'Exceptional points' give rise to counterintuitive physical effects

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No matter whether it is acoustic waves, quantum matter waves or optical waves of a laser—all kinds of waves can be in different states of oscillation, corresponding to different frequencies. Calculating these frequencies is part of the tools of the trade in theoretical physics. Recently, however, a special class of systems has caught the attention of the scientific community, forcing physicists to abandon well-established rules.

When waves are able to absorb or release energy, so-called "exceptional points" occur, around which the waves show quite peculiar behaviour: lasers switch on, even though energy is taken away from them, light is being emitted only in one particular direction, and waves which are strongly jumbled emerge from the muddle in an orderly, well-defined state. Rather than just approaching such an exceptional point, a team of researchers at TU Wien (Vienna, Austria) together with colleagues in Brazil, France, and Israel now managed to steer a system around this point, with remarkable results that have now been published in the journal *Nature*.

Waves with Complex Frequencies

"Usually, the characteristic frequencies of waves in a particular system depend on several different parameters", says Professor Stefan Rotter (Institute for Theoretical Physics, TU Wien). The frequencies of microwaves in a metal container are determined by the size and by the shape of the container. These parameters can be changed, so that the frequencies of waves are changing as well.

"The situation becomes much more complicated, if the system can absorb or release energy", says Rotter. "In this case, our equations yield complex frequencies, in much the same way as in mathematics, when complex values emerge from the square root of a negative number." At first glance, this may look like a mere technicality, but in recent years new experimental findings have shown that these "complex frequencies" have indeed important physical applications.

Microwaves in a Metal Box

The strange characteristics of these complex frequencies become most apparent when the system approaches an "exceptional point". "Exceptional points occur, when the shape and the absorption of a system can be tuned in such a way that two different waves can meet at one specific complex frequency", Rotter explains. "At this exceptional point the waves not only share the same frequency and absorption rate, but also their spatial structure is the same. One may thus really interpret this as two wave states merging into a single one at the exceptional point."

Whenever such exceptional points show up in a system, curious effects can be observed: "We send two different wave modes through a wave guide that is tailored not only to approach the exceptional point, but actually to steer the waves around it", says Jörg Doppler, the first author of the study. No matter which one of the two possible modes is coupled into the system - at the output, always the same mode emerges. When waves are coupled into the waveguide from the opposite direction, the other mode is favoured. "It is like driving a car into an icy two-lane tunnel, in which one slides around wildly, but from which one always comes out on the correct side of the road", says Doppler.

In order to test the theoretical models, Stefan Rotter and his group teamed up with researchers in France working on microwave structures, i.e., hollow metal boxes through which electromagnetic waves are sent to study their behaviour. To produce the strange wave behaviour near an exceptional point the waveguides need to follow very special design rules, which were devised at TU Wien with support from Alexei Mailybaev from IMPA (Brazil). The experiments were carried out in the group of Ulrich Kuhl at the University of Nice, where the predicted behaviour could now indeed be observed.

New Frontiers in Wave Physics

Systems with exceptional points open up an entirely new class of possibilities for controlling waves. "Just like complex numbers have brought us new possibilities in mathematics, complex exceptional points give us new ideas for the physics of waves", says Rotter. Indeed, several research groups all over the world are currently working on exceptional points: in the same issue of Nature magazine, in which the above results are published, a team from Yale University (USA) also presents results on exceptional points in opto-mechanics. "I am sure that we will soon hear a lot more about exceptional points in many different areas of physics", says Stefan Rotter.

More information: Jörg Doppler et al, Dynamically encircling an exceptional point for asymmetric mode switching, *Nature* (2016). DOI: 10.1038/nature18605

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