

Classifying quantum secrets: Pendulum experiment reveals insights into topological materials

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Chaviva Sirote-Katz checking the system. Credit: Tel Aviv University

A recent study conducted at Tel Aviv University has devised a large mechanical system that operates under dynamical rules akin to those

found in quantum systems. The dynamics of quantum systems, composed of microscopic particles like atoms or electrons, are notoriously difficult, if not impossible, to observe directly.

However, this new system allows researchers to visualize [phenomena](#) occurring in specialized "topological" materials through the movement of a system of coupled pendula.

The research is a collaboration between Dr. Izhar Neder of the Soreq Nuclear Research Center, Chaviva Sirote-Katz of the Department of Biomedical Engineering, Dr. Meital Geva and Prof. Yair Shokef of the School of Mechanical Engineering, and Prof. Yoav Lahini and Prof. Roni Ilan of the School of Physics and Astronomy at Tel Aviv University and was recently published in the [Proceedings of the National Academy of Sciences](#).

Quantum mechanics governs the microscopic world of electrons, atoms, and molecules. An electron, which is a particle that moves in an atom or in a solid, may have properties that give rise to wave-like phenomena. For instance, it may demonstrate a probability of dispersing in space similar to waves spreading out in a pool after a stone is thrown in or the capability to exist simultaneously in more than one place.

Such wave-like properties lead to a unique phenomenon that appears in some solid isolators, where even though there is no [electric current](#) through them, and the electrons do not move due to an external electric voltage, the internal arrangement of the material shows up in a state referred to as "topological."

This means that the wave of electrons possesses a quantity that can "close on itself" in different ways, somewhat like the difference between a cylinder and a Möbius strip. This "topological" state of the electrons, for which the 2016 Nobel Prize in Physics was awarded, is considered a

new state of matter and attracts much current research.

Despite the theoretical interest, there is a limitation in measuring these phenomena in [quantum systems](#). Due to the nature of quantum mechanics, one cannot directly measure the electron's wave function and its dynamical evolution. Instead, researchers indirectly measure the wave-like and topological properties of electrons in materials, for instance, by measuring the electrical conductivity at the edges of solids.

In the current study, the researchers considered the possibility of constructing a sufficiently large mechanical system that would adhere to dynamical rules akin to those found in quantum systems and in which they could directly measure everything. To this end, they built an array of 50 pendula, with string lengths that slightly varied from one pendulum to the other. The strings of each neighboring pair of pendula were connected at a controlled height, such that each one's motion would affect its neighbors' motion.

On the one hand, the system obeyed Newton's laws of motion, which govern the physics of our everyday lives, but the precise lengths of the pendula and the connections between them created a magical phenomenon: Newton's laws caused the wave of the pendula's motion to approximately obey Schrödinger's equation—the fundamental equation of quantum mechanics, which governs the motion of electrons in atoms and in solids. Therefore, the motion of the pendula, which is visible in the macroscopic world, reproduces the behaviors of electrons in periodic systems such as crystals.

The researchers pushed a few pendula and then released them. This generated a wave that propagated freely along the chain of pendula, and the researchers could directly measure the evolution of this wave—an impossible mission for the motion of electrons. This enabled the direct measurement of three phenomena.

The first phenomenon, known as Bloch oscillations, occurs when electrons within a crystal are influenced by an electric voltage, pulling them in a specific direction. In contrast to what one would expect, the electrons do not simply move along the direction of the field, but they oscillate back and forth due to the periodic structure of the crystal.

This phenomenon is predicted to appear in ultra-clean solids, which are very hard to find in nature. In the pendula system, the wave periodically moved back and forth, exactly according to Bloch's prediction.

The second phenomenon that was directly measured in the pendula system is called Zener tunneling. Tunneling is a unique quantum phenomenon that allows particles to pass through barriers, in contrast to classical intuition. For Zener tunneling, this appears as the splitting of a wave, the two parts of which then move in opposite directions. One part of the wave returns as in Bloch oscillations, while the other part "tunnels" through a forbidden state and proceeds in its propagation.

This splitting, and specifically its connection to the motion of the wave in either direction, is a clear characteristic of the Schrödinger equation. In fact, such a phenomenon is what disturbed Schrödinger, and is the main reason for the suggestion of his famous paradox; according to Schrödinger's equation, the wave of an entire cat can split between a live-cat state and a dead-cat state.

The researchers analyzed the pendula motion and extracted the parameters of the dynamics, for instance, the ratio between the amplitudes of the two parts of the split wave, which is equivalent to the quantum Zener tunneling probability. The experimental results showed fantastic agreement with the predictions of Schrödinger's equation.

The pendula system is governed by classical physics. Therefore, it cannot mimic the full richness of quantum systems. For instance, in quantum

systems, the measurement can influence the system's behavior (and cause Schrödinger's cat to be dead or alive when it is viewed eventually).

In the classical system of macroscopic pendula, there is no counterpart to this phenomenon. However, even with these limitations, the pendula array allows the observation of interesting and non-trivial properties of quantum systems, which may not be directly measured in the latter.

The third phenomenon that was directly observed in the pendula experiment was the wave evolution in a topological medium. Here, the researchers found a way to directly measure the topological characteristic from the wave dynamics in the system—a task that is almost impossible in quantum materials. To this end, the pendula array was tuned twice so that they would mimic Schrödinger's equation of the electrons, once in a topological state and once in a trivial (i.e., standard) state.

The researchers could classify the two states by comparing small differences in the pendular motion between the two experiments. The classification required a very delicate measurement of a difference between the two experiments of exactly half a period of oscillation of a single pendulum after 400 full oscillations that lasted 12 minutes. This small difference was found to be consistent with the theoretical prediction.

The experiment opens the door to realizing further situations that are even more interesting and complex, like the effects of noise and impurities or how energy leakage affects wave dynamics in Schrödinger's equation. These are effects that can be easily realized and seen in this system, by deliberately perturbing the pendula motion in a controlled manner.

More information: Izhar Neder et al, Bloch oscillations,

Landau–Zener transition, and topological phase evolution in an array of coupled pendula, *Proceedings of the National Academy of Sciences* (2024). [DOI: 10.1073/pnas.2310715121](https://doi.org/10.1073/pnas.2310715121)

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