New discoveries about the nature of light could improve methods for heating fusion plasma

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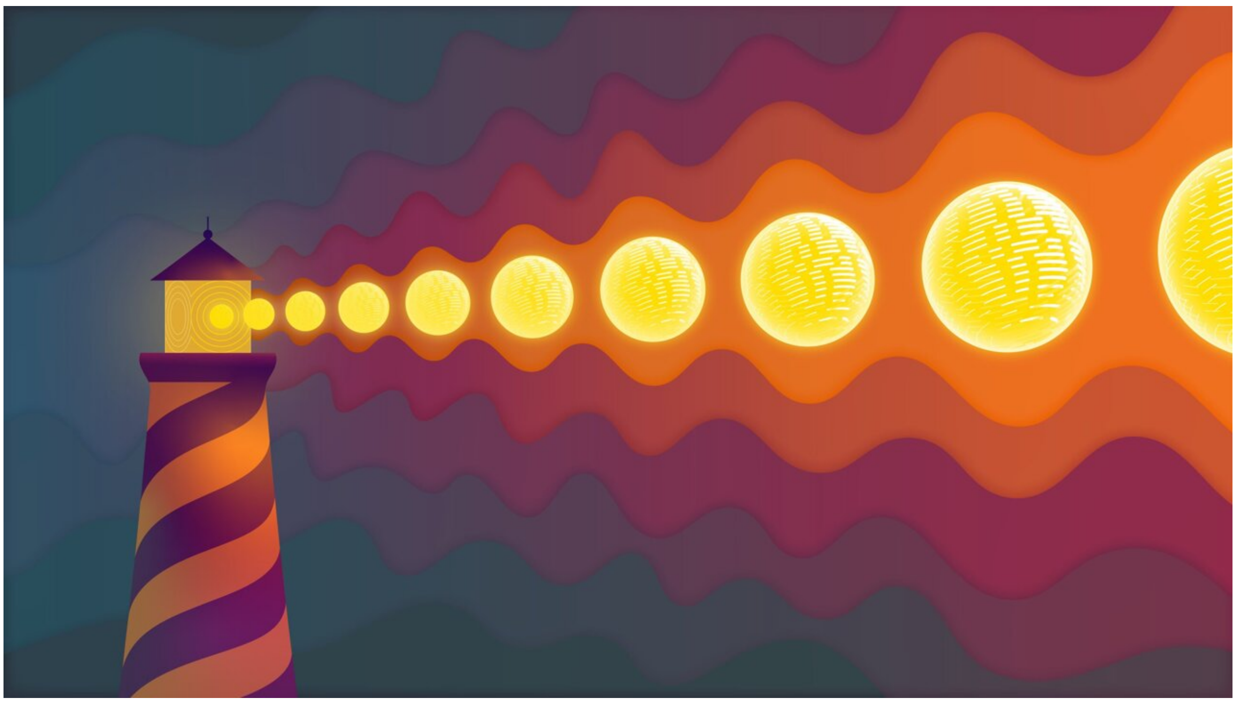

An artist's conception of photons, the particles that make up light, perturbing plasma. Credit: Kyle Palmer / PPPL Communications Department

Both literally and figuratively, light pervades the world. It banishes darkness, conveys telecommunications signals between continents and makes visible the invisible, from faraway galaxies to the smallest bacterium. Light can also help heat the plasma within ring-shaped devices known as tokamaks as scientists worldwide strive to harness the fusion process to generate green electricity.

Now, scientists have made discoveries about light particles known as photons that could aid the quest for fusion energy. By performing a series of mathematical calculations, the researchers found that one of a photon's basic properties is topological, meaning that it doesn't change even as the photon moves through different materials and environments.

This property is polarization, the direction—left or right—that electric fields take as they move around a photon. Because of basic physical laws, a photon's polarization helps determine the direction the photon travels and limits its movement. Therefore, a beam of light made up of only photons with one type of polarization cannot spread into every part of a given space. These findings demonstrate the Princeton Plasma Physics Laboratory's (PPPL) strengths in theoretical physics and fusion research.

"Having a more accurate understanding of the fundamental nature of photons could lead to scientists designing better light beams for heating and measuring plasma," said Hong Qin, a principal research physicist at the U.S. Department of Energy's (DOE) PPPL and co-author of a paper reporting the results in *Physical Review D.*

Simplifying a complicated problem

Though the researchers were studying individual photons, they were doing so as a way to solve a larger, more difficult problem—how to use beams of intense light to excite long-lasting perturbations in the plasma that could help maintain the high temperatures needed for fusion.

Known as topological waves, these wiggles often occur on the border of two different regions, like plasma and the vacuum in tokamaks at its outer edge. They are not especially exotic—they occur naturally in Earth's atmosphere, where they help produce El Niño, a gathering of warm water in the Pacific Ocean that affects weather in North and South America.

To produce these waves in plasma, scientists must have a greater understanding of light—specifically, the same sort of radio-frequency wave used in microwave ovens—which physicists already use to heat plasma. With greater understanding comes the greater possibility of control.

"We are trying to find similar waves for fusion," said Qin. "They are not easily stopped, so if we could create them in plasma, we could increase the efficiency of plasma heating and help create the conditions for fusion."

The technique resembles ringing a bell. Just as using a hammer to hit a bell causes the metal to move in such a way that it creates sound, the scientists want to strike plasma with light so it wiggles in a certain way to create sustained heat.

Solving a problem by simplifying it happens throughout science. "If you're learning to play a song on the piano, you don't start by trying to play the whole song at full speed," said Eric Palmerduca, a graduate student in the Princeton Program in Plasma Physics, which is based at PPPL, and lead author of the paper.

"You start playing it at a slower tempo; you break it into small parts; maybe you learn each hand separately. We do this all the time in science—breaking a bigger problem up into smaller problems, solving them one or two at a time, and then putting them back together to solve the big problem."

Turn, turn, turn

In addition to discovering that a photon's polarization is topological, the scientists found that the spinning motion of photons could not be separated into internal and external components. Think of Earth: It both spins on its axis, producing day and night, and orbits the sun, producing the seasons.

These two types of motion typically do not affect each other; for instance, Earth's rotation around its axis does not depend on its revolution around the sun. In fact, the turning motion of all objects with mass can be separated this way. But scientists have not been so sure about particles like photons, which do not have mass.

"Most experimentalists assume that the angular momentum of light can be split into spin and orbital angular momentum," said Palmerduca. "However, among theorists, there has been a long debate about the correct way to do this splitting or whether it is even possible to do this splitting. Our work helps settle this debate, showing that the angular momentum of photons cannot be split into spin and orbital components."

Moreover, Palmerduca and Qin established that the two movement components can't be split because of a photon's topological, unchanging properties, like its polarization. This novel finding has implications for the laboratory. "These results mean that we need a better theoretical explanation of what is going on in our experiments," Palmerduca said.

All of these findings about photons give the researchers a clearer picture of how light behaves. With a greater understanding of light beams, they hope to figure out how to create topological waves that could be helpful for fusion research.

Insights for theoretical physics

Palmerduca notes that the photon findings demonstrate PPPL's strengths in theoretical physics. The findings relate to a mathematical result known as the Hairy Ball Theorem.

"The theorem states that if you have a ball covered with hairs, you can't comb all the hairs flat without creating a cowlick somewhere on the ball. Physicists thought this implied that you could not have a light source that sends photons in all directions at the same time," Palmerduca said.

He and Qin found, however, that this is not correct because the theorem does not take into account, mathematically, that photon electric fields can rotate.

The findings also amend research by former Princeton University Professor of Physics Eugene Wigner, who Palmerduca described as one of the most important theoretical physicists of the 20th century. Wigner realized that using principles derived from Albert Einstein's theory of relativity, he could describe all the possible elementary particles in the universe, even those that hadn't been discovered yet.

But while his classification system is accurate for particles with mass, it produces inaccurate results for massless particles, like photons. "Qin and I showed that using topology," Palmerduca said, "we can modify Wigner's classification for massless particles, giving a description of photons that works in all directions at the same time."

A clearer understanding for the future

In future research, Qin and Palmerduca plan to explore how to create beneficial topological waves that heat plasma without making unhelpful varieties that siphon the heat away.

"Some deleterious topological waves can be excited unintentionally, and we want to understand them so that they can be removed from the system," Qin said. "In this sense, topological waves are like new breeds of insects. Some are beneficial for the garden, and some of them are pests."

Meanwhile, they are excited about the current findings. "We have a clearer theoretical understanding of the photons that could help excite topological waves," Qin said. "Now it's time to build something so we can use them in the quest for fusion energy."

More information: Eric Palmerduca et al, Photon topology, *Physical Review D* (2024). DOI: 10.1103/PhysRevD.109.085005. On *arXiv*: DOI: 10.48550/arxiv.2308.11147

Provided by Princeton Plasma Physics Laboratory

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