Thought experiments and conservation laws: Reevaluating quantum conservation principles

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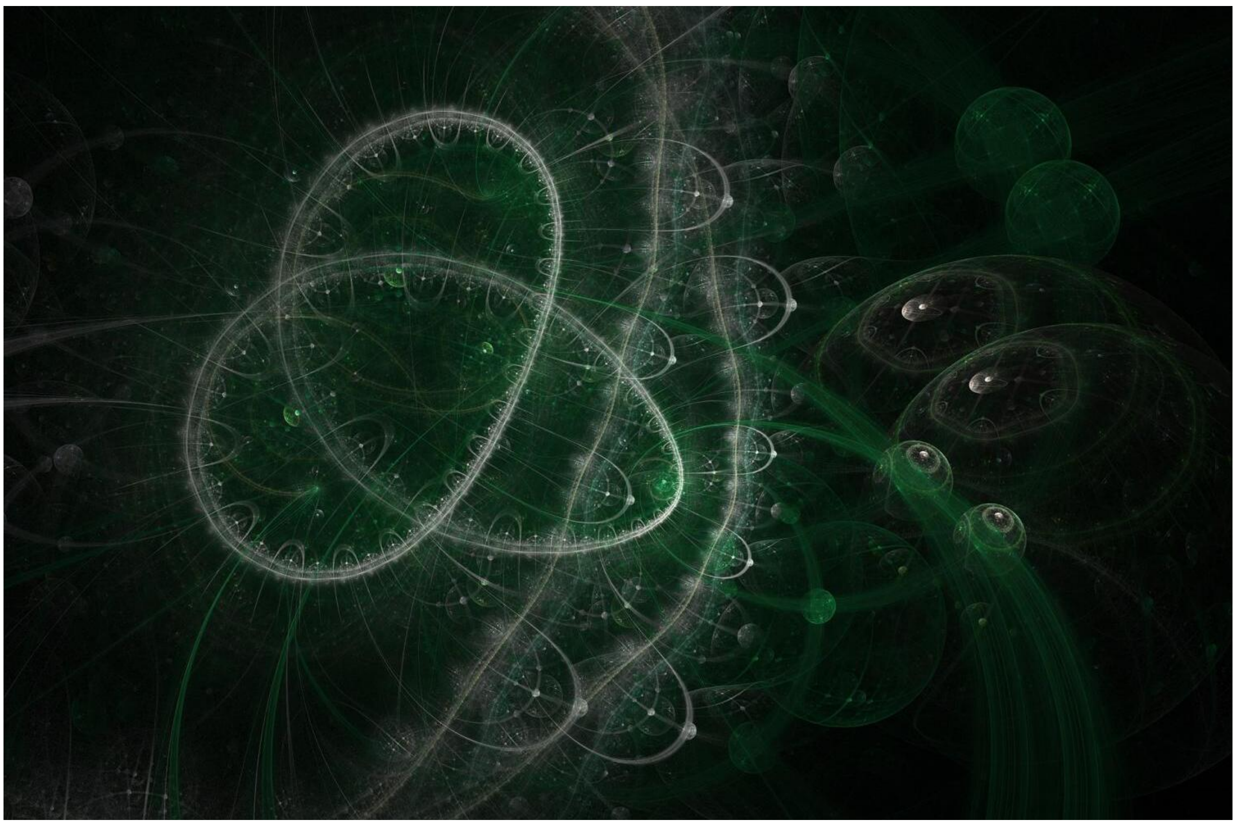

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Conservation laws are central to our understanding of the universe, and now scientists have expanded our understanding of these laws in quantum mechanics.

A conservation law in physics describes the preservation of certain quantities or properties in isolated physical systems over time, such as mass-energy, momentum, and electric charge.

Conservation laws are fundamental to our understanding of the universe because they define the processes that can or cannot occur in nature. For example, the conservation of momentum reveals that within a closed system, the sum of all momenta remains unchanged before and after an event, such as a collision.

This translates to explaining the behavior of objects in motion, from the motion of planets in space to the complex dynamics of subatomic particles.

However, things get more interesting when we look at the world of quantum mechanics. In quantum mechanics, conservation theorems can be derived from principles like the symmetries of physical systems, unlike classical mechanics, where they are starting points.

Quantum mechanics boasts a repertoire of conservation laws, some of which have classical counterparts, while others are uniquely quantum. Sandu Popescu, one of the authors of a new study published in *Proceedings of the National Academy of Sciences*, pointed out that despite its incredible success in explaining a multitude of phenomena, quantum mechanics still eludes a deep, intuitive grasp of its underlying principles.

In Dr. Popescu's own words, "Despite its long-standing presence, the counterintuitive behavior of microscopic particles leaves me with a universal acceptance that a deep, intuitive understanding remains elusive. The ongoing discovery of surprising and paradoxical effects underscores my need to achieve this understanding."

To do so, the researchers devised a thought experiment.

Thought experiments and conservation laws in quantum mechanics

A thought experiment is a hypothetical scenario used to explore the consequences of theories and principles, providing new perspectives and insights, often challenging prevailing beliefs.

These experiments are intentionally crafted to investigate the consequences of a specific principle. The experiment's structure may render it impractical to execute, and even if feasible, there may not be an intent to carry it out. To illustrate the significance of thought experiments, let's delve into a simple example presented by Dr. Popescu.

This thought experiment features two characters, Alice and Bob, each perched on a chair with wheels, positioned to face one another. These chairs glide gracefully across the floor with minimal friction, setting the stage for an intriguing exploration of conservation laws within the quantum realm.

They have the same mass, and when they push each other, they move in opposite directions at the same speed, resulting in a constant sum of speeds equal to zero. As Dr. Popescu elucidated, "The sum of the speeds remains constant, both before and after their interaction."

He continued, "This is a remarkable finding because it holds regardless of the specific nature of their interaction. You can predict that the sum of their speeds is zero without knowing details of how they pushed each other."

Understanding the broader significance of this thought experiment requires acknowledging its universal applicability. The principle it illustrates extends to various scenarios, accommodating differences in mass, initial motion, or complex multi-dimensional interactions, highlighting its enduring and invaluable predictive capacity.

Dr. Popescu explained, "At a deeper level, certain conservation laws emerge from the symmetries found in nature. In the case of the example, it's evident that the location in the universe doesn't affect the experiment's outcome. Other conservation laws dictate limitations such as not being able to extract more energy than what was initially invested."

Challenges with traditional conservational laws in quantum mechanics

In classical physics, the concept of conservation is relatively straightforward. You measure a specific quantity at the beginning of an experiment, and you measure it again at the end. If the values match, the quantity is considered conserved.

"This doesn't work in quantum mechanics. The reason is that performing a measurement disturbs the system," explained Dr. Popescu.

Measuring a quantity immediately after preparation disrupts the system, fundamentally altering its subsequent evolution. Despite matching measurement results at the end, it fails to reveal the original state, as the system's time evolution has been irreversibly changed.

To navigate these challenges, researchers devised a thought experiment. Their experimental setup involved preparing a quantum system in a specific initial state and measuring a conserved quantity—position—immediately after its preparation.

Subsequently, they allowed the system to evolve without any measurement disturbance. "Now the evolution proceeded as desired since you didn't disturb the system at the beginning," said Dr. Popescu. Researchers chose the states where the particle was in a superoscillatory region, known for its high-frequency or varied behavior. They then measured the particle's angular momentum and checked whether it fell within a specific range.

They compared the result of the second measurement, the angular momentum measurement, with the initial measurement, that characterized the particle's initial state. If these two measurements were the same, it indicated that the measured quantity of interest, in this case, angular momentum, was conserved throughout the experiment.

The conservation is statistical because individual cases can't definitively prove it due to quantum randomness. It is confirmed by comparing outcome probabilities between experiments measuring the quantity right after preparation and at the end using the same initial state.

The researchers found two key insights. First, they showed that "preparation nonconservation" and "measurement nonconservation" cancel each other out, leading to the conservation of angular momentum even in individual cases. This challenges classical conservation laws.

Second, the paper argued that the proposed pure state, which appeared non-conservative in individual cases, is unrealistic and doesn't exist in nature. This emphasizes the importance of considering frames of reference and the system-measuring device interaction to understand quantum conservation laws.

This study challenges conventional quantum conservation laws, emphasizing the impact of frames of reference and unphysical states, and calls for a reconsideration of statistical conservation in quantum mechanics.

Dr. Popescu concluded by saying, "We do not claim that there is anything incorrect with the standard way to define conservation laws in quantum mechanics. We claim, however, that one can do better than that."

More information: Yakir Aharonov et al, Conservation laws and the foundations of quantum mechanics, *Proceedings of the National Academy of Sciences* (2023). DOI: 10.1073/pnas.2220810120