Scientists discover quantum fingerprints of chaos

October 7 2009

Professor Poul Jessen of the UA College of Optical Sciences runs an experiment that provides long-sought evidence that two very different worlds of quantum mechanics and classical chaos are connected. Credit: Lori Stiles, University of Arizona

Chaotic behavior is the rule, not the exception, in the world we experience through our senses, the world governed by the laws of classical physics.

Even tiny, easily overlooked events can completely change the behavior

of a complex system, to the point where there is no apparent order to most natural systems we deal with in everyday life.

The weather is one familiar case, but other well-studied examples can be found in chemical reactions, population dynamics, neural networks and even the stock market.

Scientists who study "chaos" - which they define as extreme sensitivity to infinitesimally small tweaks in the initial conditions - have observed this kind of behavior only in the deterministic world described by classical physics.

Until now, no one has produced experimental evidence that chaos occurs in the quantum world, the world of photons, atoms, molecules and their building blocks.

This is a world ruled by uncertainty: An atom is both a particle and a wave, and it's impossible to determine its position and velocity simultaneously.

And that presents a major problem. If the starting point for a quantum particle cannot be precisely known, then there is no way to construct a theory that is sensitive to initial conditions in the way of classical chaos.

Yet quantum mechanics is the most complete theory of the physical world, and therefore should be able to account for all naturally occurring phenomena.

"The problem is that people don't see [classical] chaos in quantum systems," said Professor Poul Jessen of the University of Arizona. "And we believe quantum mechanics is the fundamental theory, the theory that describes everything, and that we should be able to understand how classical physics follows as a limiting case of quantum physics."

EXPERIMENTS REVEAL CLASSICAL CHAOS IN QUANTUM WORLD

Now, however, Jessen and his group in UA's College of Optical Sciences have performed a series of experiments that show just how classical chaos spills over into the quantum world.

The scientists report their research in the Oct. 8 issue of the journal *Nature* in an article titled, "Quantum signatures of chaos in a kicked top."

Their experiments show clear fingerprints of classical-world chaos in a quantum system designed to mimic a textbook example of chaos known as the "kicked top."

The quantum version of the top is the "spin" of individual laser-cooled cesium atoms that Jessen's team manipulate with magnetic fields and laser light, using tools and techniques developed over a decade of painstaking laboratory work.

"Think of an atom as a microscopic top that spins on its axis at a constant rate of speed," Jessen said. He and his students repeatedly changed the direction of the axis of spin, in a series of cycles that each consisted of a "kick" and a "twist".

Because spinning atoms are tiny magnets, the "kicks" were delivered by a pulsed magnetic field. The "twists" were more challenging, and were achieved by subjecting the atom to an optical-frequency electric field in a precisely tuned laser beam.

They imaged the quantum mechanical state of the atomic spin at the end of each kick-and-twist cycle with a tomographic technique that is

conceptually similar to the methods used in medical ultrasound and CAT scans.

The end results were pictures and stop-motion movies of the evolving quantum state, showing that it behaves like the equivalent classical system in some significant ways.

One of the most dramatic quantum signatures the team saw in their experiments was directly visible in their images: They saw that the quantum spinning top observes the same boundaries between stability and chaos that characterize the motion of the classical spinning top. That is, both quantum and classical systems were dynamically stable in the same areas, and dynamically erratic outside those areas.

A NEW SIGNATURE OF CHAOS CALLED 'ENTANGLEMENT'

Jessen's experiment revealed a new signature of chaos for the first time. It is related to the uniquely quantum mechanical property known as "entanglement."

Entanglement is best known from a famous thought experiment proposed by Albert Einstein, in which two light particles, or photons, are emitted with polarizations that are fundamentally undefined but nevertheless perfectly correlated. Later, when the photons have traveled far apart in space, their polarizations are both measured at the same instant in time and found to be completely random but always at right angles to each other.

"It's as though one photon instantly knows the result for the other and adjusts its own polarization accordingly," Jessen said.

By itself, Einstein's thought experiment is not directly related to quantum chaos, but the idea of entanglement has proven useful, Jessen added.

"Entanglement is an important phenomenon of the quantum world that has no classical counterpart. It can occur in any quantum system that consists of at least two independent parts," he said.

Theorists have speculated that the onset of chaos will greatly increase the degree to which different parts of a quantum system become entangled.

Jessen took advantage of atomic physics to test this hypothesis in his laboratory experiments.

The total spin of a cesium atom is the sum of the spin of its valence electron and the spin of its nucleus, and those spins can become quantum correlated exactly as the photon polarizations in Einstein's example.

In Jessen's experiment, the electron and nuclear spins remained unentangled as a result of stable quantum dynamics, but rapidly became entangled if the dynamics were chaotic.

Entanglement is a buzzword in the science community because it is the foundation for quantum cryptography and quantum computing.

"Our work is not directly related to quantum computing and communications," Jessen said. "It just shows that this concept of entanglement has tendrils in all sorts of areas of quantum physics because entanglement is actually common as soon as the system gets complicated enough."

Source: University of Arizona (news : web)