Physicists show ion pairs perform enhanced 'spooky action'

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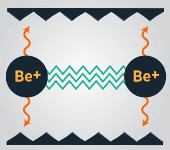
VERY SPOOKY ACTION BETWEEN IONS AT NIST

Do pairs of ions (electrically charged atoms) obey the **"spooky" rules of quantum mechanics**, in which they have **fuzzy undetermined properties** or seem to send **hidden messages** to each other faster than light or any forces could travel between them?

Or can their behavior be explained through **classical physics**, in which particles have **well defined properties** and can only influence each other at light speeds or slower?

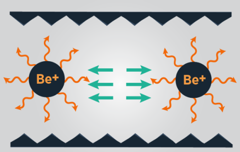
A new **NIST experiment** measured the degree to which measurements of two ions depart from classical physics.

In the experiment, two beryllium ions are **"entangled"** in a trap. This means their **spins are correlated** or interlinked.



DETECTION LOOPHOLE:
The detectors that measure the particles may not capture enough data to show what is really happening between the particles.

Detection loophole closed!
Detection was almost 100% efficient.



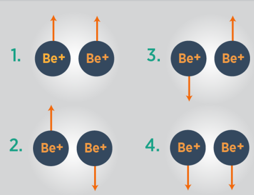
The pair is **separated** and researchers use lasers to **rotate the spins of ions** by a random amount from a set of 2-15 angles.

This makes it a **"chained" Bell test**—the choice of angle on one ion affects the choice for the angle on the second ion.

MEMORY LOOPHOLE:
Happens when each experimental measurement influences the next one, or the experimental conditions change over time, skewing the results.

Memory loophole closed!
Measurement choices were randomized. Robust analysis of data.

FOUR POSSIBLE OUTCOMES



The researchers measure whether the **spins** are the same or different. The measurements indicated **"non-spooky"** classical physics can explain the ions' behavior during at most 33% of the measurements.

Conclusion: The ions are **67% SPOOKY!**

DESIGN: K. IRVINE/NIST

NIST National Institute of Standards and Technology U.S. Department of Commerce

www.nist.gov

Infographic accompanying news story entitled NIST Physicists Show Ion Pairs Perform Enhanced 'Spooky Action' Credit: K. Irvine/NIST

Adding to strong recent demonstrations that particles of light perform what Einstein called "spooky action at a distance," in which two separated objects can have a connection that exceeds everyday experience, physicists at the National Institute of Standards and Technology (NIST) have confirmed that particles of matter can act really spooky too.

The NIST team entangled a pair of beryllium ions (charged atoms) in a trap, thus linking their properties, and then separated the pair and performed one of a set of possible manipulations on each ion's properties before measuring them. Across thousands of runs, the pair's measurement outcomes in certain cases matched, or in other cases differed, more often than everyday experience would predict. These strong correlations are hallmarks of quantum entanglement.

What's more, statistical calculations found the ion pairs displayed a rare high level of spookiness.

"We are confident that the ions are 67 percent spooky," said Ting Rei Tan, lead author of a new *Physical Review Letters* paper about the experiments.

The experiments were "chained" Bell tests, meaning that they were constructed from a series of possible sets of manipulations on two ions. Unlike earlier experiments, these were enhanced Bell tests in which the number of possible manipulations for each ion was chosen randomly from sets of at least two and as many as 15 choices.

This method produces stronger statistical results than conventional Bell tests. That's because as the number of options grows for manipulating each ion, the chance automatically decreases that the ions are behaving by classical, or non-quantum, rules. According to classical rules, all objects must have definite "local" properties and can only influence each other at the speed of light or slower. Bell tests have been long used to show that through quantum physics, objects can break one or both of these rules, demonstrating spooky action.

Conventional Bell tests produce data that are a mixture of local and spooky action. Perfect chained Bell tests can, in theory, prove there is zero chance of local influence. The NIST results got down to a 33 percent chance of local influence—lower than conventional Bell tests can achieve, although not the lowest ever reported for a chained test, Tan said.

However, the NIST experiment broke new ground by closing two of three "loopholes" that could undermine the results, the only chained Bell test to do this using three or more options for manipulating material particles. The results are good enough to infer the high quality of the entangled states using minimal assumptions about the experiment—a rare achievement, Tan said.

Last year, a different group of NIST researchers and collaborators closed all three loopholes in conventional Bell tests with particles of light. The new ion experiments confirm again that spooky action is real.

"Actually, I believed in quantum mechanics before this experiment," Tan said with a chuckle. "Our motivation was we were trying to use this experiment to showcase how good our trapped ion quantum computing technology is, and what we can do with it."

The researchers used the same ion trap setup as in previous quantum computing experiments. With this apparatus, researchers use electrodes and lasers to perform all the basic steps needed for quantum computing, including preparing and measuring ions' quantum states; transporting ions between multiple trap zones; and creating stable quantum bits (qubits), qubit rotations, and reliable two-qubit logic operations. All these features were needed to conduct the chained Bell tests. Quantum computers are expected to one day solve problems that are currently intractable such as simulating superconductivity (the flow of electricity without resistance) and breaking today's most popular data encryption codes.

In NIST's chained Bell tests, the number of settings (options for different manipulations before measurement) ranged from two to 15. The manipulations acted on the ions' internal energy states called "spin up" or "spin down." The researchers used lasers to rotate the spins of the ions by specific angles before the final measurements.

Researchers performed several thousand runs for each setting and collected two data sets 6 months apart. The measurements determined the ions' spin states. There were four possible final results: (1) both ions spin up, (2) first ion spin up and second ion spin down, (3) first ion spin down and second ion spin up, or (4) both ions spin down. Researchers measured the states based on how much the ions fluoresced or scattered light—bright was spin up and dark was spin down.

The NIST experiment closed the detection and memory loopholes, which might otherwise allow ordinary classical systems to appear spooky.

The detection loophole is opened if detectors are inefficient and a subset of the data are used to represent the entire data set. The NIST tests closed this loophole because the fluorescence detection was near 100 percent efficient, and the measurement outcomes of every trial in each experiment were recorded and used to calculate results.

The memory loophole is opened if one assumes that the outcomes of the trials are identically distributed or there are no experimental drifts. Previous chained Bell tests have relied on this assumption, but the NIST test was able to drop it. The NIST team closed the memory loophole by performing thousands of extra trials over many hours with the set of six possible settings, using a randomly chosen setting for each trial and developing a more robust statistical analysis technique.

The NIST experiments did not close the locality loophole, which is open if it is possible for the choice of settings to be communicated between the ions. To close this loophole, one would need to separate the ions by such a large distance that communication between them would be impossible, even at light speed. In the NIST experiment, the ions had to be positioned close together (at most, 340 micrometers apart) to be entangled and subsequently measured, Tan explained.

More information: Chained Bell Inequality Experiment with High-Efficiency Measurements, T. R. Tan, Y. Wan, S. Erickson, P. Bierhorst, D. Kienzler, S. Glancy, E. Knill, D. Leibfried, and D. J. Wineland, *Phys. Rev. Lett.* 118, 130403 – Published 28 March 2017, journals.aps.org/prl/abstract/ … ysRevLett.118.130403

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