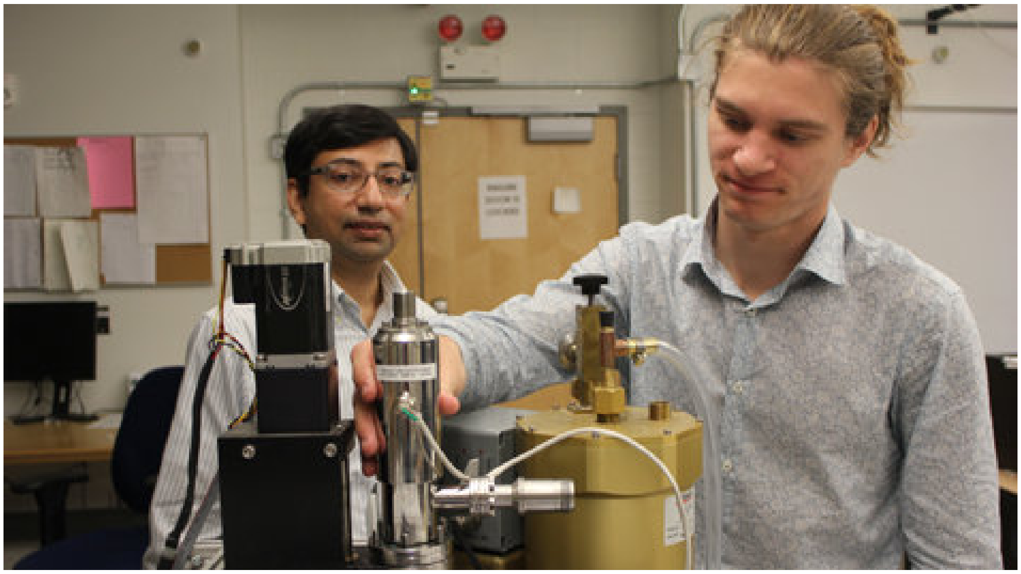
Testing whether Planck's radiation law applies at a very small scale

September 4 2018, by Adrienne Berard



Associate Professor of Physics Mumtaz Qazilbash (left) and Ph.D. student Patrick McArdle (right) partnered with a team of engineers from the University of Michigan to test whether Planck's radiation law applies at a very small scale. Credit: Adrienne Berard

A recent discovery by William & Mary and University of Michigan researchers transforms our understanding of one of the most important laws of modern physics. The discovery, published in the journal *Nature*, has broad implications for science, impacting everything from nanotechnology to our understanding of the solar system.

"This changes everything, even our ideas about planetary formation," said Mumtaz Qazilbash, associate professor of physics at William & Mary and co-author on the paper. "The full extent of what this means is an important question and, frankly, one I will be continuing to think about."

Qazilbash and two W&M graduate students, Zhen Xing and Patrick McArdle, partnered with a team of engineers from the University of Michigan to test whether Planck's radiation law, a foundational scientific principle grounded in quantum mechanics, applies at the smallest length scales.

The other co-authors on the *Nature* paper include Dakotah Thompson, Linxiao Zhu, Rohith Mittapally, Seid Sadat, Pramod Reddy and Edgar Meyhofer. Qazilbash's research was funded by the National Science Foundation.

Through a series of experiments, the team was able to show Planck's law does not apply for objects smaller than a certain length scale—and the result is 100 times higher than what the law would predict. Qazilbash said the real challenge was not only proving the discrepancy, but also explaining it.

"That's the thing with physics," Qazilbash said. "It's important to experimentally measure something, but also important to actually understand what is going on."

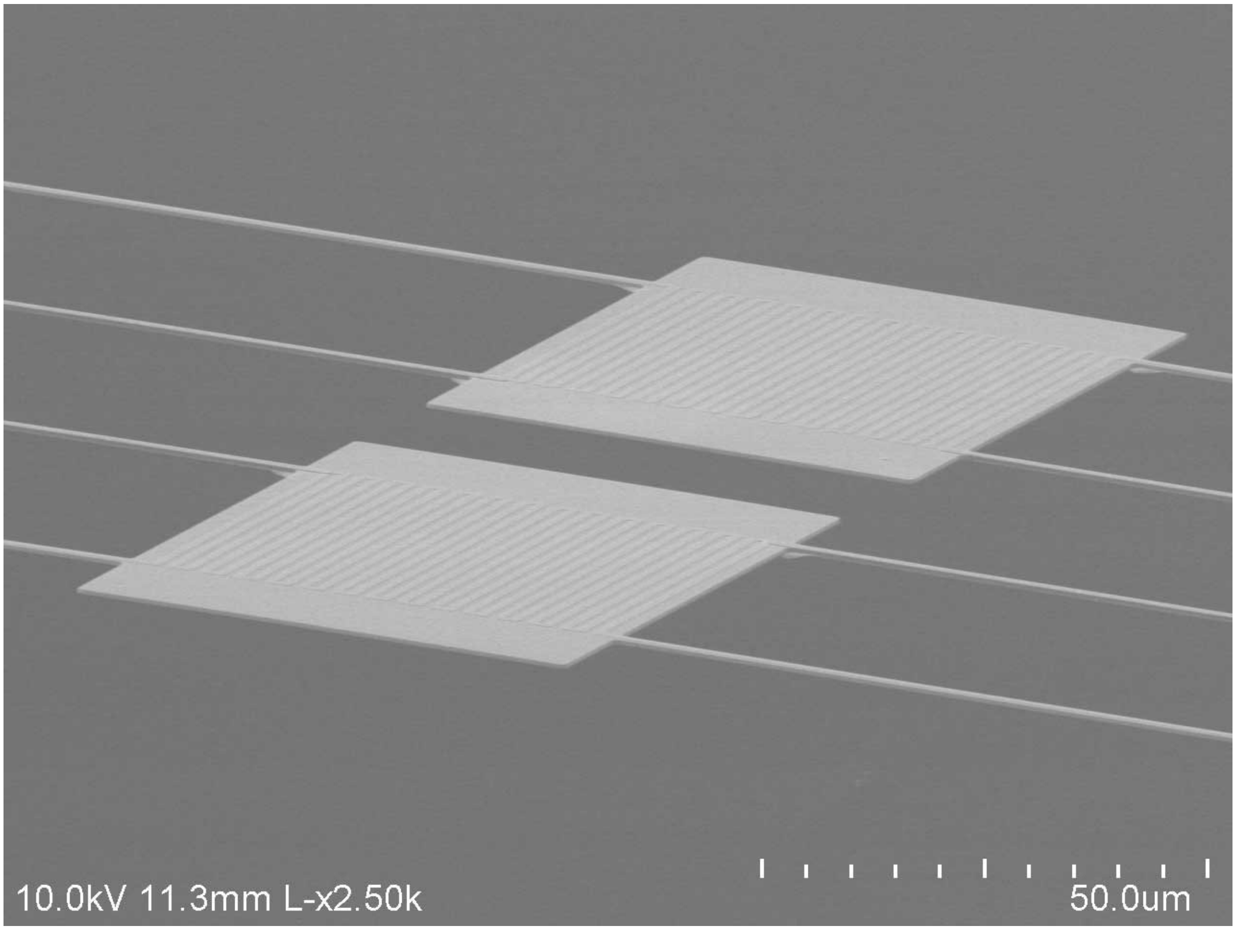
Planck's radiation law is a pillar of modern physics and one of the most important results in quantum mechanics. Formulated in 1900 by German physicist Max Planck, the law is a mathematical equation that explains the relationship between the temperature of an object and the energy emitted from that object in the form of electromagnetic radiation.

At the turn of the 20th century, physicists began to understand that, at the atomic level, everything in the universe behaves as both a particle and a wave. They came to this conclusion by studying light and sub-atomic particles. Light is simultaneously a stream of particles called photons and a wave of fluctuating electric and magnetic fields. The waves of light (of which visible light is only a small part of the spectrum) were called electromagnetic radiation, a largely invisible interaction between all objects in the universe.

"The full spectra of these wavelengths from hot objects were measured well before Max Planck came along, but nobody understood what was going on," Qazilbash said. "The theories at that time could not explain it."

Planck theorized an answer that would become the bedrock of quantum physics.

"Planck came up with quantization," Qazilbash said. "His theory was that light is not just simply an electromagnetic wave, but that it is a quantized electromagnetic wave. It's emitted and absorbed in discrete quanta called photons. That's how he was able to explain this phenomena."



An electron microscope image of the experimental set-up with two plates, each 0.06 x 0.08 mm. At their thinnest, with a thickness of just 0.00027 mm, the heat flow between them was 100 times higher than expected. Credit: Dakotah Thompson, Michigan Engineering

Moreover, Planck based his theory on the hypothesis that a photon's energy depends on its frequency, meaning the energy of electromagnetic waves is also quantized. He articulated the relationship between energy and frequency in his radiation law. Until recently, the law was assumed to apply to all objects in the universe.

Then in 2009, physicists attempted to apply the law to two objects that were so close there was less than a wavelength of radiation between them. The scientists found that the law did not hold up when the objects were in what is termed the "near field." Qazilbash and his research team decided to test the law in the far field—farther apart than a wavelength of radiation—with objects that were smaller than a wavelength in thickness.

"What our work shows is that if the objects are very small, there is a violation of the law," Qazilbash said. "This has never been experimentally shown before."

Such an experiment required collaboration between disciplines, Qazilbash explained. The William & Mary physics team partnered with the engineering department at University of Michigan for this project. The wavelengths of infrared light that are relevant for testing the law were only about 10 microns (about a fifth of the average cross-section of a human hair), so the engineers had to create an object even smaller. They eventually developed a membrane of silicon nitride only a few hundred nanometers (or less than half a micron) thick.

To see if the law applied, the researchers placed two identical membranes at a relatively large distance apart. Next, they heated one of the membranes and measured the heat increase in the second. If Planck's law holds true, then the heat increase in the second membrane should have been in accord with Planck's prediction. What the researchers found instead was a 100-fold difference in radiative heat transfer than what Planck's law would have predicted.

"Planck's radiation law says if you apply the ideas that he formulated to two objects, then you should get a defined rate of energy transfer between the two," Qazilbash said. "Well, what we have observed experimentally is that rate is actually 100 times higher than Planck's law predicts if the objects are very, very small."

The reason for such a huge disparity has to do with the nature of waves, Qazilbash explained.

"Think of a guitar string," he said. "It has some fundamental resonances. The frets are at a particular length to align with the best harmonics. If you pluck it in those places, it's going to resonate at certain wavelengths more efficiently. It's the same thing here with light. If the material and geometry of an object are such that electromagnetic waves can couple more effectively to it, then it will emit and absorb radiation more effectively."

The implications for discovering a 100-fold discrepancy in Planck's radiation law are broad and touch nearly all aspects of modern physics, Qazilbash said. In the digital age, hardware developers are looking for ways to design smaller and faster technology. This discovery has the potential to change the future of nanotechnology.

"Now we know that nanoscale objects can emit and absorb radiation much more effectively than we ever thought was possible," Qazilbash said.

Qazilbash added that it's not only a revelation for small-scale objects and nanotechnology. The discovery also relates to climate science, planetary atmospheres, astrophysics and the makeup of solar systems.

"This discovery touches so many fields," Qazilbash said. "Wherever you have radiation playing an important role in physics and science, that's where this discovery is important."

More information: Dakotah Thompson et al. Hundred-fold enhancement in far-field radiative heat transfer over the blackbody limit, *Nature* (2018). DOI: 10.1038/s41586-018-0480-9

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