Engineering quasiperiodicity with two-dimensional moiré structures

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Layering two-dimensional periodic materials to form moiré structures is a convenient method of constructing emergent periodicity with length scales in between those typical of crystals and optically defined atomic lattices. This scheme has proven fruitful for engineering new electronic structures with on-demand properties like superconductivity, strong electronic interactions, topology, and even simulations of certain lattice models. In contrast, quasiperiodic structures, without periodicity or a Bloch description, have proven more challenging to engineer. Here, I demonstrate how moiré lattices can be used to generate emergent quasiperiodicity with both a high degree of tunability and conditions favorable for interacting electronic phenomena. I will discuss a graphene-based realization of a moiré quasiperiodic system that exhibits a surprising array of phenomena, including superconductivity, flavor symmetry-breaking, quantum oscillations, and signatures of both periodic-like and quasiperiodic regimes in the electronic structure.

Acknowledgements: This work was supported by the Army Research Office MURI W911NF2120147 (AU), the National Science Foundation (DMR-1809802, MR and DRL), the STC Center for Integrated Quantum Materials (NSF grant no. DMR-1231319, SdlB, TD, PJDC, and NP), and the Gordon and Betty Moore Foundation's EPiQS Initiative through grant GBMF9463 to PJH. AU acknowledges support from the MIT Pappalardo Fellowship and from the VATAT Outstanding Postdoctoral Fellowship in Quantum Science and Technology. MTR acknowledges support from the MIT Pappalardo Fellowship. RL is supported by the Israel Science Foundation (ISF) through Grant No. 1259/22.

Emergence of marginal critical states in non-Penrose type rhombic decagonal tilings

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Popular toy models for investigating the electronic properties of quasicrystals are based on the simplest quasilattices, such as the Fibonacci chain or rhombic Penrose tiling. These models are known to exhibit 'critical states', indicating intermediate behavior that is neither fully localized nor extended [1,2]. Meanwhile, it has been well established that there exists a wider variety of quasilattices with different long-range characteristics, distinct from those mentioned above [3,4]. One study showed that electronic states in such quasiperiodic chains can even fall on the margin of localized and critical states [5]. In this work, we show that there exists similar diversity in the characteristics of electronic states in planar quasilattices with different long-range characteristics.

We focus specifically on four tilings with 10-fold symmetry that use the same two kinds of rhombi, including (I) the rhombic Penrose tiling [6], (II) the generalized Penrose tiling with 10-fold symmetry [7], and (III, IV) two kinds of binary tilings derived from the Penrose tiling [8] and Tübingen tiling [9]. The tilings, (I) and (III), are mutually locally derivable (MLD) from each other [10], hence sharing the same long-range characteristics, whereas the tilings, (II) and (IV), belong to separate MLD classes. The electronic states are calculated within the tight-binding approach, under periodic boundary conditions applied to a series of periodic approximations of up to ~500,000 vertices. A comparative assessment of participation number (P), which is a metric to quantify the spatial extent of individual wave functions, as shown in Fig.1, reveals stronger localization tendencies in non-Penrose type systems, analogous to marginal criticality in the one-dimensional case [5]. Such non-conventional behavior may be associated with enhanced long-range structural fluctuations in non-Penrose type systems [11].

Acknowledgements: N.F. acknowledges financial support from the Japan Society for the Promotion of Science (JSPS) under KAKENHI (Grant Number JP19H05819).

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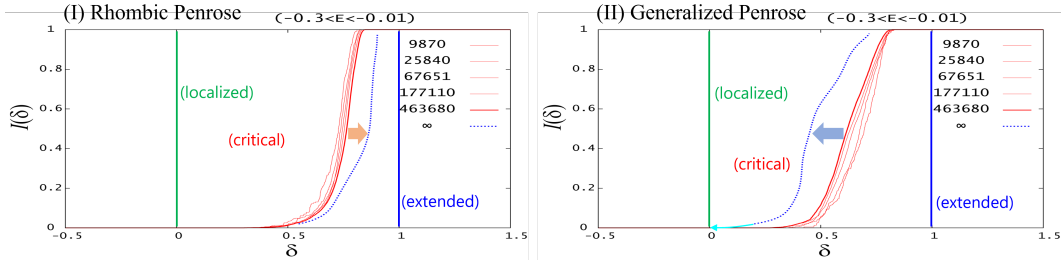

Fig.1: The cumulative distribution function $I(\delta)$ of the exponent δ that describes the participation number as a power law function $P \sim N^{\delta}$ of the system size N.

Emergence of criticality through a cascade of delocalization transitions in quasiperiodic chains

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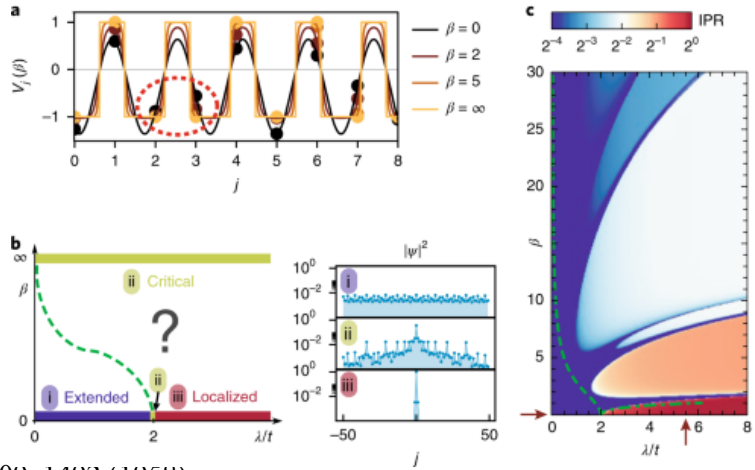
Conduction through materials crucially depends on how ordered the materials are. Periodically ordered systems exhibit extended Bloch waves that generate metallic bands, whereas disorder is known to limit conduction and localize the motion of particles in a medium [1,2]. In this context, quasiperiodic systems, which are neither periodic nor disordered, demonstrate exotic conduction properties, self-similar wavefunctions and critical phenomena [3]. Here, we explore the localization properties of waves in a novel family of quasiperiodic chains obtained when continuously interpolating between two paradigmatic limits [4]: the Aubry–André model [5,6], famous for its metal-to-insulator transition, and the Fibonacci chain [7,8], known for its critical nature. We discover that the Aubry–André model evolves into criticality through a cascade of band-selective localization/delocalization transitions that iteratively shape the self-similar critical wavefunctions of the Fibonacci chain. Using experiments on cavity-polariton devices, we observe the first transition and reveal the microscopic origin of the cascade. Our findings offer (1) a unique new insight into understanding the criticality of quasiperiodic chains, (2) a controllable knob by which to engineer band-selective pass filters and (3) a versatile experimental platform with which to further study the interplay of many-body interactions and dissipation in a wide range of quasiperiodic models.



a) The interpolating Aubry–André-Fibonacci potential.
b) Left: Explored localization phase diagram. Right: typical spatial distribution for extended (i), critical (ii) and localized (iii) modes.
c) Inverse participation ratio (IPR) of the lowest eigenmode of the model as a function of β and λ.

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Semiconducting quasicrystal and its approximant as thermoelectric materials

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More than 80 different types of thermodynamically stable quasicrystals (QCs) have been identified so far [1]. However, all of them are metallic, and no semiconducting or insulating QCs have been found. The search for semiconducting QCs is not only one of the challenging problems in solid-state physics, but also has great potential for application to high-performance thermoelectric materials. The performance of a thermoelectric material can be evaluated using the dimensionless figure of merit $zT = S^2\sigma T/(\kappa_{el} + \kappa_{lat})$, where S, σ, T, κ_{el}, and κ_{lat} are the Seebeck coefficient, electrical conductivity, absolute temperature, electronic thermal conductivity, and lattice thermal conductivity, respectively. Aluminum based quasicrystals have been expected to have high thermoelectric performance due to their deep pseudogap in the density of states and low thermal conductivity. However, all the quasicrystals discovered so far are metals, with Seebeck coefficients S up to 100 μV/K and a maximum dimensionless figure of merit zT of 0.26[1]. In addition the Π-type module, which is the mainstream structure as a thermoelectric power generation module, requires materials with carrier transport properties of both p-type and n-type. However, in quasicrystals, no materials with good performance for n-type have been found.

In this works, we searched for a semiconducting quasicrystalline approximant (QCA) by both calculations based on the density functional theory (DFT) and experiments. Recently we successfully found a semiconducting 1/0 QCA in Al–Si–Ru system from a DFT calculation (Fig.1) and thermoelectric transport measurements [2]. We have successfully controlled the thermoelectric properties of both p-type and n-type in an Al-Si-Ru approximant by various carrier doping. Moreover, each Seebeck coefficient showed a value exceeding 200 μV/K at the maximum.

Acknowledgements: This work is supported by a KAKENHI Grant (No. 19H05818) from the Japan Society for the Promotion of Science (JSPS).

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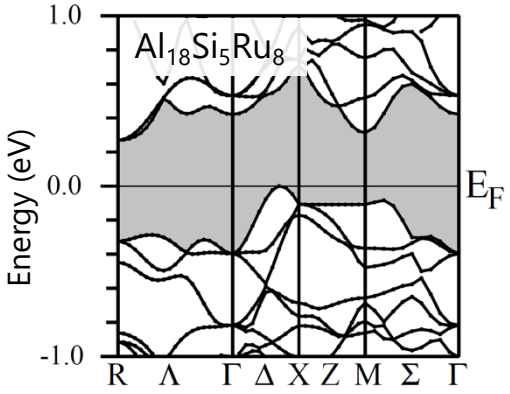

Fig.1: Band structure of Al-Si-Ru 1/0 approximant model $Al_{18}Si_5Ru_8$.[2]