Discovering ultrafast dynamics

Professor Chih Wei Luo has developed a time-resolved spectroscopic method dedicated to understanding the ultrafast dynamics of Dirac fermions. Here, he explains his research background and motivations.

How did you become interested in the field of electrophysics?

When I was an undergraduate student in the National Chiao Tung University (NCTU), I built a mode-locked titanium-sapphire laser with Professor Kaung-Hsiung Wu and then improved its specifications. Meanwhile, I also joined a high-temperature superconductor project in the Solid State Physics Lab, which was led by Professor Yi-Shun Gou.

At that time, the mechanism of high-temperature superconductivity was still unclear. Therefore, when I undertook my PhD at NCTU I thought of using time-resolved spectroscopy with femtosecond lasers to study the electron dynamics in high-temperature superconductors. I believed that this would reveal the mysteries of high-temperature superconductivity by illuminating details of the relaxation processes of quasiparticles and the recombination processes of Cooper pairs. Later, I extended my research from cuprate superconductors to other strongly correlated materials.

What is the potential of combining novel functional materials, including those that you study, and why have they gained significant scientific interest?

So-called novel functional materials – eg. 2D, multiferroic and intermetallic materials; topological crystalline insulators (TIs); topological crystalline insulators (TCIs); iron-based superconductors; and oxide heterostructures – possess rich physical characteristics and significant potential for various applications. Therefore, there is great scientific interest in studying the interplay between electron, phonon, spin and orbit in bulk or at the interfaces between dissimilar functional materials.

Could you briefly explain your study on terahertz (THz) generation from strongly correlated quantum materials and the significance of this work?

We generated THz radiation from TIs using an 800 nm femtosecond laser. Two-channel free carrier absorption with bulk and surface carriers were indispensable to the strong dependence of THz emission power on carrier concentration. Surface carriers in TIs are significantly better absorbers of THz radiation than bulk carriers at room temperature. Moreover, the characteristics of THz emission provide valuable information regarding the fundamental properties of Dirac fermions.

Why is it important to explore the Dirac fermions in TIs?

Our recent focus on 3D TIs is due to scientific interest in the new state of quantum matter and the technological potential for a new generation of THz optoelectronics, spintronics and quantum computation. For both purposes, it is important to elucidate the dynamics of the Dirac fermions in the topologically protected surface state. Some of the key issues regarding TIs have been the identification of the gapless surface electronic states and the characterisation of their fundamental properties.

Can you provide examples of any novel discoveries you have made in recent studies?

Relating to our work on ultrafast laser micromachining, due to the high peak power of femtosecond laser pulses, we fabricated periodic nanostructures and self-organised nanodots and nanolines on the surfaces of indium-tin-oxide (ITO) films. From this we have shown that ITO films with unique optical transmission properties can be fabricated using this simple method and have considerable potential in optoelectronics applications for polarising optical elements and smart window technology in visible spectroscopy.

Will you be conducting further research on ultrafast techniques in the near future?

The ultrafast technique and related research have become important, hot topics in technology and science, and they have been attracting extensive interest. Hence, we are intending to develop a fast and precise 3D ultrafast laser micromachining system with which we can fabricate microstructures with nanoparticles, dots, ripples, smaller holes and narrower line width – all with higher precision.

How is your current activity contributing to the field of electrophysics and, more broadly, to the advancement of electronics?

Using the results of the ultrafast dynamics studies on TIs – including the dynamic parameters we found and their dependence on extrinsic parameters, such as doping level and TI preparation conditions – we can describe and predict the high-speed properties of Dirac fermion devices at various conditions. Moreover, surface carriers in TIs are significantly better absorbers of THz radiation than bulk carriers at room temperature. Thus, we have demonstrated that TIs would be good candidates for THz sensors. Very recently, our studies in 2D materials of monolayer molybdenum disulphide show that spin valley coupled polarisation provides a promising way to build ultrafast valleytronics at room temperature.
**A strong correlation**

The mechanisms driving the unique properties of strongly correlated materials remain elusive. A team at the National Chiao Tung University in Taiwan, Republic of China are examining carrier, phonon and spin dynamics to discover their contribution to these materials’ properties.

**THE STRONGLY CORRELATED materials field** – which focuses on 2D materials such as graphene, multiferroics and topological insulators with peculiar electronic and magnetic properties – is booming, and scientists are proposing many potential applications. However, there is a definite need for a clearer understanding of the quantum events underlying these properties, including how Dirac fermions, the charge carriers in gapless electronic states, function. Comprehending charge carrier behaviour will be essential to determining the performance of ultrafast devices containing these strongly correlated materials. However, new methods are required to measure such subtle events.

**FEMTOSECOND TIME-RESOLVED SPECTROSCOPY**

Pioneering a pump-probe method, Professor Chih Wei Luo leads a research group at the National Chiao Tung University in Taiwan, Republic of China, aiming to unveil the fundamental agents responsible for the characteristics of strongly correlated materials. Luo uses femtosecond lasers to study these fascinating materials; employing an 800 nm wavelength femtosecond titanium-sapphire laser pump, he observes the response of the material by detecting emissions in the terahertz (THz) frequency range, as a broadband infrared probe. THz radiation is an understudied and relatively unexploited frequency range that lies between the infrared and microwave portions of the electromagnetic spectrum.

More traditional methods used to observe massive and massless fermions only indirectly detect their electronic structure; however, with Luo’s innovative spectroscopy systems, these fermions can be discerned in the time domain due to the nature of the THz waves being detected. Additionally, Luo’s technique allows the fermion-phonon coupling strength to be observed in the Dirac cone – a representation of the dispersion of the material’s electronic band structure. Taken together, the novel capabilities of Luo’s method provide a new layer of understanding regarding the underlying processes in strongly correlated materials.

**TOPOLOGICAL INSULATORS**

One particular success story for the research group has been the study of 3D topological insulators (TIs). They are made up of a bulk insulating component and charge carriers that behave like Dirac fermions on a metallic-like surface with a zero bandgap that enables charge carriers to move more easily, making them highly conductive.

Previous to Luo’s studies, research had identified Dirac fermions in some TIs using angle-resolved photoemission spectroscopy (ARPES) and scanning tunnelling microscopy (STM). However, Luo’s pump-probe method is set to be more sensitive in characterising the charge carriers. “The experimental data are then analysed by fitting them to a model and extracting the fundamental dynamical parameters, such as various carrier relaxation and recombination rates, which characterise various processes,” Luo explains.

After analysing the Dirac fermions in Bi$_2$Se$_3$ and copper-doped Bi$_2$Se$_3$ single crystals, Luo and his team made three main observations.
Specifically, physicists are interested in the relationship between superconductivity and temperature. This is intriguing due to their unusual relationship and how they contribute to strongly correlated materials. To solid-state physicists, iron (Fe)-based superconductors are particularly important in conferring superconductivity to the material at low temperatures. The group further observed that the actual, measured electron-phonon coupling constant, λ, was 0.16, equal to the theorised constant. “Such a small λ demonstrates an unconventional origin of superconductivity in FeSe,” Luo states. “Our results provide vital understanding of the competing picture between spin fluctuations and superconductivity, and the role of phonons in Fe-based superconductors.”

**DIRAC FERMIONS NEAR THE DIRAC POINT IN TOPOLLOGICAL INSULATORS**

**OBJECTIVES**

- To understand the ultrafast dynamics of Dirac fermions
- To examine carrier, phonon and spin dynamics to discover how they contribute to strongly correlated materials

**KEY COLLABORATORS**

Professor Kaung-Hsiung Wu; Professor Jenh-Yih Juang; Professor Atsushi Yabushita; Professor Jiunn-Yuan Lin; Professor Ying-Hao Chu, National Chiao Tung University (NCTU), Republic of China

Professor Takayoshi Kobayashi, University of Electro-Communications, Japan

Professor Alexander Nikolaevich Vasiliev, Moscow State University, Russia

Professor Yury Andreev, Russian Academy of Sciences

**FUNDING**

Ministry of Science and Technology, Taiwan, Republic of China

Grant Ministry of Education ATU Program at NCTU, Republic of China

**CONTACT**

Professor Chih Wei Luo
Group Leader
Department of Electrophysics
National Chiao Tung University
1001 Ta Hsueh Road, Hsinchu City
Taiwan, 30010
Republic of China

T +886 3571 2121 ext 56196
F +886 3572 5230
cwluo@g2.nctu.edu.tw

**INTENSITY**

**A FAIRER PROSPECT FOR IRON-BASED SUPERCONDUCTORS**

Superconductors – materials that exhibit extremely high conductivities with zero resistance at low temperatures – are also a field of interest not only to Luo, but to other researchers and commercial partners alike. To solid-state physicists, iron (Fe)-based superconductors are particularly intriguing due to their unusual relationship with superconductivity and temperature. Specifically, physicists are interested in the superconductors’ critical temperature (Tc) – the temperature at which the material actually becomes superconducting. Improved knowledge of quasiparticle dynamics in Fe-based superconductors is necessary and could be invaluable to understanding their high-Tc properties, a useful characteristic for allowing superconductors to be utilised in everyday applications.

“In our experiments with superconductors, we used time-resolved femtosecond spectroscopy to study FeSe and tellurium-doped FeSe single crystals to elucidate the ultrafast quasiparticle dynamics and phonon softening,” Luo describes. He also analysed quasiparticle by recording the transient reflectivity of the probe laser beam on the sample, and he used the probe beam to detect the phonon relaxation process. From its experiments, Luo’s group deduced that a structure phase transition at 90 K (-183 °C) occurs as well as a previously unknown feature of the phase diagram at 230 K (-43 °C). Both of these parameters may be important in conferring superconductivity to the material at low temperatures. The group further observed that the actual, measured electron-phonon coupling constant, λ, was 0.16, equal to the theorised constant. “Such a small λ demonstrates an unconventional origin of superconductivity in FeSe,” Luo states. “Our results provide vital understanding of the competing picture between spin fluctuations and superconductivity, and the role of phonons in Fe-based superconductors.”

**MICROMACHINING AND MORE**

By studying the ultrafast dynamics of strongly correlated materials to understand fundamental events underlying their unique properties, Luo is contributing to the body of information that will inform new technologies. He is expanding his work on TIs and superconductors to 2D materials, such as MoS2, and he is developing 3D ultrafast micromachining systems. molybdenum disulphide is of particular interest as it switches between two types of semiconductors – a direct and indirect band gap – depending on whether it is in monolayer or 3D form, respectively.

Another area of study that interests Luo is multiferroic materials, as they hold great promise and are being explored for application in oxide electronic, spintronic and green energy device technologies. However, the interactions between photons and multiferroics are little understood, such as the mechanism of how light can cause electronic excitations.

Many of these quantum phenomena can be explored using Luo’s pump-probe and similar time-resolved techniques, illustrating the flexibility and versatility of the method. Potentially, understanding ultrafast particle and quasiparticle dynamics will help the realisation and optimisation of the proposed applications of these extraordinary correlated materials.