Greetings from the fourth dimension: Scientists glimpse 4D crystal structure using surface wave patterns

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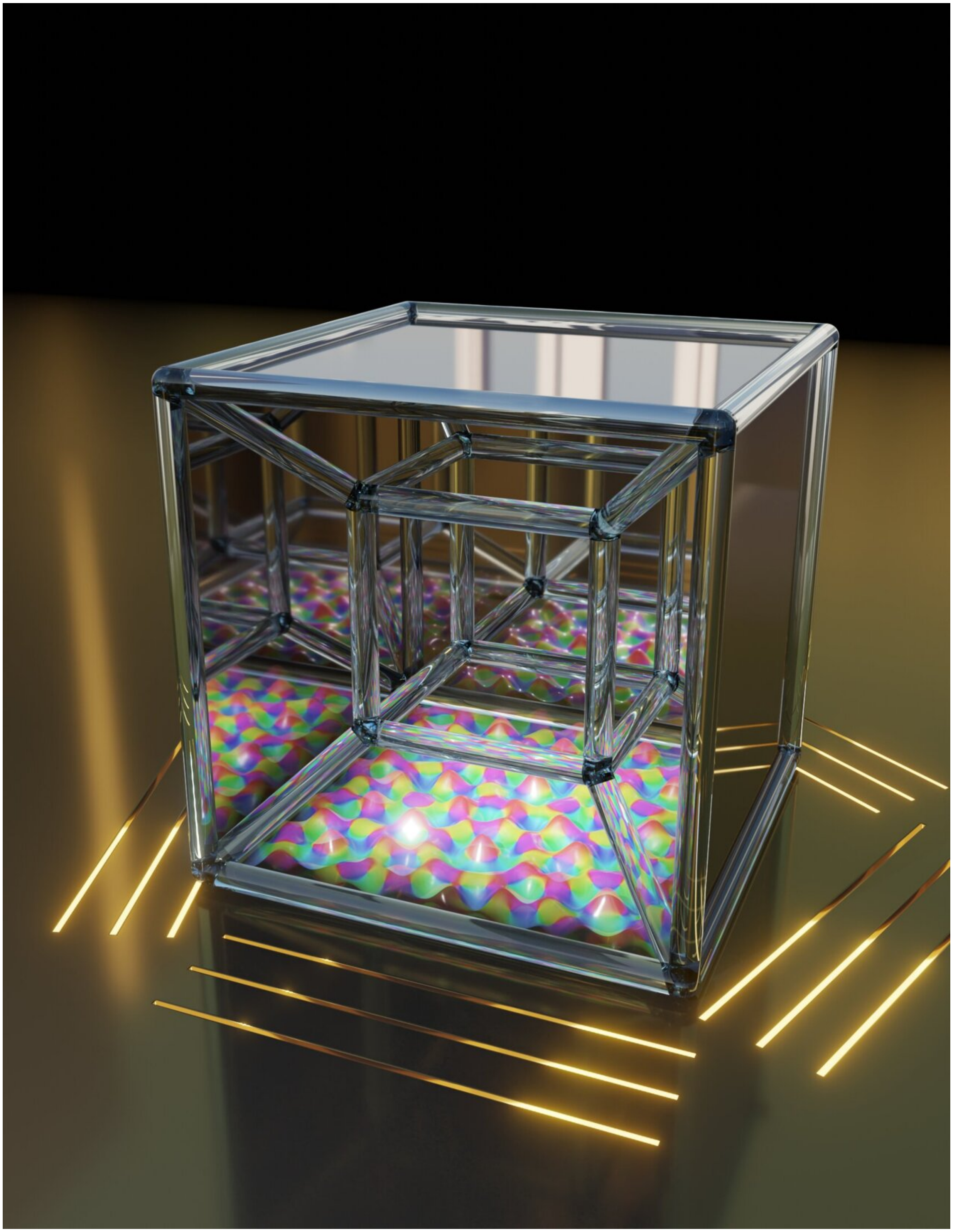

In the illustration: A tesseract (a four-dimensional cube) and the "shadow" it casts on a plane—the quasicrystal discovered by Shechtman. According to Prof. Bartal, "The fact that a quasicrystal is a 'shadow' of a periodic crystal in a higher dimension is not new in itself. What we discovered is that the projection includes not only the structure but also topological properties such as vortices."). Credit: Florian Sterl, Sterltech Optics

In April 1982, Prof. Dan Shechtman of the Technion–Israel Institute of Technology made the discovery that would later earn him the 2011 Nobel Prize in Chemistry: the quasiperiodic crystal. According to diffraction measurements made with an electron microscope, the new material appeared "disorganized" at smaller scales, yet with a distinct order and symmetry apparent at a larger scale.

This form of matter was considered impossible, and it took many years to convince the scientific community of the discovery's validity. The first physicists to theoretically explain this discovery were Prof. Dov Levine, then a doctoral student at the University of Pennsylvania and now a faculty member in the Technion Physics department, and his advisor, Prof. Paul Steinhardt.

The key insight that enabled their explanation was that quasicrystals were, in fact, periodic—but in a higher dimension than the one in which they exist physically. Using this realization, the physicists were able to describe and predict mechanical and thermodynamic properties of quasicrystals.

The concept of higher spatial dimension extends our familiar three-dimensional space—length, width, and height—by introducing additional directions which are perpendicular to all three. This is difficult to visualize, as we can only perceive the world around us as a three-dimensional space, and even more challenging to measure. An example of a four-dimensional object is the tesseract, also known as hypercube.

Just as a cube consists of six square facets, a tesseract comprises eight cubic cells. Although we cannot fully visualize a tesseract, we can represent it through its projections, much like looking at the shadow of a three-dimensional cube on a two-dimensional piece of paper.

In a new study published in *Science*, researchers from the Technion, together with the University of Stuttgart and University of Duisburg-Essen in Germany, shed new light on this phenomenon. In their study, led by Prof. Guy Bartal and Dr. Shai Tsesses from the Andrew and Erna Viterbi Faculty of Electrical and Computer Engineering, Prof. Harald Giessen from the University of Stuttgart, and Prof. Frank Meyer zu Heringdorf from the University of Duisburg-Essen, the research group demonstrated that not only do the higher dimensional crystals dictate the mechanical properties of quasiperiodic crystals, they also determine their topological properties.

Topology is a branch of mathematics that investigates the geometric properties that remain unchanged under continuous deformations. The topology of higher-dimensional spaces focuses on the properties of objects in more than three dimensions and can assist researchers, for example, in studying the structure of the universe and developing quantum computing algorithms.

The researchers examined quasiperiodic interference patterns of electromagnetic surface waves and discovered, to their surprise, that although the patterns appeared different, their topological properties in two dimensions could not be used to differentiate between them. They found the only way to distinguish between the patterns was by referring to an "original" higher-dimensional crystal.

This understanding agrees with the explanation given by Levine and

Steinhardt, which was based on an earlier discovery by British mathematician, Sir Roger Penrose (2020 Nobel Prize laureate in Physics) and later conveyed by Nicolaas de Bruijn.

The researchers also discovered another intriguing phenomenon: Two different topological patterns of surface waves appeared identical when measured after a specific time interval. This interval was extremely short, measured in attoseconds—a billionth of a billionth of a second. The original theory by Levine and Steinhardt again explains this phenomenon as a "competition" between the topological and thermodynamic (energetic) properties of the crystals.

The findings were achieved using two methods: near-field scanning optical microscopy conducted in Prof. Guy Bartal's lab by Dr. Kobi Cohen and two-photon photoemission electron microscopy, measured in collaboration between the University of Stuttgart and the University of Duisburg-Essen in Germany. The discoveries reported in the manuscript pave the way for new methods to measure the thermodynamic properties of quasiperiodic crystals.

In the near future, the researchers plan to expand their findings to other physical systems and examine more deeply the interplay between thermodynamic and topological properties. Potentially, the unique higher-dimensional topological properties of quasicrystals could be used in the future to represent, encode, and transfer information.

More information: Shai Tsesses et al, Four-dimensional conserved topological charge vectors in plasmonic quasicrystals, *Science* (2025). DOI: 10.1126/science.adt2495

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