ^{3}He spontaneously breaks the gauge symmetry and the rotational symmetries in spin and orbital spaces in a complex way. In one of the superfluid phases called the A phase (^{3}He-A), symmetry breaking results in the orbital chirality, which is described by the direction of the angular momentum of Copper pairs (denoted by a unit vector $\hat{\mathrm{l}}$). We detected chirality directly[1] by finding an unusual force, called the intrinsic Magnus force[2,3], acting on an electron bubble moving in ^{3}He-A. The intrinsic Magnus force originates from the skew scattering of quasiparticles by the electron bubble, and acts on the electron bubble in the direction perpendicular to both $\hat{\mathrm{l}}$ and the velocity of the electron bubble. We demonstrate the observation of the intrinsic Magnus force and the detection of chirality for chiral monodomains with $\hat{\mathrm{l}}$ pointing either upward or downward at the free surface of ^{3}He-A. We also present observation of multiple chiral domains.

[1] H. Ikegami, Y. Tsutsumi, and K. Kono, *Science* **341**, 59-62 (2013).
[2] R. H. Salmelin, M. M. Salomaa, and V. P. Mineev, *Phys. Rev. Lett.* **63**, 868 (1989).
[3] R. H. Salmelin and M. M. Salomaa, *Phys. Rev. B* **41**, 4142 (1990).

P05

Effects of collective excitations on single particle properties in a two-dimensional Dirac electrons system with a superconducting interaction

D. Inotani[1], S. Okada[2], Y. Ohashi[1]
[1] Faculty of Science and Technology, Keio University, 3-14-1 Hiyoshi, Kohoku-ku, Yokohama 223-8522, Japan ;
[2] Graduate School of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Ibaraki 305-8571, Japan
E-mail address: dinotani@rk.phys.keio.ac.jp

We theoretically investigate how the collective excitations associated with a superconducting fluctuations affect the single-particle properties in a two-dimensional Dirac electrons system. To determine the collective properties, we calculate the generalized density-density correlation function within the random phase approximation in both normal and superconducting phase with $T = 0$. We find that the collective excitations become stable both in normal and superconducnting phase because of the dispersion relation of the electrons[1] and the two-dimensionality of the system. Including the effects of these stable collective excitations within a T-matrix approximation, we calculate the single-particle spectral weight. We show that the spectral peak becomes broad and the dispersion relation of the electrons is strongly modified in high energy region near the quantum critical point [fig. 1(a)], because of the enhancement of the scattering processes through the stable collective excitations.

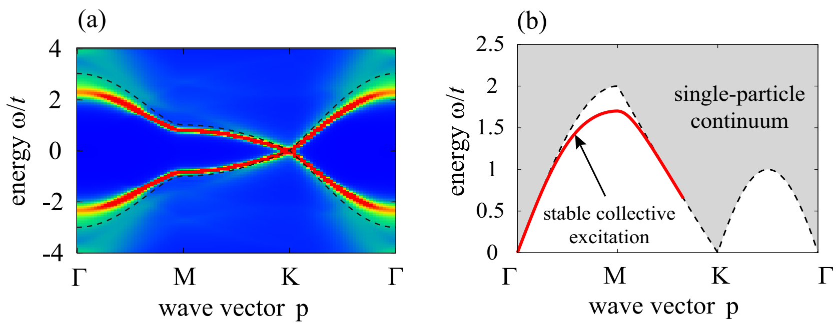

Figure 1: (a) Single-particle spectral weight and (b) dispersion relation of the collective excitation at the quantum critical point. The doted line in panel (a) shows the dispersion relation of the noninteracting electrons.

[1] S. Tsuchiya, R. Ganesh, T. Nikuni, Phys. Rev. B **88**, 014527 (2013)

P06

Nambu-Goldstone bosons and the Higgs mechanism without Lorentz invariance

S. Gongyo[1,2], S. Karasawa[1]
[1] Department of Physics, Kyoto University, Kyoto 606-8502, Japan
[2] Department of Physics, New York University, New York, 10003, USA
E-mail address: karasawa@ruby.scphys.kyoto-u.ac.jp

Spontaneous symmetry breaking (SSB) and the Higgs mechanism are well known phenomena in a wide area ranging from the particle physics to condensed matter physics [1,2,3]. Through SSB, Nambu-Goldstone (NG) bosons appear in both Lorentz invariant and noninvariant systems. In the Lorentz invariant case, the dispersion of NG bosons is always linear and the number of NG bosons coincides with that of the generators of the broken symmetries, while in the noninvariant case, the dispersion of NG bosons may be nonlinear and the number of NG bosons does not alway coincide with that of the broken symmetries [4,5,6].

Recently a general counting rule for these bosons has been given based on Mori's projection operator method by Hidaka [4] and Leutwyler's effective Lagrangian by Watanabe and Murayama [5,6]. Furthermore, in addition to these NG bosons, the appearance of massive NG bosons whose dispersion is a finite mass at zero momentum has also been reported in Refs. [4,7,8,9,10].

Meanwhile, to our knowledge, the Higgs phenomenon with these NG bosons has not been discussed generally except for some model analysis [9,10]. From the theoretical viewpoint, the number of "eaten" degrees of freedom (DOF) by the gauge fields is of interest. Whether the DOF correspond to the number of NG bosons or broken symmetries in the non-Lorentz invariant systems is not clear in contrast to the Lorentz invariant systems.

First, we develop Watanabe and Murayama's counting rule for NG bosons to the system including two-time derivative terms. In this case, the type-II NG bosons appear along with the massive NG ones. Next, we study a Higgs phenomenon with these NG bosons on the basis of the theory of constrained systems. We show that the gauge fields in this system absorb all of the NG bosons such as the type-I, type-II and massive ones [11].

[1] Y. Nambu and G. Jona-Lasinio, Phys. Rev. **122**, 345.
[2] J. Goldstone, A. Salam and S. Weinberg, Phys. Rev. **127**, 965.
[3] P. W. Anderson, Phys. Rev. **130**, 439;
P. W. Higgs, Phys. Lett. **12**, 132, Phys. Rev. Lett. **13**, 508;
F. Englert and R. Brout, Phys. Rev. Lett. **13**, 321.
[4] Y. Hidaka, Phys. Rev. Lett. **110**, 091601.
[5] H. Watanabe and H. Murayama, Phys. Rev. Lett. **108**, 251602.
[6] H. Leutwyler, Phys. Rev. D **49**, 3033.
[7] A. Kapustin, arXiv:1207.0457.
[8] H. Watanabe, T. Brauner and H. Murayama, Phys. Rev. Lett. **111**, 021601.
[9] V. P. Gusynin, V. A. Miransky and I. A. Shovkovy, Phys. Lett. B **581**, 82.
[10] Y. Hama, T. Hatsuda and S. Uchino, Phys. Rev. D **83**, 125009.
[11] S. Gongyo and S. Karasawa, arXiv:1404.1892.

P07

Atomic simulation of lattice gauge-Higgs model: Realization of lattice gauge model by atoms with dipole-dipole interaction

K. Kasamatsu[1], Y. Kuno[2], Y. Takahashi[3], I. Ichinose[2], T. Matsui[1],
[1] Department of Physics, Kindai University, Higashi-Osaka, Osaka 577-8502, Japan;
[2] Department of Applied Physics, Nagoya Institute of Technology, Nagoya, 466-8555, Japan;
[3] Department of Physics, Kyoto University, Sakyo-ku, Kyoto 606-8502, Japan
E-mail address: kenichi@phys.kindai.ac.jp

Recently, the possibility of quantum simulation of dynamical gauge fields was pointed out by using a system of cold atoms trapped on each link in an optical lattice [1]. However, to implement exact local gauge invariance, fine-tuning the interaction parameters among atoms is necessary. In the present work, we study the effect of violation of the U(1) local gauge invariance by relaxing the fine-tuning of the parameters and showing that a wide variety of cold atoms is still to be a faithful quantum simulator for a U(1) gauge-Higgs model containing a Higgs field sitting on sites [2]. Clarification of the dynamics of this gauge-Higgs model sheds some lights upon various unsolved problems including the inflation process of the early universe. In this presentation, we propose how to implement a quantum simulator of the U(1) gauge-Higgs model with asymmetric nearest-neighbor Higgs coupling by using a system of dipolar Bose-Einstein condensates in an optical lattice. The constraint of the Gauss's law can be realized by the suitable control of the orientation of the dipoles at each link. We study the phase structure of this model by path-integral quantization and Monte Carlo simulations, and also discuss the atomic characteristics of the Higgs phase in each simulator. The deviation from the fine-tuned system parameters leads to the gauge-Higgs coupling in the imaginary time direction of the path integral. A general method to supply the Higgs coupling in all space-time directions may be realized by coupling atoms in an optical lattice to another particle reservoir filled with the Bose-condensed atoms via laser transitions.

[1] U.-J. Wiese, arXiv:1305.1602 (2013).
[2] K. Kasamatsu, I. Ichinose, and T. Matsui, Phys. Rev. Lett. **111**, 115303 (2013).

P08

Nambu-Goldstone modes in phase-separated two-component Bose-Einstein condensates

H. Takeuchi[1] , K. Kasamatsu[2]
[1] Department of Physics, Osaka City University, Sumiyoshi-ku, Osaka 558-8585, Japan;
[2] Department of Physics, Kindai University, Higashi-Osaka, Osaka 577-8502, Japan
E-mail address: kenichi@phys.kindai.ac.jp

Nambu-Goldstone modes in phase-separated two-component Bose-Einstein condensates are studied theoretically. In a uniform system, a flat domain wall is stabilized and then the translational invariance normal to the wall is spontaneously broken in addition to the breaking of two U(1) symmetries in the presence of two complex order parameters. We confirm that, despite the number of broken symmetries is three, there exist two Nambu-Goldstone modes, in-phase phonon with a linear dispersion $\propto p$ and a ripplon with a fractional dispersion $\propto p^{3/2}$, in the low-energy limit by carefully calculating the system size dependence of the dispersion relation through the numerical analysis of the Bogoliubov-de Genne equation. The signature of the characteristic dispersion can be verified in segregated condensates in a harmonic potential.

[1] H. Takeuchi and K. Kasamatsu, Phys. Rev. A **88**, 043612 (2013).

P09

Superfluidity of a Bose system in a non-uniform potential

S. Koshida, Y. Kato
Department of Basic Science, The University of Tokyo, Meguro, Tokyo 153-8902, Japan
E-mail address: koshida@vortex.c.u-tokyo.ac.jp

There are many concepts that characterize superfluidity. We focus on the non-classical rotational inertia (NCRI), which characterizes the extent of how a liquid in a rotating container does not rotate with the container and defines the superfluid fraction $\rho_{\rm s}/\rho$ of the liquid.
Using the superfluid fraction defined by NCRI, the superfluidity of various systems has been discussed [1−4]. Although Leggett [1] says that Bose-Einstein condensation (BEC) implies superfluidity, there are systems which exhibit superfluidity without BEC, e.g., a 2-dimensional system with KT-transion at finite temperature and Lieb-Liniger model. Thus BEC does not necessarily explain all physics of superfluidity. Then what is the essence of superfluidity?
We have to notice that if the potetial is rotationally symmetric around the axis, the system trivially shows 100% superfluidity, i.e., $\rho_{\rm s}/\rho = 1$. Thus when we consider the superfluidity, a non-uniform potential is necessary.
We investigate how robust the superfluid fraction of an arbitrary Bose system is against a non-uniform potential. We treat the non-uniform potential as a perturbation, and expand the superfluid fraction in terms of the strength of the non-uniform potential. Our method is called the analytic perturbation theory, by which we can show that the expansion has a finite convergence radius if the non-uniform potential is a bounded function.
We discuss the coefficient of the leading term of the expansion. We will show detailed results on the superfluid fraction of ideal and interacting Bose systems.

[1] A. J. Leggett, Physica Fenica **8**, 125 (1973).
[2] A. J. Leggett, J. Stat. Phys **93**, 927 (1998).
[3] A. J. Leggett, Phys. Rev. Lett. **25**, 1543 (1970).
[4] E. H. Lieb, R. Seiringer and J. Yngvason, Phys. Rev. B **66** 134529 (2002).

P10

Metastable Spin Textures and Excitations of Spin-1 Bose-Einstein Condensates in a Ring Trap

Masaya Kunimi
Department of Engineering Science, University of Electro-Communications,
Tokyo 182-8585, Japan;
E-mail address: kunimi@hs.pc.uec.ac.jp

Various properties of superfluidity, such as critical velocity, persistent current, and hysteresis, were investigated by recent experiments of Bose-Einstein condensates trapped in a ring geometry[1,2,3]. Motivated by these experiments, we investigate properties of spin-1 Bose-Einstein Condensates in a quasi-one-dimensional rotating ring by solving the Gross-Pitaevskii and the Bogoliubov equation. We find analytical solutions of metastable energy branches, which exhibit spin textures. These solutions correspond to one-dimensional version of the polar-core vortex. We also find that the number of type-I and type-II Nambu-Goldstone(NG) modes changes at a certain rotation velocity(type-I-type-II transition[4]). The physical origin of the change of the number of the NG modes will be discussed.

[1] K. C. Wright, R. B. Blakestad, C. J. Lobb, W. D. Phillips, and G. K. Campbell, Phys. Rev. Lett. 110, 025302 (2013).
[2] S. Beattie, S. Moulder, R. J. Fletcher, and Z. Hadzibabic, Phys. Rev. Lett. 110, 025301 (2013).
[3] S. Eckel, J. G. Lee, F. Jendrzejewski, N. Murray, C. W. Clark, C. J. Lobb, W. D. Phillips, M. Edwards, and G. K. Campbell, Nature 506, 200 (2014).
[4] D. A. Takahashi and M. Nitta, arXiv:1404.7696 (2014).

P11

Atomic simulation of lattice gauge-Higgs model: Phase diagram and time-evolution of atomic simulator

Y. Kuno[1], K. Kasamatsu[2], Y. Takahashi[3], I. Ichinose[1], and T. Matsui[2]
[1] Department of Applied Physics, Nagoya Institute of Technology, Nagoya, 466-8555, Japan;
[2] Department of Physics, Kindai University, Higashi-Osaka, Osaka 577-8502, Japan;
[3] Department of Physics, Kyoto University, Sakyo-ku, Kyoto 606-8502, Japan
E-mail address: cjb16503@stn.nitech.ac.jp

Cold atoms in an optical lattice (OL) have been used as versatile quantum simulators for various many body quantum systems. There have been several proposals to realize a lattice gauge theory in cold atom systems [1].

We discuss quantum simulators of U(1) gauge-Higgs model (U(1)GHM) by using Bose-Einstein condensates (BECs) in an OL. In the formulation, the BECs are located on lattice links instead of lattice sites, and electric flux and U(1) gauge variables of U(1)GHM correspond to density fluctuation and U(1) phase variables of BEC at each link. We study the U(1) GHM by using Gross-Pitaevskii equations (GPE), revealing the stability of the electric flux connecting two charges.

By varying strength of the Gauss's law constraint and the atomic tunneling, confinement phase and Higgs phase are realized on cold atomic system. In each of two phases, we observe different dynamical behavior of the electric flux connecting two charges. We obtained the following findings. (1) If Gauss's law is broken, Higgs phase appears, in which large density fluctuations appear sporadically due to existence of charge sources. (2) If Gauss's law is satisfied and the on-site interaction is so large, confinement phase appears and the flux string is stable for 10 ms above. (3) If Gauss's law is satisfied and atomic tunneling acts on the system, Higgs phase appears, in which the set flux string vanishes suddenly and density fluctuations grow. Furthermore, we measure dynamical fluctuation of the flux string in each of two phases.

[1]K. Kasamatsu, I. Ichinose, and T. Matsui, Phys. Rev. Lett. **111**, 115303 (2013)

P12

First-Order Magnetic Raman Scattering from Pressure-Induced Higgs Mode through Second-Order Magnetic Raman Process

H. Kuroe[1] and T. Sekine[1]
[1] Physics Division, Sophia University, Chiyoda-ku, Tokyo 102-8554, Japan
E-mail address: kuroe@sophia.ac.jp

Inelastic light scattering (Raman scattering) from the pressure-induced Anderson-Higgs mode in the spin dimer system $KCuCl_3$ is discussed. According to the bond-operator theory [1], the triplet excited states, namely the trliprons, can hop between the neighboring spin dimers in a crystal. This causes the dispersive magnetic excitations and the spin gap with the energy much smaller than the one expected from the strength of the exchange interaction forming the spin dimers. Application of high pressures can control the hopping integral, i.e., the band width in the magnon dispersion curve. At the critical pressure P_c, all of the magnon branches touch on the nonmagnetic ground state. This leads the property distinguished from the Anderson-Higgs and the Goldstone modes under magnetic fields. Neglecting magnetic anisotropy, a typical Mexican-hat shape (or a bottom-of-wine-bottle shape) potential curve is obtained, i.e, well defined Anderson-Higgs and Goldstone modes appear above P_c.

We have reported the first-order magnetic Raman scattering (one-magnon Raman scattering) from the singlet-triplet mixed ground state to the Anderson-Higgs mode under isotropic pressures [2,3]. Based on the results in these papers, we present the pressure dependence of the Raman spectrum including the magnetic Raman peak due to the Anderson-Higgs mode above P_c and the quantitative spectrum parameters of it. Especially, we focus on the lifetime of the Anderson-Higgs mode which is inversely proportional to its energy. The origin of this effect is discussed based on the anharmonicity caused by the decay channel from one Anderson-Higgs mode to two Goldstone modes. We compare our results with the recent ones obtained from the inelastic neutron scattering in $TlCuCl_3$ under high pressures [4].

This work was supported in part by a Grant-in-Aid for Scientific Research (C) (No. 22540350).

[1] M. Matsumoto *et al.*, Phys. Rev. B **69** (2004) 054423.
[2] H. Kuroe *et al.*, J. Phys.: Conf. Ser. **400** (2012) 032042.
[3] M. Matsumoto *et al.*, J. Phys. Soc. Jpn. **77** (2008) 033702.
[4] P. Merchant *et al.*, Nature Phys. **10** (2014) 373.

P13

New results for quantum antiferromagnets in high magnetic fields

G. Marmorini[1,2], T. Momoi[1,3]
[1] Condensed Matter Theory Laboratory, RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan;
[2] Research and Education Center for Natural Sciences, Keio University, 4-1-1 Hiyoshi, Kanagawa 223-8521, Japan;
[3] RIKEN Center for Emergent Matter Science, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan.
E-mail address: giacomo@riken.jp

Frustrated antiferromagnets are a very rich class of physical systems, in which various new phases of matter are expected to be realized. From a theoretical point of view, however, they present challenging difficulties and typically defy a full quantum treatment. A possible strategy is to restrict oneself to a specific region of the parameter space, namely the one of high applied magnetic field, where the problem can be mapped to a dilute Bose gas of magnons. In this way we can provide benchmarks for the latest numerical approaches, such as in the case of the prototypical spin-1/2 XXZ model on the triangular lattice [1]. In more complicated models with competing exchange interactions, we find new types of magnetic order, such as a double-q state with striped chiral order [2]. We will describe Goldstone and pseudo-Goldstone modes in this phase.

[1] D. Yamamoto, G. Marmorini and I. Danshita, Phys. Rev. Lett. 112, 127203 (2014) .
[2] G. Marmorini and T. Momoi, arXiv:1312.5935, Phys. Rev. B 89, 134425 (2014)

P14

Anderson-Higgs modes of superfluid ^{3}He confined in a restricted geometry

Takeshi Mizushima[1], James A. Sauls[2]
[1] Department of Physics, Okayama University, Okayama 700-8530, Japan
[2] Departments of Physics and Astronomy, Northwestern University, Evanston, IL 60208, USA
E-mail address: mizushima@mp.okayama-u.ac.jp

Superfluid ^{3}He is a prototypical system to observe the spectrum of Anderson-Higgs (AH) modes associated with spontaneous symmetry breaking. In bulk superfluid ^{3}He, AH modes have been observed experimentally through attenuation of zero sound, propagation of transverse sound and acoustic Faraday rotation of the polarization of transverse sound [1]. Starting from a Lagrangian formulation, we examine the AH modes of superfluid ^{3}He-B confined in a restricted geometry. This formalism leads to the well known spectrum of Bosonic collectives modes of the bulk B-phase labelled by the quantum numbers for total angular momentum, $J = 0, 1, 2, \ldots$, the projection along an axis, $J_z = -J, \ldots, +J$, and the parity under particle-hole conversion, $K = \pm 1$. For the equilibrium phases of ^{3}He confinement induces pair breaking and leads to symmetry breaking, giving rise to a rich topological phase diagram [2,3]. In terms of the Bosonic excitations, we find that confinement induces symmetry breaking and leads to mixing of modes with different J, as well as to level splittings of the AH modes that are otherwise degenerate in bulk ^{3}He-B. In addition, we show that a new spectrum of modes is generated that are bound to the surface of superfluid ^{3}He-B in a restricted geometry. In this talk we will present an analysis of the properties of these new surface modes, as well as the effects of confinement on the AH modes in a restricted geometry for ^{3}He-B, including results for the Nambu sum rule and the coupling of the AH modes to NMR and ultra-sound.

[1] J. P. Davis, J. Pollanen, H. Choi, J. A. Sauls, and W. P. Halperin, Nature Physics **4**, 571 (2008).
[2] T. Mizushima, M. Sato, and K. Machida, Phys. Rev. Lett. **109**, 165301 (2012).
[3] A. B. Vorontsov and J. A. Sauls, Phys. Rev. Lett. **98**, 045301 (2007).

P16

Flux quench in the S = 1/2 XXZ chain

Yuya Nakagawa[1], Grégoire Misguich[2] and Masaki Oshikawa[1]
[1] Insitute for Solid State Physics, The University of Tokyo, Kashiwanoha, Kashiwa, Chiba 277-8581, Japan
[2] Institut de Physique Théorique, CNRS URA 2306, CEA, 91191 Gif-sur-Yvette, France
E-mail address: y-nakagawa@issp.u-tokyo.ac.jp

Nonequilibrium quantum systems have become a major subject of study in condensed matter recently[1]. One of the most important questions is the equilibration and thermalizatiton in isolated quantum systems. Quantum quenches, sudden changes of the Hamiltonian of a system, offer simple protocols to investigate such problems.

In this work, we study a *flux quench* in the spin-$1/2$ Heisenberg XXZ chain and the time evolution of the spin current after the quench. The flux quench is a quantum quench where the flux ϕ piercing the XXZ chain is turned off at $t = 0$ abruptly. If we formulate the XXZ chain as a spinless fermion model, the flux ϕ corresponds to a vector potential on each bond and this flux quench can be viewed as imposing pulse (delta function) of electric field. Therefore the flux quench induces some particle (or spin) current at the initial time $t = 0$. The question we address here is the nature of the evolution that follows, and we focus on the current itself.

We numerically calculate the time evolution of the current and entanglement entropy of one half-chain, using the infinite time-evolving block decimation (iTEBD) method. We find that the current oscillates and decays after the quench and that the frequency of the oscillations and the rate of decay depend strongly on the anisotropy parameter Δ of XXZ chain. We discuss the way in which the current relaxes and the relationship between the relaxation of the current and the integrability of XXZ chain.

[1] A. Polkovnikov, K. Sengupta, A. Silva, and M. Vengalattore, Rev. Mod. Phys. **83**, 863 (2011).

P17

Quantum state for Nambu-Goldstone mode of Bose-Einstein condensate

Y. Nakamura[1], J. Takahashi[1] Y. Yamanaka[1]
[1] Department of Electronic and Photonic Systems, Waseda University, Shinjuku-ku, Tokyo 169-8555, Japan.
E-mail address: yusuke.n@asagi.waseda.jp

We investigate the quantum state for the Nambu-Goldstone (NG) mode, considering the system of cold atomic gas with Bose-Einstein condensate. The condensate is associated with the spontaneous breakdown of the global phase symmetry, and involves the NG mode according to the Nambu-Goldstone theorem [1]. The NG mode plays a crucial role not only in creating and retaining the ordered state, the coherent condensate, but in retaining the canonical commutation relations of the field operators, which is a fundamental requirement of quantum field theory. Nevertheless, it is often neglected (ex. Bogoliubov approximation) at the sacrifice of the theoretical consistency mainly because of its infrared singular property and of a naive and groundless expectation that it does not affect the system very much.

While the bilinear unperturbed Hamiltonian of the excitation mode sector is diagonalizable, that of the NG mode one is not [2]. The corresponding Hamiltonian of the NG mode sector has the form of a free particle, which involves fatal difficulty in choosing an appropriate quantum state: if one chooses the eigenstate of the Hamiltonian as the quantum state, most physical quantities diverge. To overcome this problem, Lewenstein and You have introduced a new expansion of the field operator [2]. They have succeeded in obtaining finite physical quantities, but failed in retaining the canonical commutation relations. There the phase of the order parameter diffuses, which diffusion has not been observed experimentally.

Recently, we have proposed a new unperturbed Hamiltonian [3] to handle the NG mode sector retaining both the canonical commutation relations and the finite physical quantities. Our unperturbed Hamiltonian includes not only the first and second powers of the NG mode operators, but also the higher ones, and provides a non-singular stationary quantum state which is appropriate as the vacuum of the condensed system. Using the quantum state, we calculate physical quantities of the condensed system, such as the phase fluctuation, both at zero and finite temperatures.

[1] J. Goldstone, Nuovo Cimento **19**, 154 (1961); Y. Nambu and G. Yona-Lasinio, Phys. Rev. **122**, 345 (1961).
[2] M. Lewenstein and L. You, Phys. Rev. Lett. **77**, 3489 (1996).
[3] Y. Nakamura, J. Takahashi, and Y. Yamanaka, Phys. Rev. A **89**, 013613 (2014).

P18

Tunneling Higgs mode and Nambu-Goldstone mode in Bose condensates in optical lattices

T. Nakayama[1,3], S. Tsuchiya[2,3] ,T. Nikuni[3]

[1] Institute for Solid State Physics, University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8581, Japan

[2] Center for General Education, Tohoku Institute of Technology, 35-1 YagiyamaKasumi-cho, Taihaku-ku, Sendai, Miyagi 162-8601, Japan

[3] Department of Physics, Faculty of Science, Tokyo University of Science, 1-3 Kagurazaka, Shinjuku-ku, Tokyo 162-8601, Japan

E-mail address: t.nakayama@issp.u-tokyo.ac.jp

Higgs and Nambu-Goldstone (NG) modes are typical collective modes associated with spontaneous breaking of continuous symmetries. Tunneling problem of NG mode has been recently studied in the context of atmoic Bose gases and remarkable phenomena such as the perfect transmission of the NG mode in Bose-Einstein condensates (BECs) across a potential barrier has been predicted [1, 2].

Given the recent development of the study on Higgs mode in BECs in optical lattices [3], we study tunneling problem of this collective mode. Since the Higgs mode has a small excitation gap and becomes low energy excitation near the boundary to the Mott insulating phase, it may exhibit anomalous transmission property in this region.

In the vicinity of the phase boundary, the superfluid phase is well described by the time-dependent Ginzburg-Landau (TDGL) equation [4]

$$i\hbar K\frac{\partial\psi}{\partial t} - \hbar^2 J\frac{\partial^2\psi}{\partial t^2} = -ta^2\frac{\partial^2\psi}{\partial x^2} + r\psi + u|\psi|^2\psi. \tag{1}$$

We derive the linearized equation for phase and amplitude fluctuation of the order parameter ψ and calculate the transmission and reflection coefficients of the Higgs and NG modes for a potential barrier. We find that the total of transmission and reflection probabilities of the Higgs and NG modes should be conserved because of their coupling. This may lead to an interesting phenomenon where an injected Higgs mode converts into a NG mode after scattering by a potential barrier. We report the more detail of the results in the poster.

[1]Y. Kagan, *et al*., Phys. Rev. Lett. **90**, 130402 (2003).
[2]S. Tsuchiya and Y. Ohashi, Phys. Rev. A **90**, 013628 (2008).
[3]M. Endres, *et al*., Nature (London) **487**, 454 (2012).
[4]S. Sachdev, *Quantum Phase Transitions* (Cambridge University Press, Cambridge, 1999).

P19

Alpha particle condensation in light nuclei

S. Ohkubo
Research Center for Nuclear Physics, Osaka University, Ibaraki,
Osaka 567-0047, Japan
and
University of Kochi, Kochi 780-8515, Japan
E-mail address: ohkubo@yukawa.kyoto-u.ac.jp

The 0_2^+ state in ^{12}C at excitation energy E_x=7.65 MeV, the Hoyle state, is a key state for nucleosynthesis, the evolution of stars and the emergence of life. The three α structure of ^{12}C was most thoroughly investigated by Uegaki *et al.* [1] in their pioneering work, which showed that the Hoyle state has a dilute structure in a new "α-boson gas phase" and clarified the systematic existence of a "new phase" of the three α particles above the α threshold. Inspired by the observation of Bose-Einstein condensation of cold atomic gas clusters, much attention has been paid to investigate whether Bose-Einstein condensation of α particles occurs in light nuclei where α cluster structure widely exists [2,3]. It is evident theoretically and experimentally that the Hoyle state has a larger radius compared with the ground state and has a dilute matter distribution. The Hoyle is now considered to be an α particle condensate. Also in ^{16}O the $K = 0_2^+$ band with a very large moment inertia starting at E_x=16.6 MeV has been suggested to have a locally α condensate with the α+^{12}C(0_2^+) structure and the 0^+ state at 15.1 MeV just above the four α particle threshold has a four α condensate structure [3,4]. The Nambu-Goldstone boson caused by the spontaneous symmetry breaking of the global phase symmetry due to α particle condensation [5] is discussed.

[1] E. Uegaki *et al.*, Prog. Theor. Phys. **57**, 1262 (1977).
[2] A. Tohsaki *et al.*, Phys. Rev. Lett. **87**, 192501 (2001).
[3] Y. Funaki *et al.*, Phys. Rev. Lett. **101**, 082502 (2008).
[4] S. Ohkubo and Y. Hirabayashi, Phys. Lett. **B684**, 127 (2010).
[5] S. Ohkubo, arXiv:1301.7485v1 [nucl-th] (2013).

P20

Lee-Yang cluster expansion approach to the BCS-BEC crossover

Naoyuki Sakumichi[1], Yusuke Nishida[2], Masahito Ueda[3]
[1] Theoretical Research Division, Nishina Center, RIKEN, Wako, Saitama 351-0198, Japan;
[2] Department of Physics, Tokyo Institute of Technology, Meguro, Tokyo 152-8551, Japan;
[3] Department of Physics, The University of Tokyo, Bunkyo, Tokyo 113-0033, Japan
E-mail address: naoyuki.sakumichi@riken.jp

A dilute Fermi gas with an attractive contact interaction can continuously evolve from Cooper pairing to Bose-Einstein condensation (BEC) of tightly-bound dimers by changing the strength of interaction. This is called BCS-BEC crossover and has attracted much attention in recent years because of realizations of Fermi superfluids by using an ultracold atomic gases [1]. In this work, we propose a new systematic approach to describe the BCS-BEC crossover based on a cluster expansion method of Lee and Yang [2-4]. Here, the cluster expansion is a systematic expansion of the equation of state in terms of the fugacity $z := \exp(\beta\mu)$ as $\beta p \lambda^3 = 2z + b_2 z^2 + b_3 z^3 + \cdots$, with inverse temperature $\beta = (k_B T)^{-1}$, chemical potential μ, pressure p, and thermal de Broglie length $\lambda := (2\pi\hbar\beta/m)^{1/2}$. We show the following results [4]: (i) in the weak-coupling limit, the Thouless criterion and the number equation of Nozières and Schmitt-Rink [5] are derived, and thereby the critical temperature is identical with that of the BCS theory; (ii) in the strong-coupling limit, the critical temperature is identical with that of the BEC of non-interacting dimers; (iii) The exact second cluster integral b_2, which is dominant in the high-temperature region, is also included in the expansion for any value of an s-wave scattering length a.

[1] “The BCS-BEC Crossover and the Unitary Fermi Gas”, edited by W. Zwerger (Springer, 2012), and references their in.
[2] T. D. Lee and C. N. Yang, Phys. Rev. 113, 1165 (1958); 117, 22 (1960).
[3] NS, N. Kawakami and M. Ueda, Phys. Rev. A 85, 043601 (2012); arXiv:1202.6532 (2012).
[4] NS, Y. Nishida and M. Ueda, Phys. Rev. A 89, 033622 (2014).
[5] P. Nozières and S. Schmitt-Rink, J. Low Temp. Phys. 59, 195 (1985).

P21

High-pressure ESR measurement of spin gap system and future prospects for Higgs mode research

T. Sakurai[1], R. Matsui[2], S. Okubo[3], H. Ohta[3], K. Matsubayashi[4], Y. Uwatoko[4], and H. Tanaka[5]

[1] Center for Supports to Research and Education Activities, Kobe University, Nada, Kobe 657-8501, Japan;

[2] Graduate School of Science, Kobe University, Nada, Kobe 657-8501, Japan;

[3] Molecular Photoscience Research Center, Kobe University, Nada, Kobe 657-8501, Japan;

[4] Institute for Solid State Physics, University of Tokyo, Kashiwa, Chiba 277-8581, Japan;

[5] Department of Physics, Tokyo Institute of Technology, Meguro-ku, Tokyo 152-8551, Japan

E-mail address: tsakurai@kobe-u.ac.jp

High-field and multi-frequency ESR is a very powerful means to study quantum spin gap system. The pressure effect of the spin gap system has attracted much attention due to its novel excitation mode ”Higgs mode” above the quantum critical point which can be tuned by the pressure. However, there has been few high pressure ESR system having wide magnetic field and frequency range. We have developed the high pressure ESR system by combining the single pass transmission type high-field and multi-frequency ESR system and the electromagnetic wave transmission type pressure cell [1]. As already reported in refs [2], we applied this high pressure ESR system to the well known spin gap system $KCuCl_3$ and successfully observed that the gap energy was reduced by applying the pressure. However, we have not succeeded in observing the Higgs mode because the pressure range was limited and the sensitivity was not enough. Therefore, we have developed recently new high pressure ESR system which has the higher pressure range and sensitivity [3]. The newly developed high pressure ESR system will be shown and the possibility of the observation of Higgs mode by this system will be discussed in detail.

[1] T. Sakurai *et al.*, Rev. Sci. Instrum. **78** (2007) 065107. T. Sakurai *et al.*, J. Magn. Reson. **223** (2012) 41.
[2] T. Sakurai *et al.*, J. Phys. Conf. Ser. **51** (2006) 565. T. Sakurai *et al.*, AIP Conf. Proc. **850** (2006) 1057.
[3] T. Sakurai *et al.*, Appl. Magn. Reson. **44** (2013) 893.

P22

Higgs Modes in Superfluid ^{3}He

Keiya Shirahama, Hayate Obuchi, Satoshi Murakawa
Department of Physics, Keio University, Yokohama 223-8522, Japan;
E-mail address: keiya@phys.keio.ac.jp

Recent interests to topological superconductivity shed new light on the physics of superfluid ^{3}He, the most-established p-wave spin-triplet superfluid [1]. Since the symmetry breaking occur not only in U(1) gauge but SO(3)$_L$ (orbital) and SO(3)$_S$ (spin), there are generally 18 bosonic excitations in both the A and B phases. They are called order-parameter collective modes, and the massive collective modes are classified as amplitude, i.e. Higgs, modes. In this poster we discuss new aspects of the Higgs modes in superfluid ^{3}He and propose an experiment searching for the new Higgs modes in ^{3}He film.

Nambu [2] proposed a quasi - supersymmetric relation between fermionic and bosonic excitations in BCS superfluids, $m_1^2+m_2^2 = 4m_f^2$, where m_1 and m_2 are the mass of the (partnered) bosonic modes and m_f is the mass of the fermionic mode, i.e. the superfluid energy gap Δ. He noticed that in the B phase the so-called real and imaginary squashing modes, each of which has a mass $m_{\mathrm{RSQ}} = \sqrt{8/5}\Delta$ and $m_{\mathrm{ISQ}} = \sqrt{12/5}\Delta$, exactly satisfy the relation. Volovik and Zubkov [3] called this relation "the Nambu sum rule" and utilize this relation to predict the "Nambu partner" of the 125 GeV Higgs, which should appear at 325 GeV given that the top quark is the corresponding fermionic excitation. This is an interesting suggestion from condensed matter physics to high energy physics. In this aspect the collective modes in thin films of the A phase are well worthy of being studied, because the symmetry breaking in the films is similar to that of the Standard Model. We will discuss our plan to search for the collective modes in superfluid ^{3}He films by ultrasound spectroscopy.

[1] D. Vollhardt and P. Wölfle, *The Superfluid Phases of Helium 3*, Dover Books on Physics (originally published in 1990 from Taylor and Fransis); *Helium Three*, eds. W. P. Halperin and L. P. Pitaevskii, North-Holland (1990).
[2] Y. Nambu, Physica D **15**, 147 (1985); See also *Broken Symmetry: Selected Papers of Y. Nambu*, eds. T. Eguchi and K. Nishijima, and *BCS:50 Years*, eds. L.N. Cooper and D. Feldman, World Scientific (2010).
[3] G. E. Volovik and M. A. Zubkov, JETP Letters **97**, 301 (2013); Phys. Rev. D **87**, 075016 (2013); J. Low Temp. Phys. **175**, 486 (2014).

P23

Bogoliubov theoretical formulation for counting rule and dispersion relations of Nambu-Goldstone modes

D. A. Takahashi[1,2], M. Nitta[2,3]
[1] RIKEN Center for Emergent Matter Science (CEMS), Wako, Saitama 351-0198, Japan;
[2] Research and Education Center for Natural Sciences, Keio University, Hiyoshi 4-1-1, Yokohama, Kanagawa 223-8521, Japan;
[3] Department of Physics, Keio University, Hiyoshi 4-1-1, Yokohama, Kanagawa 223-8521, Japan;
E-mail address: daisuke.takahashi.ss@riken.jp

The theory of counting rule of Nambu-Goldstone modes is a recent hot topic in both condensed-matter and high-energy physics [1-3]. In our presentation, we solve this problem in the framework of Gross-Pitaevskii-Bogoliubov theory [4], and clarify several new features including (i) the relation between the linear independence of the pair of zero modes and the coefficient of type-II dispersion relation, (ii) the simplified criterion for the case of spacetime symmetry breaking, and (iii) the generalization to the case where non-symmetry-originated modes such as quasi-Nambu-Goldstone modes exist.

[1] Y. Nambu, J. Stat. Phys. 115, 7 (2004).
[2] H. Watanabe and T. Brauner, Phys. Rev. D 84, 125013 (2011); H. Watanabe and H. Murayama, Phys. Rev. Lett. 108, 251602 (2012).
[3] Y. Hidaka, Phys. Rev. Lett. 110, 091601 (2013).
[4] D. A. Takahashi and M. Nitta, arXiv:1404.7696.

P24

Nambu-Goldstone mode associated with a soliton and its dynamics

J. Takahashi[1], Y. Nakamura [1], Y. Yamanaka [1]
[1] Department of Electronic and Photonic Systems, Waseda University,
Shinjuku-ku, Tokyo 169-8555, Japan.
E-mail address: j.takahashi@aoni.waseda.jp

We consider the Bose-Einstein condensate (BEC) system of cold atomic gas with a dark soliton. The simple BEC is interpreted as a spontaneous breakdown of the global phase symmetry, and there appears the NG mode. The existence of a dark soliton in BEC implies the spontaneous breakdown of the translational symmetry for an originally homogeneous system, and there appears the additional zero mode related to the translational symmetry. Treating these NG modes in quantum field theory of canonical formalism, one finds that the NG mode sector of the unperturbed Hamiltonian has a form of free particle [1]. Especially, the unperturbed dynamics of the NG mode associated with the dark soliton is described by the free particle Hamiltonian with a negative mass [2]. This fact indicates that the NG mode associated with the soliton should induce some instability.

Recently, we have discussed that the behavior of the NG mode associated with the dark soliton under an external perturbation potential breaking the translational invariance explicitly, and found in general that the NG mode becomes either a pure imaginary mode or an anomalous mode, each of which is related to the dynamical or Landau instability, respectively [3]. In this poster, we deal with a one-dimensional homogeneous Bose-Einstein condensate system with a single dark soliton under a perturbation Gaussian potential, and show that the NG mode turn to pure imaginary one. Furthermore, we analyze its dynamics to show the effects which the pure imaginary mode gives rise to.

[1] M. Lewenstein and L. You, Phys. Rev. Lett. 77 (1996) 3489.
[2] J. Dziarmaga, Phys. Rev. A 70 (2004) 063616.
[3] J. Takahashi, Y. Nakamura, and Y. Yoshiya, Ann. Phys. 347 (2014), 250-260.

P25

Axion physics in topological phases of condensed matter

Akihiro Tanaka[1], S. Takayoshi[1], T. Kikuchi[2], M. Nitta[3]

[1] National Institute for Materials Science, Sengen 1-2-1, Tsukuba, Ibaraki 305-0047, Japan,
[2] Spin Physics Theory Research Team, RIKEN, Wako, Saitama 351-0198, Japan
[3] Department of Physics, Keio University, Hiyoshi 4-1-1 Yokohama, Kanagawa 223-8251 Japan
E-mail address: TANAKA.Akihiro@nims.go.jp

Axions originated as a resolution to the strong CP problem in QCD; they are the Nambu-Goldstone bosons which accompany the breaking of the Peccei-Quinn $U(1)$-symmetry and are intimately related to topological entities such as instantons, chiral anomalies and the θ-vacua. Over the years incarnations of axions have repeatedly turned up in one or another condensed matter physics context. Most notably, in recent years, they have come to play crucial roles in the physics of topological insulators and other topological phases of matter. Here we discuss our recent work on the nonlinear sigma model description of symmetry-protected-topological phases (such as the Haldane gap phase of quantum spin chains as well as certain quantum Hall systems), focusing on how axions find their way into the wavefunction and thus dictate whether or not the state in question is topologically trivial. In addition, we discuss from a more general perpective the properties of topological defects of axion fields, especially axion vortices (which can, for instance, be relevant to studies of weak topological isulators), which are in many ways simililar to superfluid vortices but nevertheless exhibit some distinct Berry phase effects .

P26

Higgs mode in a trapped superfluid Fermi gas

J. Tokimoto[1], S. Tsuchiya[2] , T. Nikuni[1]
[1] Department of Physics, Faculty of Science, Tokyo University of Science, 1-3 Kagurazaka, Shinjuku-ku, Tokyo 162-8601, Japan
[2] Tohoku Institute of Technology, 35-1 Yagiyamakasumicho, Taihaku-ku, Sendai-shi, Miyagi 982-8577, Japan
E-mail address: 1214705@ed.tus.ac.jp

In quantum many-body systems such as superfluid Fermi gases, Higgs modes emerges as collective amplitude oscillations as a consequence of spontaneous breaking of a continuous symmetry. In uniform Fermi superfluid gases, the magnitude of superfluid order parameter$|\ \Delta\ |$ exhibits oscillations, corresponding to the Higgs mode, with the angular frequency $2\Delta_{gap}/\hbar$, where$\Delta_{gap}$is the gap in the spectrum of fermionic excitations.[1]
Recently, Higgs modes have been observed in superconductors and for in Bose gases in optical lattices near the superfluid to Mott-insulator transition.[2] However, the Higgs mode has not yet been observed in Fermi gases. In this study, we investigate the collective oscillation of trapped superfluid Fermi gases. In particular, we investigate the responce of the system to a sudden changes of the s-wave scattering length a by solving the time-dependent Bogoliubov-de Gennes equations.[3]
We observe the amplitude oscillation of the superfluid order parameter, while the density profile is almost unchanged, which corresponds to the Higgs mode in harmonically trapped system. In Fermi systems, the crossover from weak coupling Bardeen-Cooper-Schrieffer (BCS) pairing to a Bose-Einstein condensate (BEC) of tightly bound pairs occurs as a function of the attractive interaction. Therefore we will discuss the Higgs amplitude oscillations in a trapped Fermi gas in the BCS regime, crossover regime and BEC regime. We will also discuss the optimal conditions for observations of the Higgs mode in a trapped superfluid Fermi gases.

[1] A.F.Volkov and S.M.Kogan, Sov. Phys. JETP 38, 1018 (1974)
[2] M.Endres et al., Nature(London) 487, 454(2012)
[3] R.G.Scott, F.Dalfovo, L.P.Pitaevskii, and S.Stringari, Phys. Rev. A 86, 053604 (2012)

P27

Monopole mode in mesoscopic trapped Fermi gases

M. Valiente[1], D. Maldonado-Mundo [1], G. M. Bruun [2] and P. Öhberg [1]
[1] Heriot-Watt University, Edinburgh UK;
[2] Aarhus University, Aarhus Denmark
E-mail address: MV75@hw.ac.uk

We investigate the collective excitations of attractive two-dimensional ultracold trapped Fermi gases. We focus on the mesoscopic regime where the BCS Hamiltonian is of the Richardson-Gaudin type and therefore exactly solvable. In particular, we show how the dispersion of the monopole (or Higgs) mode is affected by finite particle numbers and compare our results with the mean-field approximation, which is exact in the many-body limit.

P28

Effects of phase and amplitude fluctuations on the ground state of a frustrated Bose-Hubbard system

Daisuke Yamamoto[1], Keisuke Masuda[2], and Susumu Kurihara[2]
[1] Waseda Institute for Advanced Study, Waseda University, Shinjuku, Tokyo 169-8050, Japan;
[2] Department of Physics, Waseda University, Shinjuku, Tokyo 169-8555, Japan
E-mail address: d-yamamoto@aoni.waseda.jp

Highly frustrated magnetism is one of the central issues of research in modern condensed matter physics. Recently, ultracold Bose gases trapped in a geometrically-frustrated optical lattice have attracted a great deal of interest as a simulator of the frustrated magnetism [1]. The key advance in this direction was the development of experimental techniques that inverted the sign of the hopping integral [2] of bosonic atoms. For such sign-inverted hopping, the relative phase of local condensate order parameters at neighboring lattice sites tends to be π in analogy with antiparallel alignment of antiferromagnetic spins.
Motivated by the experimental developments, we study the Bose-Hubbard model with sign-inverted hopping on the kagome lattice:

$$\hat{\mathcal{H}} = J\sum_{\langle i,j\rangle}\left(\hat{b}_j^\dagger\hat{b}_l + \mathrm{H.c.}\right) + \frac{U}{2}\sum_j \hat{n}_j\left(\hat{n}_j - 1\right) - \mu\sum_j \hat{n}_j. \tag{1}$$

The geometry of the kagome lattice and the sign-inverted hopping ($J > 0$) give rise to frustration among the local phases of the condensate. The geometric frustration creates an infinite number of degenerate ground states at the level of the Gutzwiller (site-decoupled) mean-field approximation. Therefore, we construct a flavor-wave theory for softcore boson systems based on a generalized Holstein-Primakoff transformation, and study the effects of phase and amplitude fluctuations around the mean-field ground states. Especially, we discuss the lifting of the degenerate ground states (order-by-disorder mechanism) and possible quantum-disordered states in the presence of additional long-range repulsions.

[1] J. Struck, C. Ölschläger, R. Le Targat, P. Soltan-Panahi, A. Eckardt, M. Lewenstein, P. Windpassinger, and K. Sengstock, Science **333**, 996 (2011).
[2] A. Eckardt, C. Weiss, and M. Holthaus, Phys. Rev. Lett. **95**, 260404 (2005); H. Lignier, C. Sias, D. Ciampini, Y. Singh, A. Zenesini, O. Morsch, and E. Arimondo, Phys. Rev. Lett. **99**, 220403 (2007).

P29

Time crystal phase in a superconducting ring

R. Yoshii[1, 2], S. Takada[1], S. Tsuchiya[3, 2], G. Marmorini[4, 2],
H. Hayakawa[1], and M. Nitta[5, 2]
[1] Yukawa Institute for Theoretical Physics, Kyoto University, Sakyo-ku, Kyoto 606-8502, Japan;
[2] Research and Education Center for Natural Sciences, Keio University, 4-1-1 Hiyoshi, Kanagawa 223-8521, Japan
[3] Department of Physics, Faculty of Science, Tokyo University of Science, 1-3 Kagurazaka, Shinjuku-ku, Tokyo 162-8601, Japan
[4] Condensed Matter Theory Laboratory, RIKEN, Wako, Saitama 351-0198, Japan
[5] Department of Physics, Keio University, 4-1-1 Hiyoshi, Kanagawa 223-8521, Japan
E-mail address: ryoshii@yukawa.kyoto-u.ac.jp

Spontaneous symmetry breaking is one of the most important notions in physics. Recently, the spontaneous breaking of the time translation symmetry has been proposed [1, 2]. If the time translation symmetry is spontaneously broken, a ground state in which the order parameter enjoys only discrete translation invariance in time is expected to emerge, analogous to a crystal phase which stems from the spontaneous symmetry breaking of spatial translation symmetry. This emergent phase is called a time crystal.
We demonstrate a possible setup to exhibit the spontaneous symmetry breaking of the time translation symmetry [3]. We consider a quasi-one-dimensional superconducting ring with a static Zeeman magnetic field applied along the ring and static Aharonov-Bohm magnetic flux penetrating the ring. The superconducting ring with magnetic flux produces a persistent current, whereas the Zeeman split of Fermi energy results in the spatial modulation of the pair potential. We show that these two magnetic fields stabilize the twisted kink crystal (Fulde-Ferrel-Larkin-Ovchinnikov) phase, in which both the phase and amplitude have spatial modulations. In this phase, the time translation symmetry is spontaneously broken.

[1] F. Wilczek, Phys. Rev. Lett. **109**, 160401 (2012).
[2] A. Shapere and F. Wilczek, Phys. Rev. Lett. **109**, 160402 (2012).
[3] R. Yoshii, S. Takada, S. Tsuchiya, M. Giacomo, H. Hayakawa, and M. Nitta, arXiv: 1404.3519 (2014).

P30

Direct quantum process tomography

Yu-Xiang Zhang[1,2], Shengjun Wu[2], Zeng-Bing Chen[1]
[1] National Laboratory for Physical Sciences at Microscale, Department of Modern Physics, and the Collaborative Innovation Center for Quantum Information and Quantum Frontiers, University of Science and Technology of China, Hefei, Anhui 230026, China
[2] Kuang Yaming Honors School, Nanjing Univeresity, Nanjing, Jiangsu 210093, China
E-mail address: iyxz@mail.ustc.edu.cn

Quantum process tomography is the task to determine the dynamics evolution expressed by a quantum system. Here we take advantages of the correlation between two weak measurements pointers to present a new scheme, which is characterized by its directness that each single parameter of the quantum process is determined with only one input state and two successive weak measurements. Simplified scheme can also be used to identify the coherent entities of the density matrix. We hope this method coming from the field of quantum information will be helpful for the experiments of detecting quasi-particles in condensed matter physics.