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Can quantum particles mimic gravitational waves?

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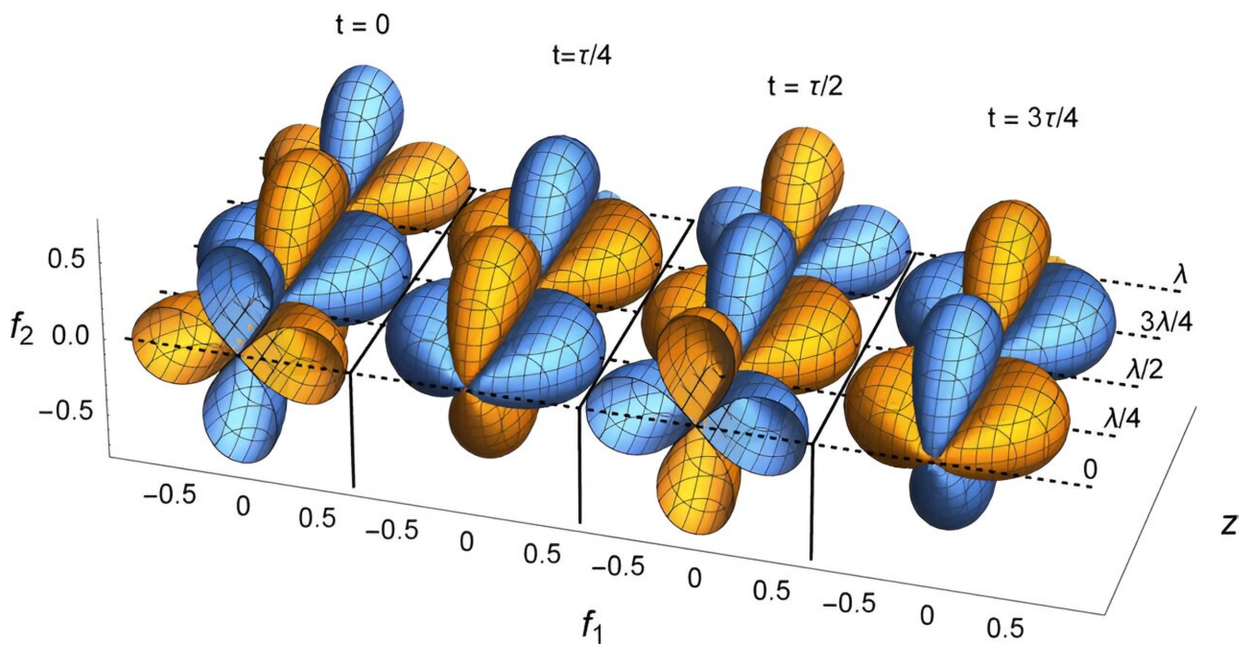

Quadrupolar nature of gravitational waves, and Goldstone modes of spin-nematic order, visualized through the associated distortions of spacetime, or the spin-nematic ground state. Credit: *Physical Review B* (2024). DOI: 10.1103/PhysRevB.109.L220407

When two black holes collide, space and time shake and energy spreads out like ripples in a pond. These gravitational waves, predicted by Einstein in 1916, were observed for the first time by the Laser Interferometer Gravitational-Wave Observatory (LIGO) telescope in

September 2015.

Observing gravitational waves is an unfathomably complicated feat of engineering: to detect a gravitational wave the size of the solar system, one must measure changes in length smaller than the diameter of an atomic nucleus.

But now, researchers from the Okinawa Institute for Science and Technology (OIST), the University of Tohoku and the University of Tokyo have proposed a method for simulating gravitational waves on the laboratory bench through the quantum condensate of cold atoms.

The scientists are all current or previous members of the Theory of Quantum Matter Unit at OIST, and their findings have now been published in the journal *Physical Review B*, where the paper was selected as the Editor's choice.

"Einstein's theory of general relativity changed the way we think about space and time," recounts Professor Nic Shannon, senior author of the study and head of the unit. "It taught us that space can bend to make a black hole, and that it can vibrate, creating waves which cross the universe at the speed of light. These gravitational waves contain important information about our universe. The problem is that they are very, very hard to observe."

To address this challenge, scientists have built giant gravitational wave telescopes such as LIGO in the U.S., the Virgo interferometer in Europe, and the Kamioka Gravitational Wave Detector (KAGRA) in Japan. But even with these instruments that measure many kilometers across, we can only detect waves coming from the most violent astronomical events, like black holes colliding.

An alternative approach is to explore phenomena on Earth that mimic different aspects of general relativity. By chance, the team realized that a quantum phenomenon they had been studying in the context of magnets and cold atoms in the lab could provide an exact analog of gravitational waves.

"This result is important," says Professor Han Yan of the University of Tokyo, "because it makes it possible to simulate and study gravitational waves in a much simpler experimental setting and use the results to help us to understand real gravitational waves."

In addition to his predictions about gravitational waves, Einstein also predicted that bosons, a type of quantum particle, could, when cooled down, exist in a state that allows for the formation of Bose-Einstein Condensate (BEC), whereby a group of particles act in perfect unison.

The team focused on matter in a specific type of BEC, called spin nematics. "Nematic phases are all around us," explains Prof. Shannon, "in the Liquid Crystal Displays (LCDs) of our smartphones, tablets and televisions." In LCDs, tiny rod-shaped molecules line up uniformly, and control the flow of light in the screen.

The OIST team had been studying the quantum versions of liquid crystals, spin nematics, for some time. Unlike the molecules in LCDs, the quantum particles in a spin-nematic state support waves, which carry energy across the system.

"We realized that the properties of the waves in the spin-nematic state are mathematically identical to those of gravitational waves," says Prof. Shannon, "and thanks to earlier work with Profs Rico Pohle and Yutaka Akagi, we knew how to simulate these waves."

"I've always been fascinated by the fact that we can describe what seem to be different phenomena by very similar underlying mathematical structures, and for me this is the most beautiful part of physics," says Dr. Leilee Chojnacki from the OIST unit and lead author of the study.

"So, it was very exciting for me to work on two very different branches of physics, gravitational waves and the quantum physics of cold atoms, and bring them together in a way which hadn't previously been explored."

More information: Leilee Chojnacki et al, Gravitational wave analogs in spin nematics and cold atoms, *Physical Review B* (2024). DOI: 10.1103/PhysRevB.109.L220407

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