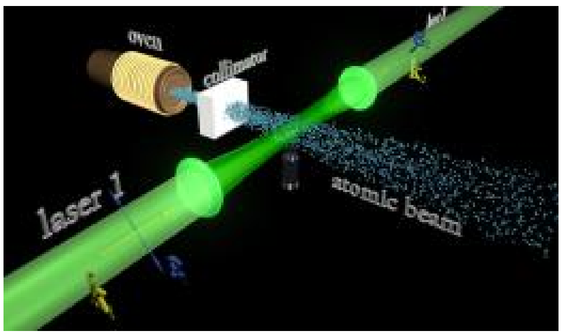
Experiment tests underpinnings of quantum field theory, Bose-Einstein statistics of photons

June 25 2010, By Bob Sanders



Two opposed laser beams, identical except for polarization, attempt to excite forbidden two-photon transitions in a beam of barium atoms. (Image Damon English)

(PhysOrg.com) -- Of all the assumptions underlying quantum mechanics and the theory that describes how particles interact at the most elementary level, perhaps the most basic is that particles are either bosons or fermions. Bosons, such as the particles of light called photons, play by one set of rules; fermions, including electrons, play by another.

Seven years ago, University of California, Berkeley, physicists asked a fundamental and potentially disturbing question: Do bosons sometimes play by fermion rules? Specifically, do photons act like bosons all the time, or could they sometimes act like fermions?

Based on the results of their experiment to test this possibility, published June 25 in the journal Physical Review Letters, the answer is a solid “no.”

The theories of physics - including the most comprehensive theory of elementary particles, Quantum Field Theory, which explains nature's electromagnetic, weak and strong nuclear forces (but not gravity) - rest on fundamental assumptions, said Dmitry Budker, UC Berkeley professor of physics. These assumptions are based on how the real world works, and often produce amazingly precise predictions. But some physicists would like to see them more rigorously tested.

"Tests of (these assumptions) are very important," said Budker. "Our experiment is distinguished from most other experimental searches for new physics in that others can usually be incorporated into the existing framework of the standard model of particles and forces. What we are testing are some of the fundamental assumptions on which the whole standard model is based."

Among these assumptions is the boson/fermion dichotomy, which is mandated by the Spin-Statistics Theorem of quantum field theory. Bosons, which are governed by Bose-Einstein statistics, are particles with an intrinsic spin of 0, 1, 2 or another integer, and include photons, W and Z bosons, and gluons. The fermions, governed by Fermi-Dirac statistics, are all particles with odd-half-integer spins - 1/2, 3/2, 5/2, etc. - and include the electron, neutrinos, muons and all the quarks, the fundamental particles that make up protons and neutrons.

Bosons can pile on top of one another without limit, all occupying the same quantum state. At low temperatures, this causes such strange phenomena as superconductivity, superfluidity and Bose-Einstein condensation. It also allows photons of the same frequency to form coherent laser beams. Fermions, on the other hand, avoid one another.

Electrons around a nucleus stack into shells instead of collapsing into a condensed cloud, giving rise to atoms with a great range of chemical properties.

"We have this all-important symmetry law in physics, one of the cornerstones of our theoretical understanding, and a lot depends on it," said Budker, who is also a faculty scientist at Lawrence Berkeley National Laboratory (LBNL). "But we don't have a simple explanation; we have a complex mathematical proof. This really bothered a lot of physicists, including the late Nobel laureate Richard Feynman."

“It’s a shame that no simple explanation exists,” said Budker, because it ties together basic assumptions of modern physics. "Among these assumptions are Lorentz invariance, the core tenet of special relativity, and invariance under the CPT (charge-parity-time) transformation, the idea that nature looks the same when time is reversed, space is reflected as in a mirror, and particles are changed into antiparticles. Lorentz invariance results from the entanglement of space and time, such that length and time change in reference frames moving at constant velocity so as to keep the speed of light constant.

”Another one of the assumptions of the spin-statistics theorem is microcausality,” said UC Berkeley post-doctoral fellow Damon English. "A violation wouldn’t exactly be the same type of paradox as travelling back in time to kill your great-grandfather, but more along the lines of receiving a flash of light before it was emitted."

In their experiment, Budker, English and colleague Valeriy Yashchuk, a staff scientist at LBNL's Advanced Light Source, were able to reduce the existing limit that photons act like fermions by more than a factor of a thousand.

"If just one pair of photons out of 10 billion had taken the bait and behaved like fermions, we would have seen it," English said. "Photons are bosons, at least within our experimental sensitivity."

In 1999, Budker, and David DeMille, now a professor of physics at Yale University, completed a similar preliminary experiment, conducted partially at Amherst College and partially at UC Berkeley, establishing that photons act as bosons, not fermions. The new experiment improves the precision of the Amherst/UC Berkeley experiment by a factor of about 3,000.

The experiment bombarded barium atoms with photons in two identical laser beams and looked for evidence that the barium had absorbed two photons of the same energy at once, thereby kicking an electron into a higher energy state. The particular two-photon transition the scientists focused on was forbidden only by the Bose-Einstein statistics of photons. If photons were fermions, the transition would "go like gang-busters," said English.

The experiment detected no such "fermionic" photons, establishing the distinctness of bosons and fermions, and validating the assumptions underlying Bose-Einstein statistics and Quantum Field Theory.

"Spacetime, causality, and Lorentz invariance are safe,…for now," English said.

Using the same tabletop experiment, they also observed for the first time that the spin of the nucleus can alter the atomic environment to allow the otherwise bose-statistics forbidden transition. The most common isotopes of barium, barium-138 and barium-136, have zero nuclear spin, so the electron levels are undisturbed and the two-photon absorption is impossible. Two other isotopes, barium-135 and -137, have a nuclear spin of 3/2, which creates a hyperfine splitting of the electron energy levels and enables still very weak, but detectable, two-photon absorption.

“We will keep looking, because experimental tests at ever increasing sensitivity are motivated by the fundamental importance of quantum statistics,” said Budker. “The spin-statistics connection is one of the most basic assumptions in our understanding of the fundamental laws of nature.”

More information: “Spectroscopic test of Bose-Einstein statistics for photons,” by Damon English, Valeriy Yashchuk, and Dmitry Budker, appears in the June 25 issue of Physical Review Letters and is available online.

Provided by University of California - Berkeley

Citation: Experiment tests underpinnings of quantum field theory, Bose-Einstein statistics of photons (2010, June 25) retrieved 23 April 2024 from
https://phys.org/news/2010-06-underpinnings-quantum-field-theory-bose-einstein.html