Physics near you: wonder and challenge in crystals

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When you hear the word “physics”, especially “modern physics”, what comes to your mind? If you are an ambitious student who loves to visit scientific museums or watch Discovery Channel, you might be thinking about the theory of relativity (with the face of Einstein sticking out his tongue), the Big Bang, or those gigantic accelerators built to investigate ultimately small particles. Yes, modern physicists do study these things (high-energy physics). They, the universe and the elementary particles, are extremes in this world that are either too big or too small for us to directly see in our daily lives.

However, there is another large field of physics residing in the intermediate region — solid-state physics. Solid-state physicists study crystals. Crystals are all around us. You can find them on the dining table (the particles of salt are crystals), in the kitchen (metals are crystals), and inside your smartphones (they are full of semiconductors, which are also crystals). Despite their commonness, crystals show various unique properties which are the manifestations of nontrivial physics. Indeed, phenomena in crystals can be as bizarre as those in high-energy physics. For instance, inside crystals electrons can no longer be viewed as particles (like sand particles moving across a desert), but rather behave as spatially spreading waves (like ripples in the ocean). The interference between those electron waves drastically changes their mobilities: sometimes they even behave as if they have no mass, or an infinite mass!

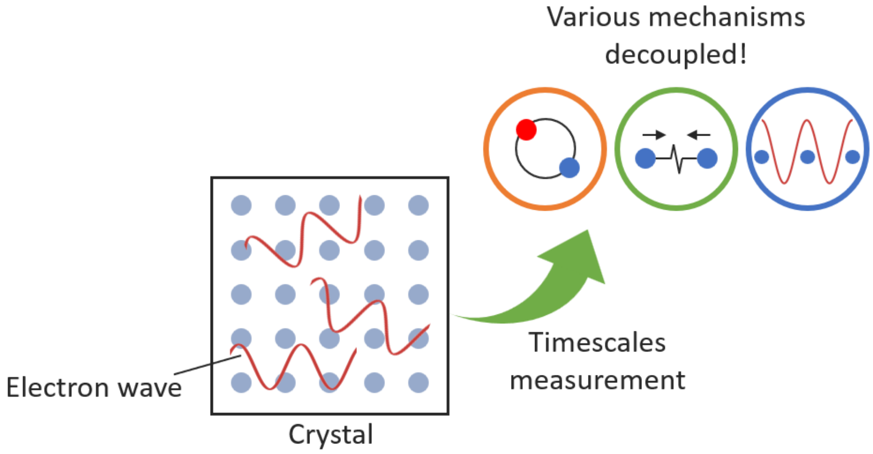
As a youngster, I have always been fascinated by scientific stories about stars, the universe, and the unusual laws governing ultimately small things. Imagine how it shocked me to know that all the strange physics far beyond our intuition is going on inside crystals, things we can easily touch. That striking notion was exactly what made me decide to specialize in solid-state physics. Besides, since the scale of crystals is close to that of our daily lives, their diverse features can lead to the development of various devices with novel functionalities. This close relationship to social implementations is another attractiveness of studying solid-state physics.

One of the biggest troubles we encounter when we study crystals is their complexity. The number of electrons and atomic nuclei contained in crystals is on the order of 10^23, and they interact with each other in various ways. (Here is to help you understand how large the number is: if you spread 10^23 grains of rice all over the surface of the Earth, you can still create a layer that is 3m thick!) To make matters worse, defects in crystals that are virtually inevitable upon synthesis can influence their properties as well. When physicists are confronted with such problems, they try to establish good approximations and construct models capturing the essence of the phenomena. This approach also helps the search for new functional materials by revealing conditions that must be satisfied. Still, with the intricacy of crystals and so many potentially relevant mechanisms, it often becomes a topic of active debate what to be included or ignored to provide simple yet effective explanations.

To be so bold, the goal of my research is to scare theorists by establishing methods to test the validity of models they propose. Of course, if we can directly control all the possible factors, solving the puzzles would be quite easy. Nevertheless, things are much messier in real systems. Although we can straightforwardly modify some parameters if we are lucky enough, (e.g., we can use strain to control crystal structures in some materials), in most cases different mechanisms are entangled with each other in a complicated way. This makes it impossible to independently assess the influence of one target component.

Given the lack of the universal “tuning knobs” that can solve all the mysteries at once, I am aiming to use a technique called terahertz time-domain spectroscopy (THz-TDS), in which we use laser pulses to investigate crystals. Most importantly, THz-TDS can track how the state of the crystal varies with time. This provides us a very strong clue for determining what is going on inside the crystals, for any physical mechanisms have their own unique timescales. To capture the essence of this idea, suppose you saw a man go into a movie theater and come back in 10 minutes. You can easily infer that he did not watch anything there, for 10 minutes is far too short for a movie. In other words, the time the man spent in the theater is not consistent with typical timescale of watching a movie (which is 1-2 hours), and you used that fact as a clue to guess what he did in the theater without directly observing it. This is how the measurement of timescales works, and fortunately, most physical phenomena can be naturally and distinctly separated by timescales. Therefore, THz-TDS can be used to decouple different physical processes involved, providing a powerful way to exclude invalid models and put an end to debates about underlying mechanisms.

I am now working on a project to study electronic responses of crystals made up of light elements, using THz-TDS. Because heavy elements like rare-earth metals have limited reserves and tend to harm environment when disposed, exploration of the functionalities of light elements is crucial to developing sustainable devices. Also, light elements contain smaller number of electrons and therefore are still less complicated than heavy elements, allowing theorists and experimentalists actively work together to investigate the properties. This boosts the search for new systems suitable for social implementations, such as highly efficient energy generators or robust and fast computer circuits. I believe my research revealing timescales of phenomena in crystals will contribute to better understanding of which mechanism describes the physics best, or how different processes interfere with each other. The findings may lead to the discovery of novel physical phenomena that have profound impact on the sustainability of our technologies, as well as the construction of well-founded theoretical understanding of them.



Upon writing this essay, I used Microsoft Copilot to correct grammatical errors.