No, You Cannot Catch An Individual Photon Acting Simultaneously As A Pure Particle And Wave

Last week, the Internet lit up with dramatic headlines from the world of science: In a Physics First, Light is Captured as Both Particle and Wave, Light Photographed as a Simultaneous Wave and Particle, and Light's Wave-Particle Duality Imaged For The First Time, to name a few. These headlines sound revolutionary, surprising, profound to any of us with even just a passing knowledge of the concepts they mention. Quantum physics suggests that every object in the universe has a dual nature. A photon, the basic building block of light, can behave like a water-like wave or a ball-like particle, depending on the situation it encounters. When a photon strikes a metal, it acts like a billiard ball, knocking off electrons from the metal. When it passes through a narrow slit, it spreads out like a water-like wave.

But until now, at least, we have generally seen objects in just one guise or the other. Kind of like how we never see Superman and Clark Kent in the same place at the same time. Yet, these headlines suggest that researchers caught light in the act of being both a particle and wave simultaneously. How and where did they see this? What implications does this have for the dual nature of matter in our universe?

Technically, the headlines are not incorrect. Yet, to me and others, they imply something more radical than what was actually observed. To cut to the chase, an individual photon cannot be observed acting as both a pure particle and wave at the same time. But if you assemble a group of many different photons, you can observe some acting like particles and others acting like waves. Many stories did not make this clear.

The researchers who performed the experiment, published in Nature Communications, are on the same wavelength with this assessment.

"I also believe that a lot of people are overinterpreting the significance of these data," senior author Fabrizio Carbone of the Swiss Federal Institute of Technology (EPFL) in Lausanne, wrote in an email. He performed the work with collaborators at EPFL, Trinity College in Hartford, Connecticut, and Lawrence Livermore National Laboratory in Berkeley, California.
The researchers trapped a wave on a super-thin "nanowire" with a thickness measured in nanometers or billionths of a meter. It's a standing wave, like a vibration of a guitar string, with peaks and valleys that stay fixed in the same position.

To be precise, it's not strictly a light wave as the headlines suggest. It's actually a hybrid of a light wave, dancing on the wire, and an electromagnetic wave slithering on the wire's surface, produced by charged particles moving along the wire. They're kind of joined at the hip. This composite object is known as a surface plasmon polariton and you can read more about it on Wikipedia.

For simplicity, let's consider it just to be a light wave. For the purposes of this discussion, it doesn't matter if the wave is made of photons or some hybrid object. It acts like a wave.

But when the researchers fired electrons at the nanowire, the electrons sometimes sped up by specific amounts, indicating that they absorbed individual photons from the wire. How can light behave like both waves and particles at the same time?

The answer is that the light was made of many different photons. Each of them behaved in a separate way. The researchers observed some photons acting like particles, and others acting like waves. Imaging both types simultaneously is what was done for the first time in their experiment.

Not textbook-changing, but still cool. The researchers witnessed important behavior in the nanowires, which may form the basis of future very small-scale electronic and optical devices. Also, they could count how many photons were in the waves they studied, and how the electrons interacted with them. But when an electron absorbed one of the photons, they couldn't pinpoint where the photon came from in the wave.

Carbone mentioned a 2011 Science paper that he said came the closest thus far to capturing a single photon's dual nature. Researchers led by Aephraim Steinberg of the University of Toronto measured a particle-like property of individual photons — their average position — without destroying the wavelike interference patterns they later created. Physics World named this experiment the 2011 Breakthrough of the Year, and it was well deserved. However, even this experiment couldn't determine the exact positions of individual photons as they went on to create a wave-like pattern of light and dark bands on a detector.

What is the fundamental reason for this limitation? It's something from quantum mechanics known as the Heisenberg uncertainty principle. Named for 20th century physicist Werner Heisenberg, it says that you can't measure two complementary variables, such as position and momentum, with complete precision. If you measure one precisely, it sacrifices the precision with which you can measure the other.

So if you measure particle-like properties of the photon, it can sacrifice its wave-like properties. Zero in on a photon's position too precisely, and it cannot participate later on in creating a wave pattern.
It is possible to measure some weakly wave-like and weakly particle-like properties in a photon simultaneously, Carbone said, as long as the combined uncertainties in the measurements do not violate the uncertainty principle.

But in the end, maybe the wave-particle duality is an artificial way of explaining the quantum world, Steinberg explained to me by email.

"Although I'm often guilty of it myself, I think it's a little misleading for physicists to keep harping on about 'wave-like' and 'particle-like' behavior," he wrote. "We have a great mathematical theory which tells us what photons...actually do. And then we have the human tendency to draw analogies and say 'hmm, in this case that looks like what I expect from a water wave' and 'but in this case that looks like what I expect from a billiard ball.' But photons are neither water waves nor billiard balls," he wrote.

"One has to be careful to define exactly what question one has in mind," Steinberg continued. "If two ripples cross in a pool, and I reach a cupped hand in and pull out a handful of water to ask you 'which ripple are these water molecules from?' there is no answer.

"There is no answer because it's not a well-posed question, not because there is any deep mystery to the physics of water waves," Steinberg pointed out.

"In the end, quantum mechanics is the same. When you ask careful, experimentally testable questions, there is no paradox," according to Steinberg.

"What it teaches us is that we haven't yet figured out how to think about quantum mechanics right – not that there is any problem with the theory itself or how we use it to make predictions."