令和３年度　９月修了

京 都 大 学 大 学 院 理 学 研 究 科

修 士 論 文 発 表 会

修 士 論 文 要 旨 集

２ ０ ２ １年７月１３日（火）

物 理 学 第 一 分 野

物理学第一分野修士論文発表会

場所：理学研究科５号館　５階・第４講義室+オンライン
発表：１５分（別に質問時間５分程度）

２０２１年7月１３日（火）１０：００～１１：００

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Thermal Hall effect in the pseudogap phase of cuprates

Quantum Condensed Matter   Andre de Oliveira Silva

Abstract We have performed measurements of thermal Hall in underdoped $La_{2-x}Sr_xCuO_4$. Compared to the previous report, the thermal Hall signal show a similar field and temperature dependences but its magnitude is four times smaller. Further measurements are needed to clarify the origin of the thermal Hall effect in the pseudogap phase.

High-T_c cuprate superconductors display a rich variety of electronic states in the temperature-doping phase diagram. The parent compound is an antiferromagnetic Mott insulator and a Fermi liquid state appears with high enough doping. In between these two states, there exist for example charge-density wave, superconductivity and in particular the pseudogap states. In the pseudogap state, it has been discussed that many symmetry breaking phenomena appear, including broken in-plane rotational and time-reversal symmetries. The pseudogap state holds the key for understanding high temperature superconductivity but its nature is controversial. Therefore both experimental and theoretical efforts are still being made even 30 years after its discovery.

Recently, a giant thermal Hall effect (THE) was reported in the parent compound and underdoped cuprates [1, 2]. The THE signal becomes negative inside the pseudogap state and its magnitude increases as the temperature decreases. Remarkably, the magnitude of the THE measured in the direction perpendicular to the CuO_2 plane (κ_{zy}) is comparable to that measured parallel to the planes (κ_{xy}) despite its layered crystal structure. The most plausible origin is phonons which are the only known quasiparticle able to propagate along the *c*-axis (out-of-plane). Although it is proposed that the phonon would be chiral inside the pseudogap, understanding the specific mechanism by which phonons couple with a magnetic field is a challenge with our current perspective of the cuprates. Therefore, elucidating the origin of the giant negative THE is expected to give further insight into the mysterious pseudogap phase. Previous measurements used thermocouple to measure the temperature gradient but it has large field dependence at lower temperatures, leading to unreliable estimates for determining the THE signal [3]. Here we measured thermal Hall conductivity κ_{xy} in underdoped $La_{2-x}Sr_xCuO_4$ in applied heat current along the *a*-axis and magnetic field along the *c*-axis, using Cernox thermometers which show negligible field dependence above 20 K. The observed THE shows a nonzero negative value at lower temperatures, which is consistent with the previous reports [1]. Although the field and temperature dependence looks similar, we find that its magnitude is much smaller than the previously reported values. Moreover, at high temperatures above 80 K we observed a sign change of κ_{xy}, which has not been reported in Ref. [1]. We will discuss the possible reasons for the discrepancies.

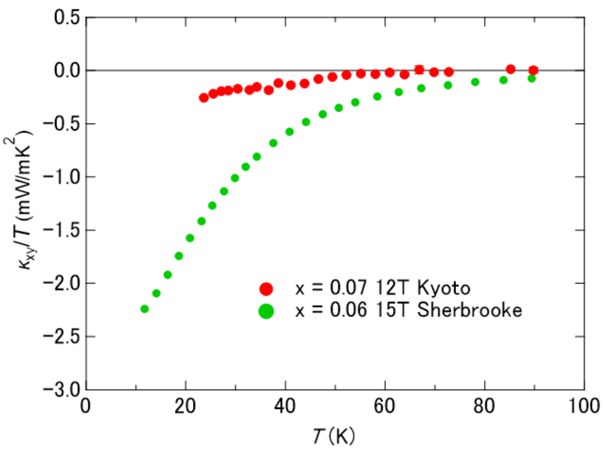

Fig. 1: Temperature dependence of the thermal Hall conductivity κ_{xy}/T in $La_{2-x}Sr_xCuO_4$. Red and green circles represent our data for $x = 0.07$ at 12 T and Sherbrooke's data for $x = 0.06$ at 15 T [1], respectively.

References

[1] G. Grissonnanche *et al.*, *Nature* **571**, 376-380 (2019).
[2] G. Grissonnanche *et al.*, *Nat. Phys.* **16**, 1108-1111 (2020).
[3]Y. Nakamura, *et al.*, *Physica C.* **185**, 1409-1410 (1991).

Mott Transition and Magnetism in a fragile topological insulator

Condensed matter theory group   Ashish Joshi

Abstract We study the effects of electronic correlations on fragile topology using dynamical mean-field theory. Discovered recently, fragile topological insulators offer Wannier obstructions that can be removed without closing the bulk gap. Here, we analyze the Mott-insulator transition due to strong correlations and show a topological phase transition to stable topology in presence of a magnetic field.

Topological insulators are characterized by a gapped bulk band structure with gapless edge states crossing the bandgap. This is known as the 'bulk-boundary correspondence'. A new type of topological insulator has been recently discovered that does not show this bulk-boundary correspondence. Dubbed as fragile topological insulators (FTIs), these insulators offer obstruction to the formation of exponentially localized Wannier functions, just like the conventional stable topological insulators do [1]. But this obstruction in FTIs can be removed by adding certain trivial degrees of freedom. For the same reason, FTIs do not host symmetry-protected flow of edge states between bulk bands but are expected to have a spectral flow between the fragile bands and other bands under certain twisted boundary conditions. Thus, showing a new form of 'twisted bulk-boundary correspondence' [2]. In this work, we study the effects of electronic correlations on the fragile topology and the twisted boundary states using dynamical mean-field theory. We analyze commonly observed effects of strong correlations, such as the Mott-insulator transition and magnetism, on a known model hosting fragile topology. We show that in the nonmagnetic case, fragile topology, along with the twisted boundary states, is stable with interactions below a critical interaction strength. Above this interaction strength, a transition to the Mott insulating phase occurs, and the twisted boundary states disappear. Furthermore, by applying a homogeneous magnetic field, the fragile topology is destroyed. However, we show that a magnetic field can induce a topological phase transition which converts a fragile topological insulator to a Chern insulator (Fig. 1, C denotes the Chern number). Finally, we study ferromagnetic solutions of the fragile topological model and find that a stable ferromagnetic phase exists at high interaction strengths which is topologically stable [3].

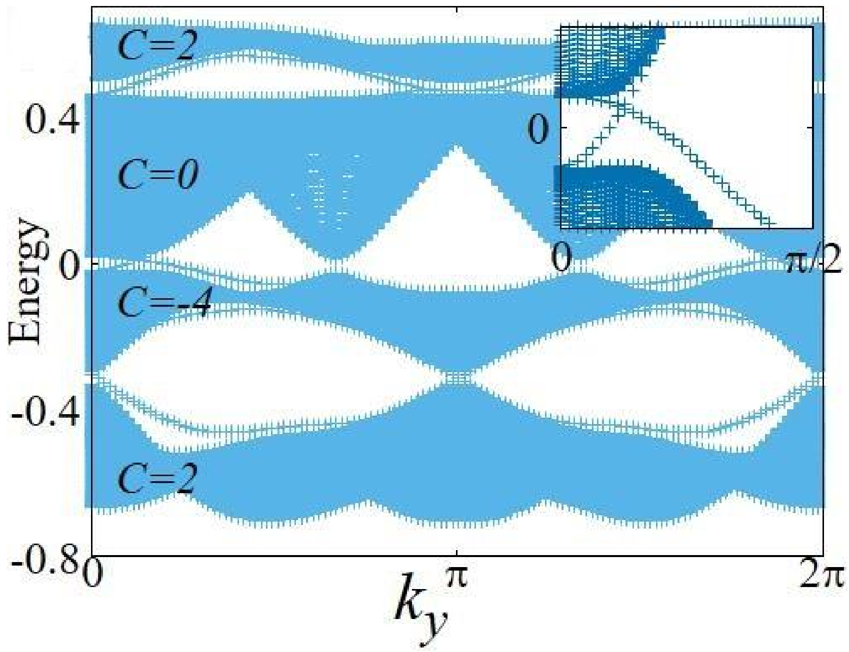

Fig 1. Band structure of our fragile topological insulator model under cylindrical boundary conditions in presence of a magnetic field. The fragile topology changes to stable topology, which results in the edge states crossing the bulk band gap. The inset shows the edge states near $k_y=0$ and C denotes the Chern number of the individual bands.

References

[1] H. C. Po, H. Watanabe, and A. Vishwanath, Physical Review Letters 121, 126402 (2018).
[2] Z.-D. Song, L. Elcoro, and B. A. Bernevig, Science 367, 794 (2020).
[3] A. Joshi and R. Peters, Physical Review B 103, 165130 (2021).

Ultrastrong coupling between phonons in halide perovskites and terahertz vacuum photons

Nanophotonics Zhenya Zhang

Abstract We demonstrate ultrastrong coupling between vacuum photons and phonons of perovskite semiconductors at the terahertz frequencies in nanometer-sized cavities. We show that the enhancement of the vacuum field in a smaller-gap split ring resonator overcomes the decrease of dipole number, resulting in the ultrastrong coupling.

When a matter is strongly coupled to the light field, a hybridized state emerges and behaves differently from the original state. As the coupling strength increases, the hybrid system reaches the regime of ultrastrong coupling (USC) which is attracting a rising attention in the field of materials science and quantum optics. In particular, the coupling of the vacuum photons to vibrational modes in molecules or phonons in solids opens up unique material engineering methods, such as modification of chemical reaction rates [1] and a novel way to induce phase transitions in solids [2]. Because stronger coupling strength is expected to lead to more drastic changes in material properties, it is necessary to understand how the coupling strength between photons and phonons can be enhanced. While the coupling strength in a cavity structure depends on the vacuum field amplitude, the dipole moment and the number of dipoles, previous studies mainly focused only on the role of dipoles. In this work, from a systematic study on the light-matter coupling in the cavities of metamaterials with different designs in the terahertz (THz) frequency region, we highlight the important role of the vacuum field strength.

Here, we demonstrate that USC between vacuum photons and phonons (oscillation of Pb-I-Pb bonds) of perovskite $CH_3NH_3PbI_3$ ($MAPbI_3$) at 0.95 THz can be realized in the nanostructured split ring resonators (SRR). In order to evaluate the coupling strength, we performed THz spectroscopy on the SRR coated with perovskite films as shown in Fig. 1. When the resonance frequency ν_p of SRR is equal to the phonon frequency ν_{TO1}, the absorption peak splits as shown in Fig. 1(b). The Rabi splitting represented by Ω_R is induced not by the incident THz field but by the coupling between vacuum photons and phonons. We find that Ω_R increases as the gap size decreases. The coupling strength defined as $\eta = \Omega_R/(2\nu_p)$ becomes 0.24 for a gap size of 100 nm, which is well in the USC regime ($\eta > 0.1$). Our analysis of the gap-size dependence shows that the enhancement of vacuum field occurs significantly at the nanometer-scale gaps and more than compensates for the reduction in the dipole number (number of Pb-I-Pb bonds) inside the cavity, thus leading to the phononic ultrastrong coupling [3].

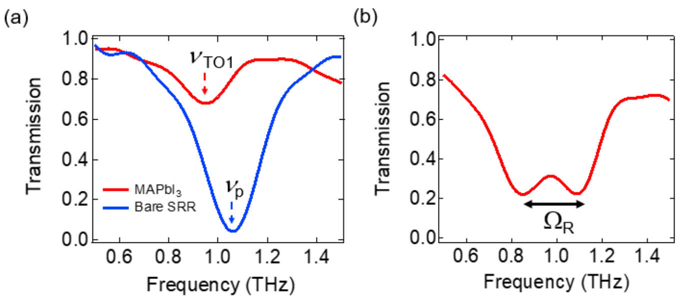

Fig. 1. Transmission spectra of the $MAPbI_3$ film and the bare SRR (a), and the coupled system (b).

References

[1] A. Thomas *et al.*, Science **363**, 615 (2019).
[2] Y. Ashida *et al.*, Phys. Rev. X **10**, 41027 (2020).
[3] Z. Y. Zhang *et al.*, under review.