August 30, 2000

'Dead' Time Between Photon Emissions From Quantum Dots Proves Quantum Theory of Light

Result Occurring at Room Temperature Surprises Researchers, Makes Applications in Quantum Computing and Optics Promising

Santa Barbara, Calif.--A research team at the University of California at Santa Barbara (UCSB) has proved that a "dead" time exists between emission of photons from a single quantum dot. The experiment, the first to detect this phenomenon variously called "photon anti-bunching" or "quantum correlation" for a single semiconductor quantum dot, represents a verification of the quantum theory of light.

Achievement of that experimental milestone alone would have merited publication of the research in Nature. But the article in the Aug. 31 issue announces another result that surprised the researchers themselves -- that quantum correlation could be detected at room temperature. That finding is significant for applications in quantum computing and quantum optics.

Quantum dots are made by enclosing a small amount of a semiconducting material within another semiconducting material. Energy added in the form of light particles or photons causes a particle (electron, hole, or an electron-hole pair) in the contained material to move to a higher energy state. Band gap refers to the difference between the original and the more energetic particle states.

In quantum dots the band gap of containing materials is higher than the band gap of the contained materials. That difference in band gaps leads to input energy being trapped in the smaller band-gap material. That energy is released in the form of a photon.

The experiment described in the Nature article "Quantum Correlation Between Photons From a Single Quantum Dot at Room Temperature" showed that an interval of time existed between the emission of photons from a single quantum dot. In other words, the energy emitted was not continuous but in packets or quanta, as the theory of quantum mechanics prescribes.

The down time between emissions is accounted for by the charge carrier moving to a lower energy state and then absorbing more energy to move to the higher state before being able to emit another photon.

Such experimental verification of the quantum nature of energy emitted from a single quantum dot was done for a single atom in 1977 and for a single molecule in 1992. The current experiment shows that in terms of absorbing and emitting energy (i.e., the electromagnetic force), quantum dots behave like atoms -- hence the appellation, "artifical" atom.

UCSB researchers with different interests teamed up to do the experiment. Ataç Imamoglu, professor of c omputer and electrical engineering and of physics, and his postdoctoral fellow and the paper's first author, Peter Michler, focused on the implications of the research for quantum computing.

The other four authors are members of the Chemistry Department, including associate professor Steve Buratto and his graduate student, Michael Mason, and postdoctoral fellow Paul Carson. Assistant professor Geoffrey Strouse, a synthetic chemist, made the nanoscale semiconductor quantum dots.

Those quantum dots consisted of a core material cadmium selenide (low band gap) enveloped in zinc selenide (high band gap) enveloped in an organic molecule that acts like a greaseball to keep the aggregates in a solvent from clumping together. Synthesizing semiconductors via the techniques of chemistry (in contrast to the more standard Molecular Beam Epitaxy [MBE] and Metal-Organic Chemical Vapor Deposition [MOCVD] techniques of engineering) is about 10 years old.

Quantum Computing

Imamoglu has laid out a multi-step research program which represents, in effect, a campaign he means to conduct on the overarching problem of quantum information processing. Proving the quantum correlation effect for quantum dots is the first step in his program because it shows that quantum dots consist of a two-level system.

The idea eventually is to use spin states of electrons as the quantum-bits or Q-bits analogous to the zero and one binary code of electronic computing. That code requires a two-level system. The reported work demonstrates that a single quantum dot exhibits the necessary two-level system and therefore opens the way towards quantum information processing in an all semiconductor system.

Top, plot of continuous light in contrast to bottom,
showing light as discretely emitted particles or photons.

Imamoglu said, "In a sense we were expecting that a single quantum dot would behave the way we proved it behaves. But the real surprise -- something I wasn't expecting -- was getting this result at room temperature. That's exciting in terms of applications because it is so much easier to operate at room temperature than at cryogenic temperature."

Why was obtaining the result at room temperature such a surprise?

Imamoglu explains that with other features that have been identified in both atoms and quantum dots or "artificial" atoms, the similarity in features occurs when the quantum dots are at low temperature. "What is nice in our experiments," said Imamoglu, "is that this property of generating non-classical light is a robust property that survives at room temperature despite other signatures being washed away. That is our most striking result!"

Buratto's long-term research interests diverge from Imamoglu's. He and his collaborators "want to explore the fundamental photophysics of these kind of systems. We want to understand the excited state dynamics and measure the distribution of lifetimes."

He explains that for a physical chemist nanoscale quantum dots are like snowflakes, each with a different structure and a different longevity in the excited state. "The idea," said Buratto, "is to plot the distribution of lifetimes to see if we can detect a pattern and see if we can figure out what determines how long a given particle stays in the excited state."

Does Buratto envision any practical consequences of such fundamental photophysics explorations?

"Possibly a whole new way of making Light Emitting Diodes (LEDs) and lasers," he responded. "Think, for instance, of making a laser from an ordered array of self-assembled quantum dots."

Note: Professor Imamoglu can be reached in Istanbul, Turkey, by phone at 011-90-216-308-3482 or by e-mail at atac@ece.ucsb.edu. Professor Buratto can be reached at (805) 893-3393 or buratto@chem.ucsb.edu.

Images

Media Contact

Tony Rairden
trairden@engineering.ucsb.edu
805.893.4301