Hideo Aoki's research activities in 2022-2023

Our main interests are many-body effects as examplified by **superconductivity**, and **topological states** in electron and cold-atom systems. We also envisage novel **non-equilibrium** phenomena should be realised in these systems. After retirement in 2016 from the department of physics, the University of Tokyo, Aoki continues research activities as an emeritus professor.

Studies around the 2022-2023 academic years are the following:

1 BCS-BEC crossover and Fano-Feshbach resonance in two-band superconductors

Multi-band systems and flat-band systems are attracting keen interests as theoretical guiding principles for higher-Tc superconductors. As for the flat-band superconductivity[1], Aoki collaborated with Sharareh Sayyad (Institut Néel, Grenoble, now at Max-Planck Institute for the Science of Light, Erlangen), Motoharu Kitatani (Riken, now at Univ. Hyogo) et al to find that the superconductivity arising from repulsive interactions is significantly enhanced by an electron nematicity[2].

Now, Hiroyuki Tajima (Univ. Tokyo), Andrea Perali (Universitá di Camerino), Antonio Bianconi (RICMASS, Roma) and Aoki studied how the superconductivity in 2-band systems can be enhanced due to the pair-scattering between the main and accompanying bands[3].

If we consider a 2-band system with an attractive interaction, with a heavy-mass second band sitting close to the chemical potential (the situation called 'incipient'), the inter-band pair-scattering can produce a **Feshbach resonance** (Fig.1) as the chemical potential is varied, which results in an intensified attraction[4]. This occurs in the crossover region between the weak-coupling BCS and the strong-coupling BEC (Bose-Einstein condensate) regimes. In general, however, one should note that it often happens that the evaluated $T_{\rm C}$ becomes significantly reduced when the effects of fluctuations are included. One powerful method for treating fluctuations is Gor'kov-Melik-Barkhudarov (GMB) formalism [Sov. Phys. JETP **13**, 1018 (1961)], where fluctuations are taken into account in both of the particle-particle and particle-hole channels. It has not been known, however, how this framework applies to 2-band superconductors. Tajima et al started with extending the GMB theory to 2-band cases, and looked into the superconductivity in a **2-band model where a dispersive band is accompanied by a heavy, incipient band**. They found that a competition arises between the particle-hole fluctuations and a Feshbach resonance invoving the heavy band, which results in a dome-shaped $T_{\rm C}$ as a function of the mass ratio between the two bands (Fig.2). In other words, there exists an optimal mass ratio. The peaked structure is shown to occur right around the BCS-BEC crossover regime, where a kind of **Fano resonance** involving a bound state residing just below the heavy band is concomitantly at work, i.e., the $T_{\rm C}$ suppression due to the particle-hole fluctuations becomes relaxed when the chemical potential is close to the resonance.

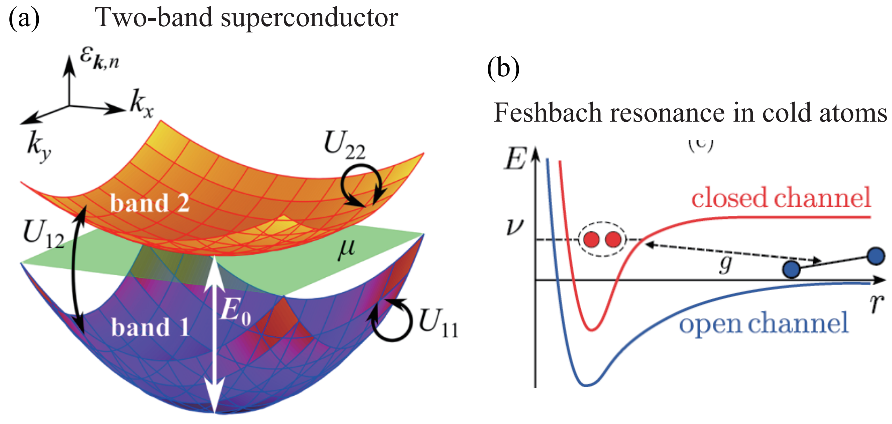

Figure 1: (a) A two-band system comprising a heavy-mass band (red) and a dispersive one (blue) is schematically shown, with intra-band pair scattering interactions (U_{11}, U_{22}) and inter-band pair scatterings (U_{12}), for a chemical potential μ and a band offset E_0. (b) In a cold-atom system comprising a closed channel (red) and an open channel (blue), a Feshbach resonance arises in the presence of a Feshbach coupling g. The horizontal axis r is the inter-atomic distance, and ν stands for the bound level. [3, 4]

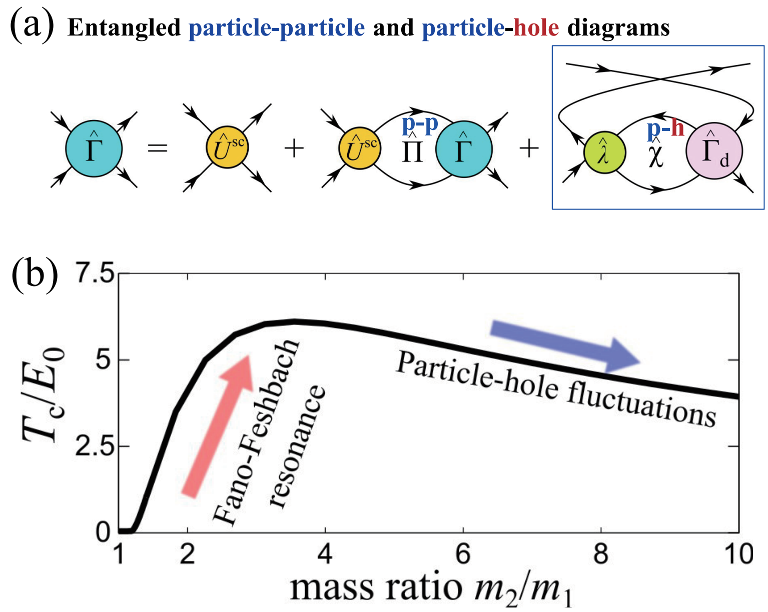

Figure 2: (a) Diagrams that are taken into account in the GMB theory, where the particle-particle and particle-hole channels are both considered. In a two-band system, each vertex becomes a 2×2 matrix. (b) For a two-band sysstem comprising heavy-mass (m_2) and light-mass (m_1) bands, the T_C estimated from the GMB theory is plotted against the mass ratio m_2/m_1. When m_2/m_1 is increased, T_C initially rises, then decreases after an optimal ratio. [3]

2 Sub-cycle multidimensional spectroscopy for strongly-correlated materials

Non-equibrium physics becomes especially intriguing in strongly-correlated systems and topological systems. In 2023 we have studied the following. Recent years witness keen interests in qauntum states generated by intense laser illuminated onto strongly-correlated electron systems, which creates light-coupled states that go drastically beyond equilibrium ones. One study that kicked-off the new field is the Floquet topological insulator proposed theoretically by Takashi Oka and Aoki in 2009. The avenue is now called the **Floquet engineering**. In this field, one usually studies the responses when a continuous or multi-cycle laser is illuminated to the system.

Now, Aoki, in collaboration with Alexander Lichtenstein's group in European XFEL（X-ray free-electron laser) in Hamburg and Hamburg University, Olga Smirnova's group in Max-Born-Institut, Berlin, and other groups, looked theoretically into the light-matter coupled states that emerge when mono-cycle, or even **sub-cycle** laser pulses are irradiated[5]. An expectation is that such sub-femtosecond laser pulses may open a new route for manipulating strongly-correlated materials. In this study, a new direction called **multidimensional spectroscopy** is introduced, where 'multidimensional' means that the carrier-envelope phase is considered as a new degree of freedom in the spectroscopy. With this idea, we clarified how the quantum states, that comprise lower and upper Hubbard bands and quasiparticle states in energy axis with quantum wavefunctions having various sizes in real space (Fig.3). The numerical simulation was done with **non-equilibrium dynamical mean-field theory** for parameter values representing the high-Tc cuprates. The results reveal that the multidimensional spectroscopy does indeed sensitively reflect the charge flow and energy flow among various correlated electron states, where the quantum states persist well after the laser pulse is gone, as a collective effect in the multi-electron responses. This indicates the spectroscopy will be powerful for probing and controlling strongly-correlated systems that goes beyond the conventional Floquet engineering.

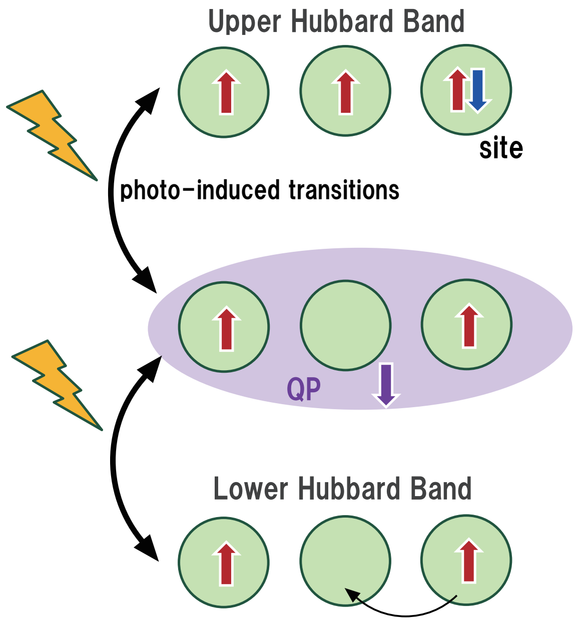

Figure 3: Schematic correlated electron states and excitations by laser. The many-body states comprise lower and upper Hubbard bands and quasiparticle(QP) states. Double arrows stand for excitations by laser. After [5].

3 Others

Aoki served as a member of the editorial committee for *Encyclopedia of Condensed Matter Physics*, 2nd edition[6]. He wrote a chapter, "Integer quantum Hall effect", for *Comprehensive Semiconductor Science & Technology*, 2nd edition[7]. Aoki also wrote a book *Physics of Superconductivity* (in Japanese)[8]. He gave invited talks on superconductivity and topological systems at international conferences [9, 10, 11].

References

< **Original papers** >

[1] H. Aoki: Theoretical possibilities for flat-band superconductivity,
J. Supercond. Nov. Magn. **33**, 2341 (2020).

[2] Sharareh Sayyad, Motoharu Kitatani, Abolhassan Vaezi, and Hideo Aoki: Nematicity-enhanced superconductivity in systems with a non-Fermi liquid behavior,
Journal of Physics: Condensed Matter **35**, 245605 (2023). [Selected in "Celebrating the impact of research published through the Max Planck transformative agreement in 2023".]

[3] Hiroyuki Tajima, Hideo Aoki, Andrea Perali, Antonio Bianconi: Emergent Fano-Feshbach resonance in two-band superconductors with an incipient quasi-flat band: Enhanced critical temperature evading particle-hole fluctuations,
Phys. Rev. B Letter **109**, L140504 (2024).

[4] Kazunari Ochi, Hiroyuki Tajima, Kei Iida, and Hideo Aoki: Resonant pair-exchange scattering and BCS-BEC crossover in a system composed of dispersive and heavy incipient bands: a Feshbach analogy, *Phys. Rev. Research* **4**, 013032 (2022).

[5] V. Valmispild, E. Gorelov, M. Eckstein, A. Lichtenstein, H. Aoki, M. Katsnelson, M. Ivanov and O. Smirnova: Sub-cycle multidimensional spectroscopy of strongly correlated materials,
Nature Photonics **18**, 432 (2024). [Featured by Eleftherios Goulielmakis: News & views — Attosecond photonics Sub-cycle photonics in correlated materials, *Nature Photonics* **18**, 407 (2024).]

< **Books** >

[6] T. Chakraborty, Ana M. Sanchez, Hideo Aoki, Robert H. Blick, Roberto Raimondi, Rudolf A. Roemer, and Vladimir Mihajlovic Fomin (editors): *Encyclopedia of Condensed Matter Physics*, 2nd edition. (Elsevier, 2023).

[7] Hideo Aoki: Integer quantum Hall effect, in *Comprehensive Semiconductor Science & Technology*, 2nd edition (Elsevier), to be published.

[8] Hideo Aoki: *Physics of Superconductivity* (in Japanese) (Shokabo, 2024, in the press).

< Invited talks at international conferences >

[9] Hideo Aoki: Engineering topological superconductivity in and out of equilibrium, Int. Conf. “Superstripes2022”, Frascati/online, 21 June 2022.

[10] Hideo Aoki: Engineering superconducting and topological systems in and out of equilibrium, Int. Workshop “CORPES 2022”, online, 14 July 2022.

[11] Hideo Aoki: Floquet generation of topological superconductivity and magnetism in the strong-correlation regime, Int. Conf. “Superstripes2023”, Ischia, 26 June 2023.