Chinese Physics Letters **43**, 030710 (2026) **Perspective**

Ultrafast Condensed Matter Physics at the Horizon

Jimin Zhao(赵继民)[1,2,3*]

[1]*Beijing National Laboratory for Condensed Matter Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China*
[2]*School of Physical Sciences, University of Chinese Academy of Sciences, Beijing 100049, China*
[3]*Songshan Lake Materials Laboratory, Dongguan 523808, China*

(Received 1 December 2025; accepted manuscript online 4 February 2026)

DOI: 10.1088/0256-307X/43/3/030710 CSTR: 32039.14.0256-307X.43.3.030710

Ultrafast optical spectroscopy was successfully introduced decades ago. Its deep relationship with condensed matter physics profoundly enriched the scientific frontier of light–matter interactions. Previously, materials such as metals, insulators, semiconductors, and superconductors were investigated, followed by magnetic materials, strongly correlated materials, complex oxides, nano-materials, topological materials, and metamaterials. Marked by the light–matter interactions, the ultrafast spectroscopy of quantum materials [1–3] stands out in the development of ultrafast light sources.

The evolution of ultrafast optical spectroscopy benefitted from the cross-section of ultrafast optics and condensed matter physics. The former is the development of versatile forms of coherent and incoherent, linear and nonlinear ultrafast optics experiments, which revealed different correlated physics. The latter is the deep interplay with condensed matter physics, characterized by charge, spin, lattice, and orbital degrees of freedom, with various nonequilibrium states, elementary excitations, orderings, and fluctuations. [3]

Ultrafast optical spectroscopy developed into various forms of ultrafast spectroscopy, classified into two categories based on whether it detects photons [4] or electrons. [5] Together, these form a kaleidoscopic collection of experimental methods that can detect the nonequilibrium states of quantum materials. A shared feature of ultrafast spectroscopy is that different physical interactions have different characteristic time scales; thus, they can be distinguished and identified. Unlike conventional experimental methods that mainly detect in one degree of freedom, ultrafast spectroscopy can be used to probe couplings between different degrees of freedom. [6–10]

Figure 1 illustrates how the electron-boson coupling strength can be interpreted from ultrafast relaxation processes. Upon laser excitation, photo-excited carriers (often termed photocarriers) are promoted from the occupied valence band to conduction band states possessing energies far above the Fermi surface, as dictated by the Fermi golden rule. The photocarriers then shift to a lower-energy state within the electronic bands, obeying both energy and momentum conservation laws. They must transfer their energy to elementary excitations before they can assume lower-energy states. Such relaxation processes inevitably occur in solids, unless some metastable states are reached.

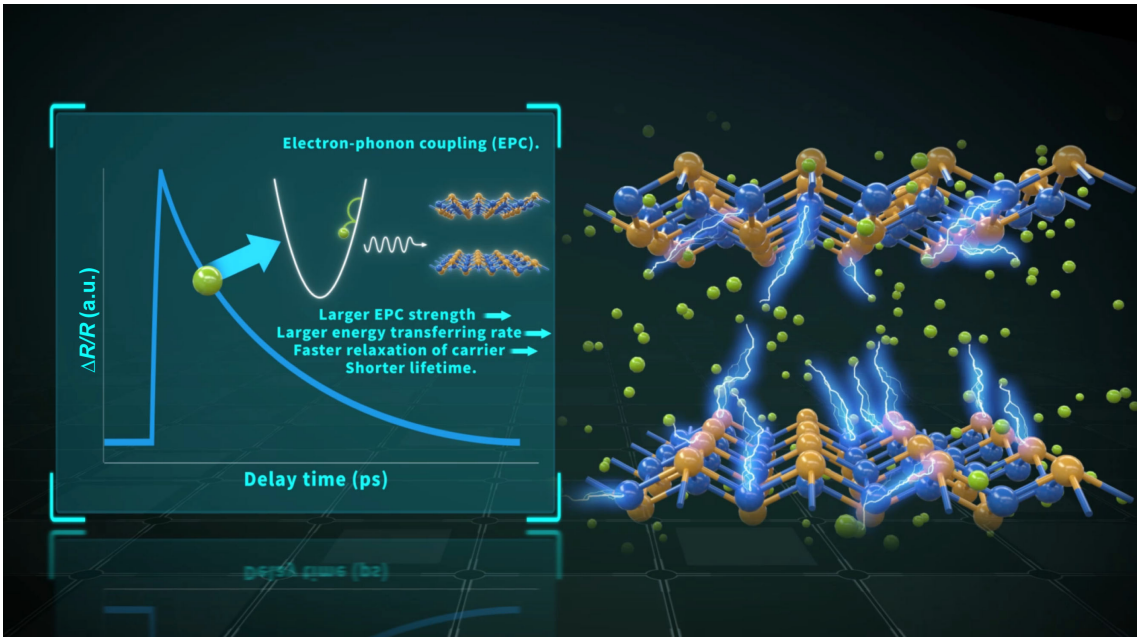

Fig. 1. Schematic illustration of detecting electron-boson coupling strength through ultrafast spectroscopy, which is usually manifested in the fast component of ultrafast relaxation. The characteristic lifetime is typically at the time scale of 1 ps, which is detected by ultrafast spectroscopy.

*Corresponding author. Email: jmzhao@iphy.ac.cn
© 2026 Chinese Physical Society and IOP Publishing Ltd. All rights, including for text and data mining, AI training, and similar technologies, are reserved.

Taking phonons as an example of bosonic elementary excitations, the stronger the electron-phonon coupling (EPC), the larger the energy transfer rate from the electrons to phonons. Thus, the faster the carrier relaxation and the shorter the lifetime. The EPC strength can be detected by measuring the lifetime. The lifetime is usually at a 1 ps time scale, which can mainly be detected by ultrafast spectroscopy. It is worth noting that the EPC is related to the fast component of ultrafast relaxation. The slow and slowest components are usually associated with other physical processes, such as phonon-phonon scattering and thermal diffusion. Figure 1 shows that it is natural and straightforward to detect the EPC using ultrafast optical spectroscopy. Through the vast efforts of experts in this field, ultrafast spectroscopy can be precise and reliable if done correctly and carefully. Its conclusions have been repeatedly verified by other experimental results and are consistent among various types of materials.

A great impetus for the development of ultrafast spectroscopy is the exploration of nonequilibrium phenomena, which paints a new backdrop for condensed matter physics. The energy-momentum space is naturally divided into three regimes: near, below, and above the Fermi surface. The space above the Fermi surface is one of the three regimes. Conventional investigations have mainly focused on the other two regimes. Thus, ultrafast spectroscopy and ultrafast dynamics investigations are very important to study the remaining unexplored part of the world.[7,11]

A direct outcome of such exploration is laser-induced novel states,[12] exhibiting unusual properties that are sometimes unavailable in equilibrium states. Such investigations also provide insights into the properties of static equilibrium states. Various laser-induced transient phase-transition-like phenomena have been reported, which have significantly enriched our understanding and control of matter states, especially in their nonequilibrium states.

The above exploration efforts usher in a new chapter in condensed matter physics—the ultrafast condensed matter physics.[13,14] A time-resolved "movie" of the microscopic world[15] offers much richer information than a time-integrated "picture", revealing the properties and uncovering the secrets of condensed matter. Hopefully, ultrafast condensed matter physics can provide some unknown physics that is unachievable or undiscernible in conventional investigations. There are several examples of this phenomenon. For instance, we have been able to experimentally detect the EPC constant through ultrafast spectroscopy, whereby conventional methods that rely on signal broadening cannot exclude the unwanted mix-up with phonon-phonon scattering (Fig. 1).[6–8,16,17] In addition, we observed the phases of optical phonons and magnons in coherent boson generation,[9,10,18–20] which is difficult to achieve by conventional means. Moreover, ultrafast light pulse-induced nontrivial transient states cannot be achieved by conventional methods.

In the future, we anticipate four pillars in the introduction of ultrafast condensed matter physics. (1) Laser-induced nonequilibrium quantum states. Laser-induced superconductivity and broken symmetry, as well as engineering of the lattices, electronic states (hidden quantum state, Floquet engineering, etc.), spins, and orbitals, all enable the unconventional control of matter. (2) Revealing the unknown ultrafast processes. The condensing process of Cooper pairs remains unknown, which hampers the understanding of superconducting pairing mechanisms of high-temperature superconductors. The same applies to excitons and polaritons. This is closely related to condensed matter physics at the attosecond regime,[14,21] which is certainly intriguing. (3) Understanding collective behaviors. Emergent physics phenomena are often associated with collective behaviors rendered by coherence, dynamics, and nonequilibrium states, which cannot be fully addressed in the conventional framework of many particle physics. (4) The search for time domain non-Abelian physical processes in the ultrafast time scale, which are otherwise undiscernible in conventional condensed matter physics. This may or may not be related to non-Hermitian processes or novel types of nonequilibrium phase transitions. The existence of non-Abelian physical processes remains an open question.

Only when we contemplate where condensed matter physics is heading and what the remaining fundamental mysteries in physics are can we realize the real essence of ultrafast condensed matter physics, explore the remaining unexplored, and uncover the ultimately covered. We believe that many new and interesting physical phenomena will arise. Ultrafast condensed matter physics is emerging at the horizon.

References

[1] Jiang L T, Jiang C Y, Tian Y C, Zhao H, Zhang J, Tian Z Y, Fu S H, Liang E J, Wang X C, Jin C Q, and Zhao J M 2024 *Chin. Phys. Lett.* **41** 047802

[2] Wang R, Ding J W, Sun F, Zhao J M, and Qiu X H 2024 *Chin. Phys. Lett.* **41** 057801

[3] Hu K, Zhu X H, Wang H L, Wei D H, and Qi J B 2025 *Chin. Phys. Lett.* **42** 057502

[4] Hasaien J Z L, Shan P F, Zhou F R, and Zhao J M 2025 *Rev. Sci. Instrum.* **96** 013004

[5] Chen W Y, Zhong H Y, Bao C H, Wang F, Cai X X, Yun C X, Teng H, Wei Z Y, and Zhou S Y 2025 *Chin. Phys. Lett.* **42** 017101

[6] Wu Q, Zhou H X, Wu Y L, Hu L L, Ni S L, Tian Y C, Sun F, Zhou F, Dong X L, Zhao Z X, and Zhao J M 2020 *Chin. Phys. Lett.* **37** 097802

[7] Wu Y L, Yu X H, Hasaien J Z L, Hong F, Shan P F, Tian Z Y, Zhai Y N, Hu J P, Cheng J G, and Zhao J M 2024 *Nat. Commun.* **15** 9683

[8] Tian Y C, Zhang W H, Li F S, Wu Y L, Wu Q, Sun F, Zhou G. Y., Wang L L, Ma X C, Xue Q K, and Zhao J M 2016 *Phys. Rev. Lett.* **116** 107001

[9] Hasaien J Z L, Wu Y L, Shi M Z, Zhai Y N, Wu Q, Liu Z, Zhou Y, Chen X H, and Zhao J M 2025 *Proc. Natl. Acad. Sci. USA* **122** e2406464122

[10] Hu L L, Yang M, Wu Y L, Wu Q, Zhao H, Sun F, Wang W, He R, He S L, Zhang H, Huang R J, Li L F, Shi Y G, and Zhao J M 2019 *Phys. Rev. B* **99** 094307

[11] Tian Y Z, Zheng Q J, and Zhao J 2023 *Chin. Phys. Lett.* **40** 126301

[12] Zhang S J, Pei Y F, Hu S Q, Wu N, Chen D Q, Lian C, and Meng S 2023 *Chin. Phys. Lett.* **40** 077502

[13] Hao W J, Zhai Y N, Dai Z J, Zhang H, and Zhao J M 2024 *Chin. Sci. Bull.* **69** 3177 (in Chinese)

[14] Hu S Q and Meng S 2023 *Chin. Phys. Lett.* **40** 117801

[15] Ji S Z, Chen L N, and Fu X W 2025 *Chin. Phys. Lett.* **42** 016101

[16] Hao W J, Gu M H, Tian Z Y, Fu S H, Meng M, Zhang H, Guo J D, and Zhao J M 2023 *Adv. Sci.* **11** 2305900

[17] Tian Z Y, Zhang Q Y, Xiao Y W, Gamage G A, Tian F, Yue S, Hadjiev V G, Bao J M, Ren Z F, Liang E J, and Zhao J M 2022 *Phys. Rev. B* **105** 174306

[18] Zhao J M, Bragas A V, Lockwood D J, and Merlin R 2004 *Phys. Rev. Lett.* **93** 107203

[19] Sun F, Wu Q, Wu Y L, Zhao H, Yi C J, Yian Y C, Liu H W, Shi Y G, Ding H, Dai X, Richard P, and Zhao J M 2017 *Phys. Rev. B* **95** 235108

[20] Zhai Y N, Gong P M, Hasaien J Z L, Zhou F R, and Zhao J M 2024 *Prog. Surf. Sci.* **99** 100761

[21] Zhao J, Liu J L, Wang X W, and Zhao Z X 2024 *Chin. Phys. Lett.* **41** 013201