Ultracold disappearing act: 'Matter waves' move through one another but never share space

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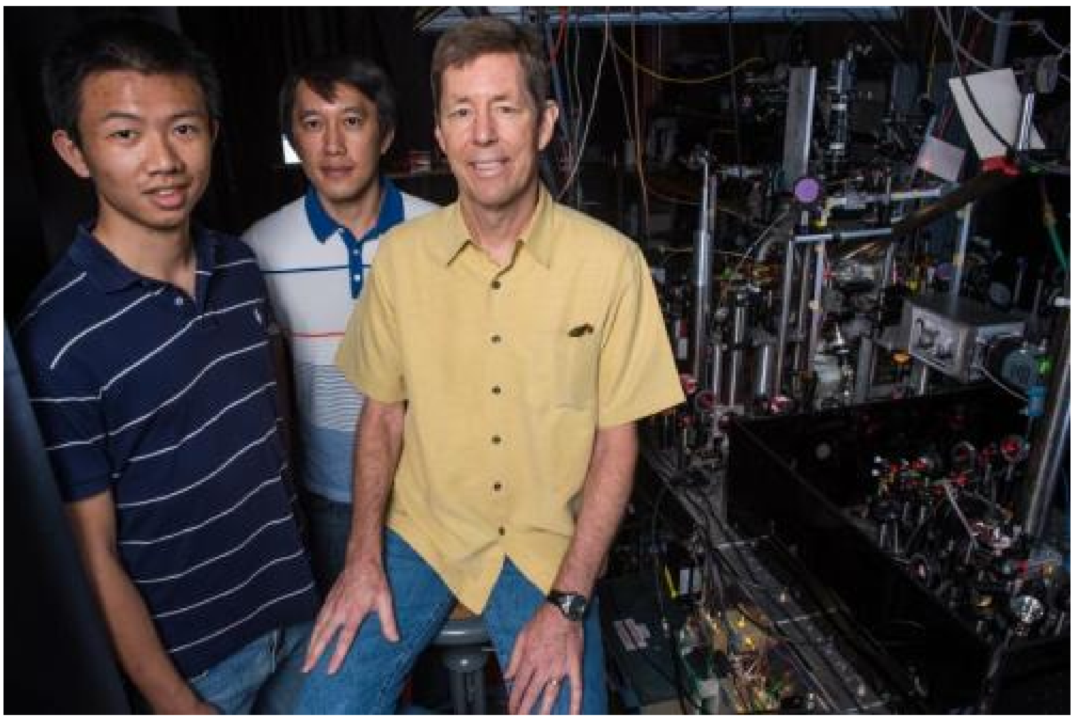

Physicists (from left) De Luo, Jason Nguyen and Randy Hulet observed a strange disappearing act during collisions between forms of Bose Einstein condensates called solitons. In some cases, the colliding clumps of matter appear to keep their distance even as they pass through each other. CREDIT: Jeff Fitlow/Rice University

A disappearing act was the last thing Rice University physicist Randy

Hulet expected to see in his ultracold atomic experiments, but that is what he and his students produced by colliding pairs of Bose Einstein condensates (BECs) that were prepared in special states called solitons.

Hulet's team documented the strange phenomenon in a new study published online this week in the journal *Nature Physics*.

BECs are clumps of a few hundred thousand lithium atoms that are cooled to within one-millionth of a degree above absolute zero, a temperature so cold that the atoms march in lockstep and act as a single "matter wave." Solitons are waves that do not diminish, flatten out or change shape as they move through space. To form solitons, Hulet's team coaxed the BECs into a configuration where the attractive forces between lithium atoms perfectly balance the quantum pressure that tends to spread them out..

The researchers expected to observe the property that a pair of colliding solitons would pass though one another without slowing down or changing shape. However, they found that in certain collisions, the solitons approached one another, maintained a minimum gap between themselves, and then appeared to bounce away from the collision.

"You never see them together," said Hulet, Rice's Fayez Sarofim Professor of Physics and Astronomy. "There is always a hole, a gap that they must jump over. They pass through one another, but they never occupy the same space while they're doing that.

"It happens because of 'wave packet' interference," he said. "Think of them as waves that can have a positive or negative amplitude. One of the solitons is positive and the other is negative, so they cancel one another. The probability of them being in the spot where they meet is zero. They pass through that spot, but you never see them there."

Hulet's team specializes in experiments on BECs and other ultracold matter. They use lasers to both trap and cool clouds of lithium gas to temperatures that are so cold that the matter's behavior is dictated by fundamental forces of nature that aren't observable at higher temperatures.

To create solitons, Hulet and postdoctoral research associate Jason Nguyen, the study's lead author, balanced the forces of attraction and repulsion in the BECs.

"First we make a Bose Einstein condensate and then we use a sheet of light to split the condensate in half and push the two halves apart," Nguyen said. "We hold them apart and turn each of them into solitons, and then we take the sheet away and let them fall back toward one another and collide."

Cameras captured images of the tiny BECs throughout the process. In the images, two solitons oscillate back and forth like pendulums swinging in opposite directions. Hulet's team, which also included graduate student De Luo and former postdoctoral researcher Paul Dyke, documented thousands of head-on collisions between soliton pairs and noticed a strange gap in some, but not all, of the experiments.

"One of the defining features of a soliton is that they are supposed to be able to pass through one another and emerge unfazed," Hulet said.

"Some of the collisions are consistent with that," he said, pointing to images of two solitons oscillating, meeting, emerging and continuing on their cycle. "These two solitons certainly appear to have passed through one another.

"In another set of collisions, there's always this gap between them," he said, pointing to a different set of images. "It doesn't look like they ever close that gap to be able to pass through. In fact, it looks like they've come together and then bounced off one another."

Hulet said the idea of solitons bouncing away from one another had been around for about 40 years, based on longstanding observations of optical solitons in fiber-optic cables. In this scenario, the gap is viewed as evidence of a force that is pushing the solitons apart.

To probe more deeply, Hulet's team needed to conduct a new set of experiments that focused on the one defining feature of a soliton that they couldn't control—its phase.

The first soliton was observed in a canal in Scotland in 1834 and they've since been observed in magnets, fiber-optic cables, atomic nuclei and even swimming pools. Hulet's team was among the first to report BEC "matter-wave bright solitons" in 2002.

Like a wave in the ocean or a light beam in a fiber-optic cable, solitons have a characteristic amplitude, frequency and phase. Hulet's team could control the amplitude but they could not control the soliton's phase.

"All waves oscillate in time," Hulet said. "They have a frequency at which their amplitude becomes positive, negative, positive, negative and so on. The rate of that oscillation, how often it switches, defines their frequency. Where they begin that cycle is something we refer to as 'the phase.' It's a kind of starting point."

The wave's phase is an angle that can vary between zero and 360 degrees. Waves that are "in-phase" have the same starting point, and waves that are "out-of-phase" are 180 degrees off, meaning that one begins at its peak while the other starts at its trough.

"When we saw the initial data we said, 'This doesn't make sense, because solitons are always supposed to pass through one another and these look like they're bouncing instead,'" Hulet said. "So we began thinking about how we could tag one of the solitons to make it distinct so that we could follow its trajectory in time and see what it did."

The team found a way to "tag" one soliton by making it larger than the other. In the next round of experiments, Nguyen and Luo captured pictures of collisions between different-sized solitons.

"We did that experiment over and over for many different relative phases, and we looked for two cases, one where the relative phase was zero, or in-phase, and another where it was 180 degrees, or completely out-of-phase," Hulet said.

For the in-phase case, the team saw the two solitons pass through one another and emerge, just as predicted by theory.

"In the out-of-phase case, the one with the gap, where it appeared that they had been bouncing off of each other, we still saw the gap but we also saw the larger soliton emerge unfazed on the other side of the gap. In other words, it jumped through the gap!"

Hulet said the experiment confirmed the theory that solitons do pass through one another, even in cases where they are out-of-phase and only appear to bounce away from each other.

Many of the events that Hulet's team measures occur in one-thousandth of a second or less. To confirm that the "disappearing act" wasn't causing a miniscule interaction between the soliton pairs—an interaction that might cause them to slowly dissipate over time—Hulet's team tracked one of the experiments for almost a full second.

The data showed the solitons oscillating back and fourth, winking in and out of view each time they crossed, without any measurable effect.

"This is great example of a case where experiments on ultracold matter can yield a fundamental new insight," Hulet said. "The phase-dependent effects had been seen in optical experiments, but there has been a misunderstanding about the interpretation of those observations."

More information: *Nature Physics*, dx.doi.org/10.1038/nphys3135

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