Entanglement in a flash (w/ video)

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(Phys.org) —JQI researchers under the direction of Chris Monroe have produced quantum entanglement between a single atom's motion and its spin state thousands of times faster than previously reported, demonstrating unprecedented control of atomic motion. This work, which may lead to faster and better quantum computer logic gates, is described a recent issue of *Physical Review Letters*.

This experiment focuses on using highly energetic laser pulses to perform qubit operations. Previously, they set a record for the fastest spin flip in these systems: a mere 50 picoseconds. Here they continue their work by blasting the ion so strongly that the qubit quickly becomes linked to its motion. Such speedy operations are more typically associated with solid state systems such as electrons in semiconductors or superconductors. Here the speed of operations combined with the pristine quantum environment of atoms provide the best of both worlds.

Though subdued, trapped ions are not entirely tame. Like caged tigers pacing back and forth, they exhibit regular motion, oscillating inside an electrostatic trap at a particular frequency. This motion is used as a medium for entangling multiple ions. The motion is also the enemy, introducing noise because logic operations and/or experiments are typically completed after many trap oscillation cycles have passed. In quantum computing, speed is critical because such noise can destroy the quantum-ness of the system.

Providing a solution, this team has achieved spin-motion entanglement on an ultrafast timescale of about 3 nanoseconds, nearly a thousand of times faster than the trap oscillation time. For reference, a beam of light travels only a foot in one nanosecond. Blinking your eye is about 100 million times slower than this entangling process.

The qubit is initially prepared in a quantum coherent superposition of two states: "spin-up" and "spin-down." Laser pulses are then used to kick spin-up in one direction and spin-down in the opposite direction. As a result, the ion is in an entangled state, which is a combination of spin-up/moving left, and spin-down/moving right.

To create this spin-dependent kick, laser pulses arrive from opposite directions, overlapping to form a diffraction grating. The ion qubit interacts with the light grating by absorbing and emitting a photon. Photons carry momentum, and so the absorption/emission cycle kicks the ion qubit. For a fixed color of light, the kick strength depends primarily on the laser power. The light spectrum also contains a frequency that induces spin flips. Thus the ion qubit "feels" this kick based on its associated spin: opposite spin states are brushed in opposite directions. This is analogous when atoms are diffracted by an optical lattice; but here the resulting diffraction pattern depends on the qubit's spin state (up or down).

In the ion trap, the arrival of the first set of overlapping pulses creates many discrete momentum states, each tangled with an alternating spin. Subsequent pulses serve to further accumulate momentum states. The goal is to apply the grating kicks in a way that builds up a particular diffraction pattern corresponding to just two momentum states, each entangled with an opposing spin. The process of building up amplitude in an interference pattern can be thought of in terms of the not-so-quantum trampoline. Say that my daughter is jumping at a rate of 0.5 bounce per second. Some of her friends can build up amplitude by simultaneously jumping at the same time, or "in phase." Some kids can also jump at a rate that is an integer (1X, 2X, 3X…) multiple of the other kids, which will create a kind of interference pattern of jumps. The kids will go the highest at the time when the most kids are simultaneously jumping. Similarly, if the team wants to accumulate more and more momentum, they need to apply the grating (kick) at a particular time with respect to the ion trap oscillations.

At the other extreme, the kids can all jump at random times and their bounces will cancel each other leading to reduced or even zero jumping amplitude over all. You could imagine that perfect cancellation could take place at special combinations of jumps as well. Likewise, the team can even gain back the original spin superposition, with the motion entirely removed. If they flash on the grating at the precise moment the motion packets overlap, this kick neatly disentangles the spin from the motion.

This exquisite control over the spin-motion entanglement by adjusting the delay between kicks is equivalent to an interferometer using pairs of spin dependent kicks. Interferometers have numerous applications, ranging from radio astronomy to cellular imaging. When the same type of ultrafast interferometer applied to multiple atoms, their internal spin states can become entangled, which is a fundamental building block of a quantum computer.

More information: Mizrahi, J. et al. Ultrafast Spin-Motion Entanglement and Interferometry with a Single Atom, *Physical Review Letters*, 103, 203001 (2013). prl.aps.org/abstract/PRL/v110/i20/e203001

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