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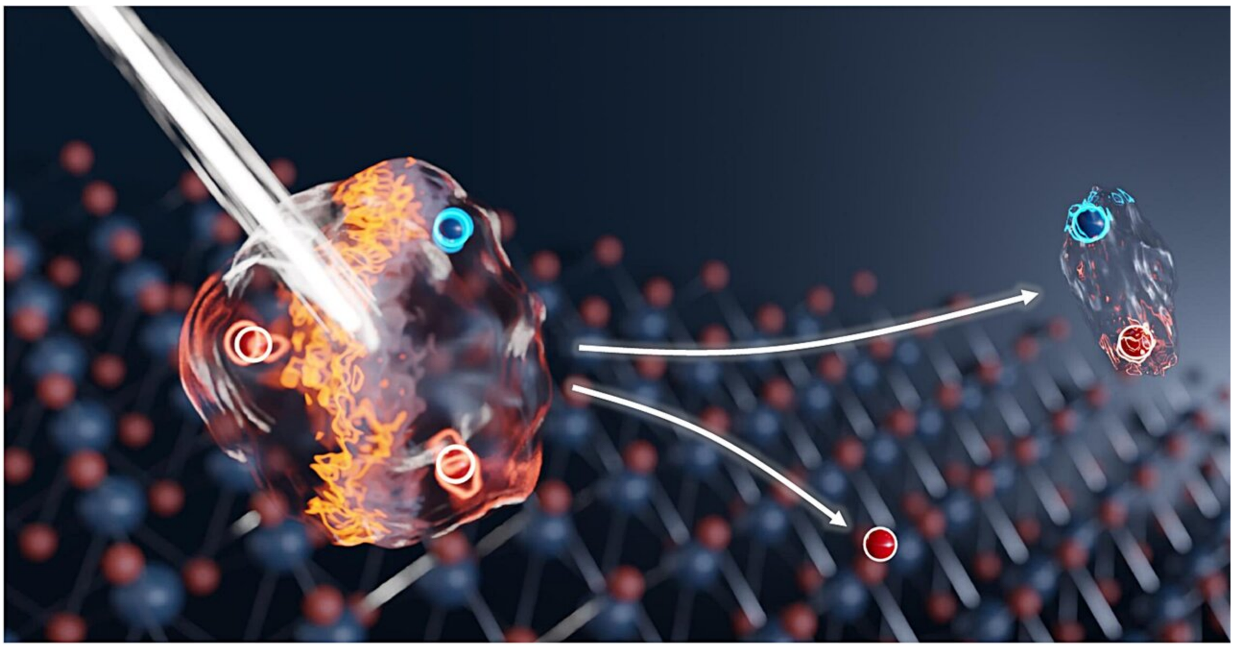
# Research team succeeds in ultra-fast switching of tiny light sources

September 27 2024



A strong light pulse in the terahertz range separates charged luminous trions into individual electrons and neutral excitons. Credit: Giuseppe Meneghini

Extremely thin materials consisting of just a few atomic layers promise applications for electronics and quantum technologies. An international team led by TU Dresden has now made remarkable progress with an experiment conducted at Helmholtz-Zentrum Dresden-Rossendorf (HZDR): The experts were able to induce an extremely fast switching process between electrically neutral and charged luminescent particles in an ultra-thin, effectively two-dimensional material.

The result opens up new perspectives for research as well as for optical data processing and flexible detectors. The research is presented in the journal *Nature Photonics*.

Two-dimensional semiconductors can exhibit fundamentally different properties compared to more conventional bulk crystals. In particular, it is easier to generate so-called exciton particles: If an electron, known to be negatively charged, is excited in the material by absorbing energy, it is removed from its original position. It leaves behind a mobile charge—a positively charged "hole."

Electrons and holes attract each other and form together a bound state called an exciton, a kind of electronic pair. If another electron is nearby, it is pulled towards it to form a three-particle state—known as a trion in scientific jargon. The special feature of the trion is the combination of electrical charge with strong light emission, which allows simultaneous electronic and optical control.

For quite some time, the interplay between exciton and trion has been considered as a switching process that is both intriguing in itself and could also be of interest for future applications. In fact, many laboratories have already succeeded in switching between the two states in a targeted manner—but so far with limited switching speeds.

The study was led by Prof. Alexey Chernikov from TU Dresden and HZDR physicist Dr. Stephan Winnerl has now been able to significantly accelerate this switching. The work was conducted within the frame of the Würzburg-Dresden Cluster of Excellence "Complexity and Topology in Quantum Materials, ct.qmat." Researchers from Marburg, Rome, Stockholm and Tsukuba provided important contributions to the project.

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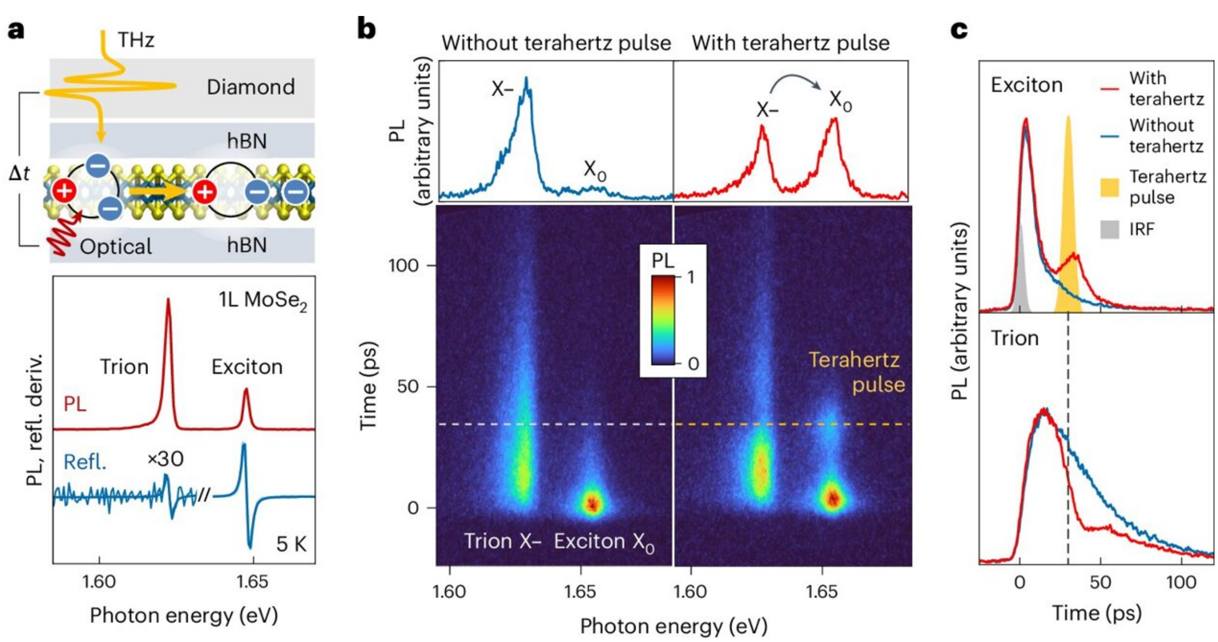
## First catch, then separation

The experiments took place using a special facility at the HZDR. The FELBE free-electron laser delivers intense terahertz pulses—a frequency range that lies between radio waves and near-infrared radiation. The researchers first illuminated an atomically-thin layer of molybdenum diselenide at cryogenic temperatures with short laser pulses, generating the excitons. As soon as they were created, each exciton captured an electron from those already present in sufficient numbers in the material, and thus became trions.

"When we then shot terahertz pulses at the material, the trions formed back into excitons extremely quickly," explains Winnerl. "We were able to show it because excitons and trions emitted near-infrared radiation at different wavelengths."




Impact of strong terahertz radiation on the exciton–electron complexes in monolayer $MoSe_2$. Credit: *Nature Photonics* (2024). DOI:

10.1038/s41566-024-01512-0

The decisive factor in the experiment was the matching frequency of the terahertz pulses to break the weak bond between the exciton and electron—hence a pair consisting of just one electron and one hole was recreated again. Soon afterwards, this exciton captures another electron and becomes a trion again.

The separation into excitons took place at record speed. The bond was broken within a few picoseconds—trillionths of a second. "This is almost a thousand times faster than previously possible with purely electronic methods and can be generated on demand with terahertz radiation," emphasizes TU scientist Chernikov.

The new method offers interesting prospects for research. The next step could be to extend the demonstrated processes to a variety of complex electronic states and material platforms. Unusual quantum states of matter, which arise from the strong interaction between many particles, would thus come within reach, as would applications at room temperature.

## Prospects for data processing and sensor technology

The results could also become useful for future applications, for example in sensor technology or optical data processing.

"It would be conceivable to adapt the effect for new types of modulators with rapid switching," explains Winnerl. "In combination with the ultra-thin crystals, this could be used to develop components that are both extremely compact and capable of electronically controlling optically encoded information."

Another field would be applications in the detection and imaging of technologically relevant terahertz radiation.

"Based on the demonstrated switching processes in atomically thin semiconductors, it may be possible in the long term to develop detectors that work in the terahertz range, are adjustable in a wide frequency range, and could be realized as terahertz cameras featuring a large number of pixels," suggests Chernikov. "In principle, even a comparatively low intensity should be sufficient to trigger the switching process."

Converting trions to excitons leads to characteristic changes in the emitted near-infrared light wavelength. Detecting this and converting it into images would be fairly straightforward and could be achieved using already existing state-of-the-art technology.

**More information:** Tommaso Venanzi et al, Ultrafast switching of trions in 2D materials by terahertz photons, *Nature Photonics* (2024). DOI: 10.1038/s41566-024-01512-0

Provided by Helmholtz Association of German Research Centres