Correlated electronic states in quasicrystals

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Strong correlations in quasiperiodic systems have attracted much interest since the observation of quantum critical behavior in the Tsai-type quasicrystal compound $Au_{51}Al_{34}Yb_{15}$ [1]. Possible long-range electronic orders in such systems have also been widely debated. This talk will review some of the experimental work [1,2] regarding correlation effects in quasicrystals, as well as our theoretical investigations on correlation effects in quasiperiodic systems, such as the Mott transition [3], valence transition [4], and superconductivity [5,6]. In particular, we have discovered unconventional weak-coupling superconductivity formed by Cooper pairs in quasiperiodic systems (Fig. 1), which deviates from that of Bardeen-Cooper-Schrieffer superconductivity in periodic systems. This deviation can be observed through the real-space distribution of the superconducting order parameter, jump of specific heat, current-voltage characteristic curve, and supercurrent distribution. These results indicate that the nature of superconductivity in quasiperiodic systems is qualitatively different from that in periodic and random systems, providing a clue to understanding the mechanism and properties of superconductivity recently discovered in an Al-Mg-Zn quasicrystal.

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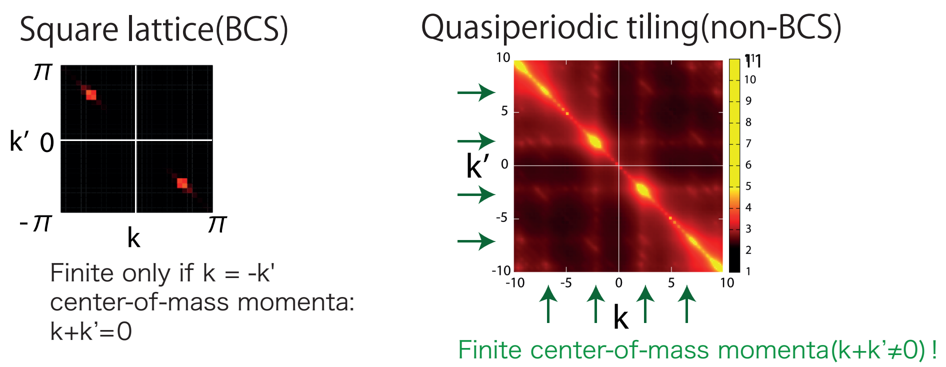
[1] K. Deguchi., *et al*., Nat. Mater. **11** (2012) 1013.
[2] K. Kamiya, *et. al.*, Nat. Comm. **9** (2018) 154.
[3] N. Takemori and A. Koga, J. Phys. Soc. Jpn. **84** (2015) 023701; N. Takemori and A. Koga, J. Phys.: Conf. Ser. **592** (2015) 012038.
[4] S. Takemura, N. Takemori and A. Koga, Phys. Rev. B **91** (2015) 165114.
[5] S. Sakai, N. Takemori, A. Koga, and R. Arita, Phys. Rev. B **95** (2017) 024509; N. Takemori, R. Arita and S. Sakai, Phys. Rev. B **102** (2020) 115108.
[6] T. Fukushima, N. Takemori, S. Sakai, M. Ichioka, A. Jagannathan, J. Phys.: Conf. Ser. **2461** (2023) 012014.



$|\langle c_{k\uparrow} c_{k'\downarrow}\rangle|$:Fourier transformed inter-site order parameter $\mathrm{OP}_{ij} = \langle c_{i\uparrow} c_{j\downarrow}\rangle$

Fig.1: Cooper pairs with finite center-of-mass momentum in Penrose tiling.

Electron interaction driven exotic superconductivity on QCs

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The recent revelation of superconductivity (SC) in the Al-Zn-Mg quasicrystal (QC) has aroused great interests. Here, we report our recent series of works on the electron-electron (e-e) interaction driven exotic SCs on both the intrinsic and the extrinsic QCs.

For the intrinsic QC, we study the Penrose tiling as an example. We generalize the Kohn-Luttinger mechanism for repulsive-interaction-driven SCs from periodic lattices to QCs, and classify the pairing symmetries [1]. Consequently, we found a series of novel superconducting phases which include two characters universal to all intrinsic QCs. Firstly, the pairing angular momentum and the spin statistics are generally independent. Secondly, there generally exist spontaneous bulk super current for time-reversal-symmetry broken topological SCs (TSCs). We further show that the Cooper instability still holds in the QC for infinitesimal attractions [2].

For the extrinsic QC, we study the twisted bilayer QCs (TB-QC), exampled by the 45°-twisted bilayer cuprates and 30°-twisted bilayer graphene. In this study, we revise the perturbational-band theory to suit it in the study of e-e interaction driven instabilities. Consequently, such high angular momentum TSCs as the g+ig and h+ih TSCs absent on crystals can emerge in the TB-QC due to its doubly enlarged rotation symmetries [3]. Particularly, one can make chiral TSCs in the TB-QC from non-topological SCs in its monolayer [4]. More interesting, the fluctuations of the total- and relative- phases of the pairing order parameters from the two layers can drive such high-temperature vestigial phases as the charge-4e SC and chiral metal in the TB-QCs [5].

Our studies open the door to study e-e interaction driven SCs on QCs.

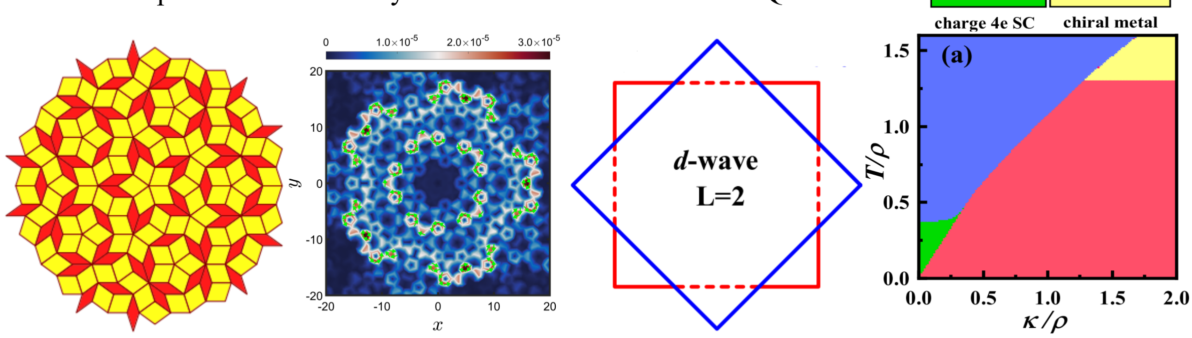

Fig.1 The Penrose tiling (a) and the super-current (b); the TB-QC (c) and phase diagram (d).

[1] Y. Cao, Y. Zhang, Y.-B. Liu, C.-C. Liu, W.-Q. Chen and F. Yang, Phys. Rev. Lett. **125** (2020) 017002.
[2] Y. Zhang, Y.-B. Liu, Y. Cao, W.-Q. Chen and F. Yang, Sci. China-Phys. Mech. Astron **65** (2022) 287411.
[3] Y.-B. Liu, Y. Zhang, W.-Q. Chen and F._Yang, Phys. Rev. B **107** (2023) 014501.
[4] Y.-B. Liu, J. Zhou, Y. Zhang, W.-Q. Chen and F. Yang, (2023) arXiv: 2301.07553.
[5] Y.-B. Liu, J. Zhou, Y. Zhang, C. Wu and F. Yang, (2023) arXiv: 2301.06357.

Self-consistent study of topological superconductivity in two-dimensional Penrose and Ammann-Beenker quasicrystals

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Superconductivity in quasicrystals (QCs) has been observed experimentally and its theoretical studies have been conducted; however, studies linking superconductivity in QCs to topology have been lacking. In a topological superconducting state, where nontrivial topology is associated with the bulk of the system, it is known that Majorana fermions can appear on the surface boundary or at a topological defect. As Majorana fermions obey non-Abelian exchange statistics, topological superconductivity (TSC) is an important research topic because its application to quantum computing is prospective. The purpose of our study is to examine the stability of TSC in QCs, and to achieve this, we numerically simulate TSC in two-dimensional QCs [1]. We examine TSC with broken time-reversal symmetry in two-dimensional Penrose (Fig.1 (a)) and Ammann-Beenker (Fig.1 (b)) QCs by solving the Bogoliubov-de Gennes equations self-consistently, for not only the superconducting order parameter, but also the spin-dependent Hartree potential [2]. We find that the self-consistently obtained mean fields are spatially inhomogeneous, but nonzero everywhere in both Penrose and Ammann-Beenker QCs. We demonstrate how the underlying quasiperiodic structure of a QC is reflected in the superconducting properties. To signify the topological nature of the system, we calculate the Bott index which is equivalent to the first Chern number in the presence of translational symmetry. Our results confirm the existence of stable TSC states in QCs and the appearance of Majorana zero modes, despite the inherent inhomogeneity of QCs.

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[1] M. Hori *et al*., to be submitted.
[2] S. L. Goertzen, K. Tanaka, Y. Nagai, Phys. Rev. B **95** (2017) 064509.

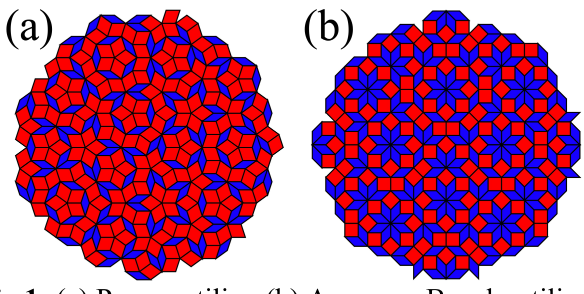

Fig.1: (a) Penrose tiling (b) Ammann-Beenker tiling.