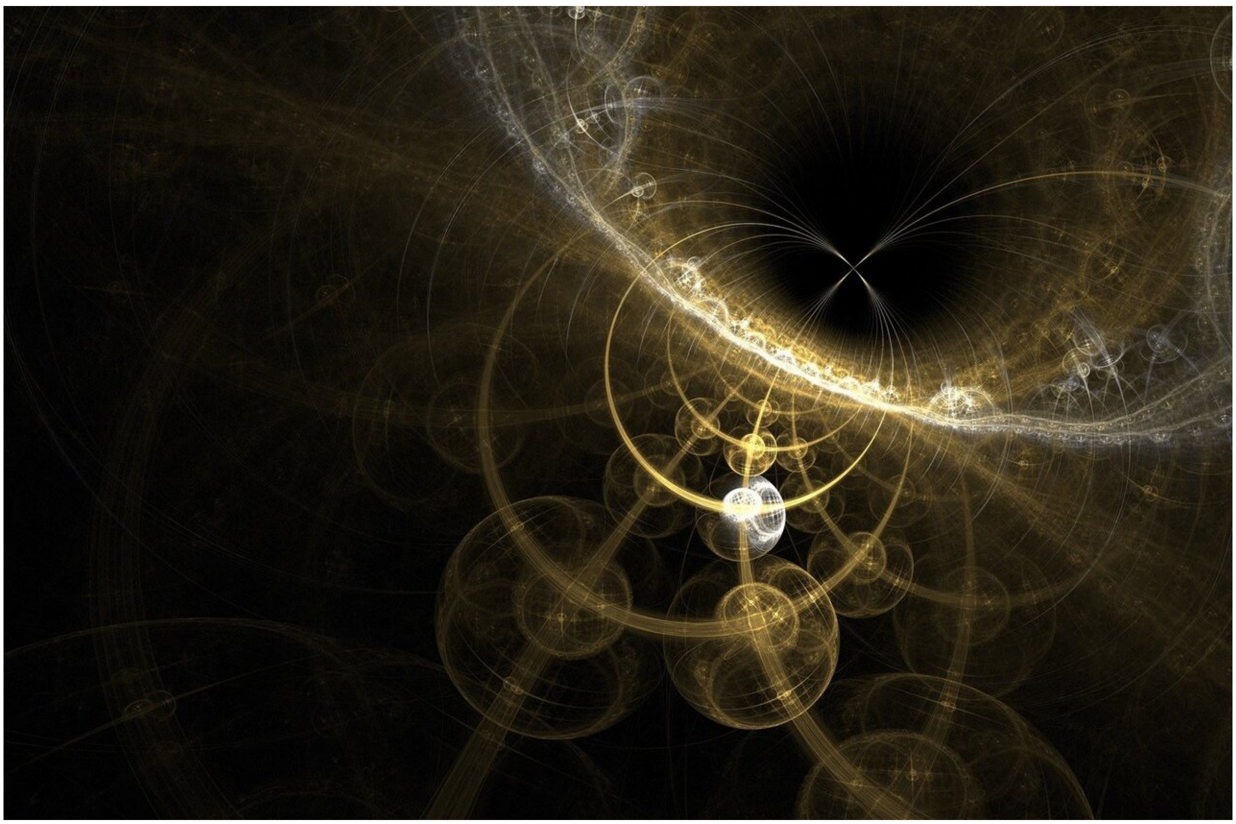
Researchers shine light on the defects responsible for messy behavior in quantum materials

February 24 2020, by Taylor Kubota



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In a future built on quantum technologies, planes and spaceships could be fueled by the momentum of light. Quantum computers will crunch through complex problems spanning chemistry to cryptography with greater speed and energy efficiency than existing processors. But before this future can come to pass, we need bright, on-demand, predictable sources of quantum light.

Toward this end, a team of Stanford University material scientists, physicists and engineers, in collaboration with labs at Harvard University and the University of Technology Sydney, have been investigating hexagonal boron nitride, a material that can emit bright light as a single photon—a quantum unit of light—at a time. And it can do this at room temperature, making it easier to use compared to alternative quantum sources.

Unfortunately, hexagonal boron nitride has a significant downside: It emits light in a rainbow of different hues. "While this emission is beautiful, the color currently can't be controlled," said Fariah Hayee, the lead author and a graduate student in the lab of Jennifer Dionne, associate professor of materials science and engineering at Stanford. "We wanted to know the source of the multi-color emission, with the ultimate goal of gaining control over emission."

By employing a combination of microscopic methods, the scientists were able to trace the material's colorful emission to specific atomic defects. A group led by co-author Prineha Narang, assistant professor of computational materials science at Harvard University, also developed a new theory to predict the color of defects by accounting for how light, electrons and heat interact in the material.

"We needed to know how these defects couple to the environment and if that could be used as a fingerprint to identify and control them," said Christopher Ciccarino, a graduate student in the NarangLab at Harvard University and co-author of the paper.

The researchers describe their technique and different categories of defects in a paper published in the March 24 issue of the journal *Nature Materials*.

Multiscale microscopy

Identifying the defects that give rise to quantum emission is a bit like searching for a friend in a crowded city without a cellphone. You know they are there, but you have to scan the full city to find their precise location.

By stretching the capabilities of a one-of-a-kind, modified electron microscope developed by the Dionne lab, the scientists were able to match the local, atomic-scale structure of hexagonal boron nitride with its unique color emission. Over the course of hundreds of experiments, they bombarded the material with electrons and visible light and recorded the pattern of light emission. They also studied how the periodic arrangement of atoms in hexagonal boron nitride influenced the emission color.

"The challenge was to tease out the results from what can seem to be a very messy quantum system. Just one measurement doesn't tell the whole picture," said Hayee. "But taken together, and combined with theory, the data is very rich and provides a clear classification of quantum defects in this material."

In addition to their specific findings about types of defect emissions in hexagonal boron nitride, the process the team developed to collect and classify these quantum spectra could, on its own, be transformative for a range of quantum materials.

"Materials can be made with near atomic-scale precision, but we still don't fully understand how different atomic arrangements influence their opto-electronic properties," said Dionne, who is also director of the Photonics at Thermodynamic Limits Energy Frontier Research Center (PTL-EFRC). "Our team's approach reveals light emission at the atomic-scale, en route to a host of exciting quantum optical technologies."

A superposition of disciplines

Although the focus now is on understanding which defects give rise to certain colors of quantum emission, the eventual aim is to control their properties. For example, the team envisions strategic placement of quantum emitters, as well as turning their emission on and off for future quantum computers.

Research in this field requires a cross-disciplinary approach. This work brought together materials scientists, physicists and electrical engineers, both experimentalists and theorists, including Tony Heinz, professor of applied physics at Stanford and of photon science at the SLAC National Accelerator Laboratory, and Jelena Vučkovic, the Jensen Huang Professor in Global Leadership in the School of Engineering.

"We were able to lay the groundwork for creating quantum sources with controllable properties, such as color, intensity and position," said Dionne. "Our ability to study this problem from several different angles demonstrates the advantages of an interdisciplinary approach."

More information: Fariah Hayee et al, Revealing multiple classes of stable quantum emitters in hexagonal boron nitride with correlated optical and electron microscopy, *Nature Materials* (2020). DOI: 10.1038/s41563-020-0616-9

Provided by Stanford University