SOLID-STATE PHYSICS

Join the dots

Galina Khitrova and H. M. Gibbs

A new variation on an old theme in atomic physics, a spectral distortion known as the Fano effect, has been revealed — not in an atom, but in an artificial nanostructure known as a quantum dot.

The Fano effect is a quantum-mechanical interference phenomenon characterized by an asymmetrical broadening of spectral lines that pops up all over the place when certain materials absorb light. In 1981, it was predicted[1] that using light from a strong resonant laser beam would completely alter the spectrum of the Fano effect. That prediction has still not been fulfilled; but on page 311 of this issue, Kroner *et al.*[2] describe how using a resonant laser beam reveals a Fano effect that had hitherto remained obscured.

Rather than using atoms, as has generally been the case in investigations of the Fano effect, the authors' demonstration uses single quantum dots. These nanoscale semiconducting structures are being used not only to study the fundamental interactions between photons and systems of energy levels similar to those in atoms, but also for constructing minuscule light-emitting diodes and lasers. Kroner and colleagues' Fano effect could have practical implications because it represents a sensitive way to detect the coupling of a transition between two energy levels to a continuum of energy states. Such couplings are usually undesirable for applications using quantum dots.

Kroner and colleagues' quantum dots are made of the semiconductor indium arsenide (InAs) capped with a thin layer of gallium arsenide (GaAs). When light is shone on one of these quantum dots, the absorption of a photon excites an electron out of the semiconductor's valence band and into its conduction band. This excitation produces not only an electron, but also a hole, equivalent to a positive charge, where the electron used to be. Both the electron and the hole are tightly confined in three dimensions within the dot. Their energies are thus quantized into a set of discrete levels, just as in an atom.

By adjusting the thickness of the GaAs capping layer and applying an electric field, the authors also created an effective quantum well, which contains a two-dimensional continuum of energy states for holes at energies overlapping the discrete energy of the hole, but spatially separated by a thin barrier. A hole, generated along with an electron by absorption of an incident photon, can tunnel into this well. By measuring the absorption spectrum of an individual quantum dot, Kroner *et al.* looked for Fano interference between these two ways of absorbing a photon: the usual transition producing an electron and a hole in discrete energy levels, and the much weaker discrete–continuum transition through the quantum tunnel.

With a very weak laser beam, the authors saw no hint of the weak tunnel coupling. But as they increased the laser power, the discrete–discrete absorption decreased towards the level of the discrete–continuum transition[2]. Interference between these two pathways when they are of almost equal strength causes the absorption spectrum to take on the asymmetrical shape characteristic of a strong Fano effect. The credibility of this interpretation is strengthened by the fact that the asymmetry in the spectrum disappears if the continuum state is removed by making the capping layer thinner.

So what? The important point to bear in mind is that the complete isolation of discrete–discrete transitions in quantum dots is essential for almost all fundamental experiments on single quantum dots. This isolation could be spoiled by a small coupling to an unknown continuum. By driving the discrete–discrete transition with a continuous-wave laser, a relatively weak leak to an unwanted continuum can be detected through the clear signal of Fano distortion. The effect will thus be a useful diagnostic tool in designing quantum-dot structures to eliminate such effects.

This research is the latest in a long progression ever since it was first proposed in 1970[3] that man-made quantum structures could be designed that would mimic the quantized energy levels of an atom's potential well. The experimental breakthrough came with the development of the technique known as molecular-beam epitaxy, which allows single layers of semiconductor materials to be grown one on top of each other. Quantized energy levels were soon observed[4] in quantum energy wells produced by growing GaAs between potential barriers consisting of the closely related semiconductor aluminium gallium arsenide (AlGaAs).

A few years later, Alexei Ekimov hypothesized that the losses in optical fibres that were then preventing their use for telecommunications were the result of semiconductor impurities. He introduced controlled amounts of semiconductor compounds into glass to test that theory. Ekimov noticed bumps in the absorption spectra of the glass that became more widely separated in energy as the volumes of the semiconductor regions were reduced. By analogy with the quantum-well phenomenon, he concluded[5] that this was a signature of three-dimensional quantum confinement[6]. The quantum dot had arrived.

Quantum dots in glass and in colloidal solutions are useful for some applications. But it was obvious that the ability to grow dots within the easily doped heterostructures that dominate the world of semiconductor light-emitters would be highly desirable. This would enable the production of quantum-dot lasers that would require a reduced threshold current and maintain greater wavelength stability against temperature changes. The development[7] of self-organization techniques that use mechanical strain to trick the usual planar growth of molecular-beam epitaxy into becoming three-dimensional has permitted the control of quantum-dot density, diameter and height. High dot densities are ideal for lasers of very small volume. Low dot densities allow the isolation of a single quantum dot, providing sources of single photons on demand and quantum entangled states for quantum information science[8].

In all this, it is curious and instructive to note the mutual benefits of basic and applied research. An applied goal, reducing losses in optical fibres, led to the fundamental discovery of quantum dots; the applied goal of growing quantum dots for lasers resulted in dots that now compete with atoms for use in basic research. A quantum dot has the distinct advantage over an atom of being nailed to one place, and not needing multiple highly stabilized laser beams to trap it; the dot structure is also monolithic, tiny and long-lived.

Indeed, quantum dots have arguably already become more useful than atoms in a number of instances, such as an efficient source of single photons on demand[9]. Kroner and colleagues' use[2] of the nonlinear Fano effect as, in essence, a tremendous sensitivity amplifier for the spectroscopic identification of weak continuum spectra adds another instance to the growing list. ■

Galina Khitrova and H. M. Gibbs are in the
College of Optical Sciences, University of
Arizona, Tucson, Arizona 85721, USA.
e-mail: galina@optics.arizona.edu

1. Rzazewski, K. & Eberly, J. H. *Phys. Rev. Lett.* **47,** 408–412 (1981).
2. Kroner, M. *et al. Nature* **451,** 311–314 (2008).
3. Esaki, L. & Tsu, R. *IBM J. Res. Dev.* **14,** 61–65 (1970).
4. Dingle, R., Wiegmann, W. & Henry, C. H. *Phys. Rev. Lett.* **33,** 827–830 (1974).
5. Ekimov, A. I. & Onushchenko, A. A. *JETP Lett.* **34,** 345–349 (1981).
6. Ekimov, A. I., Efros, Al. L. & Onushchenko, A. A. *Solid State Commun.* **56,** 921–924 (1985).
7. Petroff, P. M., Lorke, A. & Imamoglu, A. *Phys. Today* **54** (5), 46–52 (2001).
8. Khitrova, G., Gibbs, H. M., Kira, M., Koch, S. W. & Scherer, A. *Nature Phys.* **2,** 81–90 (2006).
9. Pelton, M. *et al. Phys. Rev. Lett.* **89,** 233602 (2002).