Quantum Chaos Unveiled?

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University of Utah physicist Brian Saam examines tubes of invisible xenon gas that he used to explore the relationship between chaos theory and modern quantum physics. Photo: Eric Sorte

(PhysOrg.com) -- A University of Utah study is shedding light on an important, unsolved physics problem: the relationship between chaos theory - which is based on 300-year-old Newtonian physics - and the modern theory of quantum mechanics.

The study demonstrated a fundamental new property - what appears to be chaotic behavior in a quantum system - in the magnetic "spins" within the nuclei or centers of atoms of frozen xenon, which normally is a gas and has been tested for making medical images of lungs.

The new study - published in the Aug. 8 issue of the journal *Physical*

Review Letters - was led by Brian Saam, an associate professor of physics and associate dean of the University of Utah's College of Science.

Quantum mechanics - which describes the behavior of molecules, atoms electrons and other subatomic particles - "plays a key role in understanding how electronics work, how all sorts of interesting materials behave, how light behaves during communication by optical fibers," Saam says.

"When you look at all the technology governed by quantum physics, it's not unreasonable to assume that if one can apply chaos theory in a meaningful way to quantum systems, that will provide new insights, new technology, new solutions to problems not yet known."

A Chaotic Dance of Nuclear Spins

Just as atomic nuclei and their orbiting electrons can have electrical charges, they also have another property known as "spin." The spin within an atomic nucleus or electron is like a spinning bar magnet that points either up or down.

Saam and graduate student Steven Morgan zapped xenon atoms with a strong magnetic field, laser beam and radio-wave pulse so the nuclear spins were aligned in four different configurations in four samples of frozen xenon, each containing about 100 billion billion atoms [billion twice is correct].

Despite differing initial configurations, the "dances" of the xenon spins evolved so they eventually were in sync with each other, as measured by nuclear magnetic resonance, or NMR. That took a few thousandths of a second - something physicists seriously call "long-time behavior."

"This type of common behavior has been a signature of classically chaotic (Newtonian) systems, mostly studied using a computer, but it never had been observed in an experimental system that only can be described by quantum mechanics," Saam says.

As an analogy, imagine billions of people in a huge, unfamiliar city. They start walking around in different places and directions, with little conversation among them. Yet, eventually, they all end up walking in the same direction.

Such behavior in nuclear spins had been predicted in 2005 by the study's third author, physicist Boris Fine of the University of Heidelberg in Germany. Fine had made the prediction by adapting chaos theory to quantum theory.

Order from Chaos

The evolution of disorder into order by the xenon atoms' nuclear spins is a signature of chaos theory, which, contrary to the popular notion, does not imply complete disorder. Instead, chaos theory describes how weather, certain chemical reactions, planetary orbits, subatomic particles and other dynamic systems change over time, with the changes often highly sensitive to starting conditions.

"When you have a [chaotic] system that is characterized by extreme randomness, it paradoxically can produce ordered behavior after a certain amount of time," says Saam. "There is strong evidence that is happening here in our experiment."

The sensitivity to starting conditions is known popularly as "the butterfly effect," based on the fanciful example that a butterfly flapping its wings in South America might set off subtle atmospheric changes that eventually build into a tornado in Texas.

Saam says chaos theory can make predictions about extremely complex motions of many particles that are interacting with each other. The mathematical notion of chaos first was described in the 1890s. Chaos theory was developed in the 1960s, based on classical physics developed in the late 1600s by Sir Isaac Newton. Classical physics says the motion, speed and location of any particle at any time can be determined precisely.

In contrast, quantum mechanics holds that "when things get atom small, our notions of being able to put a specific particle in a specific place with a specific speed at a specific time become blurry," Saam says. So a particle's speed and location is a matter of probability, and "the probability is the reality."

Details of the Study: ‘These Guys are Dancing Together'

Technically, spin is the intrinsic angular momentum of a particle - a concept so difficult to explain in lay terms that physicists usually use the bar magnet analogy.

A nonmagnetic material normally has random spins in the nuclei of its atoms - half the spins are up and half are down, so the net spin is zero. But magnetic fields can be applied so that the spins are aligned - with more up than down, or vice versa.

Physicists can measure the alignment or "polarization" of the spins using NMR's strong magnetic field. Nuclear spins also are used medically: When a patient lies within a magnetic resonance imaging (MRI) device's large magnet, the spins within atoms in the body generate electrical signals that are used to make images of body tissues. Doctors are testing xenon as a way to enhance MRI images of the lungs.

Saam and colleagues used xenon because its spins can be aligned relatively easily.

In each experiment, Saam and Morgan used a magnetic field and a laser to align or "hyperpolarize" the spins in a sample of about 100 billion billion xenon gas atoms so a majority of the spins either were aligned "up" or "down." Then, they froze the gas into a solid at a temperature of 321 degrees below zero Fahrenheit.

Then they applied a radio wave pulse, which "flips" the spins so they all are perpendicular to the magnetic field instead of parallel to it. That makes them start circling around the magnetic field axis like spinning tops.

In this manner, the physicists created four frozen xenon samples. Within each sample, the spins were aligned, but different radio pulses were used to make the initial alignment or configuration of the spins different from one sample to the next.

The scientists then used NMR to watch the spins decay or fade over thousandths of a second.

"Although they are held in place in the crystal structure, the spins can interact with each other and change the direction in which they're pointed in much the same way that magnets interact with each other when brought close together," Saam says.

The initial configuration of spins in each xenon sample evolved in extremely complicated ways due to the presence of billions of interacting spins, and each sample rapidly "lost its memory" of where it started. Such behavior has been known for 60 years.

The surprise was that while each sample's initial NMR signal was radically different from the other, they displayed "identical long-time behavior," says Saam.

"Somehow despite the fact these spins have very complicated interactions with each other and started out in completely different orientations, they end up all moving in the same way after several milliseconds," he says. "That's never been seen before in a quantum mechanical system. These guys are dancing together."

Saam says the technical achievement was that the huge amount of polarization made it possible for NMR to measure an extremely weak spin signal - only one-thousandth as strong as the original signal by the time the samples appeared to behave chaotically.

Provided by University of Utah

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