sions that happen to occur inside the hydrogen envelope of a massive companion. But Smith points out that SN 2006gy's record luminosity would require an implausibly massive envelope. And its spectrum has none of the telltale features one would expect from an exploding white dwarf.

So much light

How would pair-formation instability produce the observed 10^{44} J of light? The Berkeley–Texas paper argues that the very weak x-ray signal recorded by *Chandra* makes it difficult to account for most of the luminosity by collision between the supernova's ejecta and the circumstellar material. Instead the paper suggests that the light comes mainly from heating by the radioactive decay of nickel-56 produced in the supernova. The group calculates that the observed luminosity implies about 22 $M_\odot$ of ^{56}Ni, orders of magnitude more than an ordinary core-collapse supernova produces. That would require total pair-instability obliteration of the progenitor star.

Woosley and coworkers Alex Heger and Sergei Blinnikov have been comparing SN 2006gy's light curve to detailed simulations of the much gentler pulsational pair-instability scenario. Taking prior stellar-wind mass losses to be significantly less than is traditionally assumed, they argue that the progenitor star was born with a mass of something like 110 $M_\odot$. Experiencing pair-formation instability for the first time some 10 years ago, they calculate, it expelled its H envelope plus about 5 $M_\odot$ of outer core at low velocity. The resulting light show would have been too faint to see at a distance of 200 million light-years.

The superluminous SN 2006gy, they conclude, manifests the residual core's second bout of pair-formation instability, which launched less material than the first, but at much higher velocity and a total kinetic energy of about 10^{44} J. That, however, is no more than the kinetic energy of the ejecta from an ordinary type II core collapse. So what makes a pulsational pair-formation supernova so much brighter?

An ordinary type II supernova converts only about 1% of the kinetic energy of the ejected core material to light. The rest is lost adiabatically as the ejecta expand the star's envelope. But in the pulsational scenario, the ejecta first encounter the shell of liberated envelope some 10^{11} km from the star. In such an encounter, Woosley argues, almost all the kinetic energy is converted to light. Radioactivity plays no significant role, and x-ray emission would not be seen until long after the optical spectacle is over.

When observations resume in August, the matter may be settled by telltale evolution of the light curve, the spectrum, or the x-ray afterglow. "If, as it seems, there are no stars in the modern epoch massive enough for a single obliterating pair-formation explosion," says Woosley, "it may be that the brightest supernovae we ever see come from stars that can give repeat performances. And when the star finally does die in a type Ic core collapse, its passing is likely to be accompanied by a gamma-ray burst."

Bertram Schwarzschild

References

1. E. Ofek et al., *Astrophys. J. Lett.* **659**, L13 (2007).
2. N. Smith et al., *Astrophys. J.* (in press), available at http://arxiv.org/abs/astro-ph/0612617 (version 3).
3. A. Heger, S. E. Woosley, *Astrophys. J.* **567**, 532 (2002).
4. N. Smith, S. P. Owocki, *Astrophys. J. Lett.* **645**, L45 (2007).

Engineering the energy levels in quantum dots leads to optical gain

The achievement charts a straightforward path to the first colloidal quantum-dot lasers.

Quantum dots make nearly ideal photonic devices. And colloidal chemistry can make nearly ideal quantum dots. Measuring some 1–6 nm across, such QDs are semiconductor crystals in which the potential-energy barriers at the dot's boundaries strongly confine the electron wavefunctions in three dimensions. Owing to that confinement, a QD's electronic response to a photon is much like that of an atom, producing a discrete energy spectrum that arises from the excitation of electron–hole pairs. The electron and hole that make up the pair, called an exciton, attract each other electrostatically and can recombine to create a photon extremely efficiently, a property that makes the dots strong light emitters.

What's more, the wavelength of that light emission can be tuned over a wide range simply by tailoring the size of QDs grown in solution. And because such QDs can be chemically manipulated like large molecules, they can be painted onto surfaces, incorporated into polymer or glass matrices, and placed in a variety of microcavities, waveguides, or optical fibers.

Despite nearly 20 years of effort, however, no practical optical amplifier or laser has emerged from work on colloidal nanocrystals. The problem lies in the fact that the energy levels associated with their light emission are nearly degenerate. That is, the energy required to excite one electron is about the same as that required to excite a second one to form a biexciton. The stimulated emission of a photon when a conduction-band electron recombines with its valence-band hole is then balanced by the photon's reabsorption by an electron remaining in the valence band (see figure 1a). As in other lasing media, achieving optical gain—more photons out than in—in QDs requires that the number of electrons in the excited state exceed that in the ground state. Population inversion, therefore, occurs only if the number of excitons per QD is, on average, greater than one.

Perversely, although biexciton states set the stage for optical gain, they severely hamper achieving it. Confined in the tiny volume of the same QD, the two excitons interact strongly enough that one annihilates the other in a process known as Auger recombination. In that process, the energy of one exciton is transferred to the electron or hole of the other. The highly excited electron–hole pair then relaxes to the ground state through the emission of lattice phonons rather than a photon, typically within 100 picoseconds, and destroys the population inversion.

In 2000 Victor Klimov (Los Alamos National Laboratory), Moungi Bawendi (MIT), and their colleagues realized that although the competition between radiative and nonradiative decay complicates the development of stimulated emission in strongly confined QDs, it doesn't inherently prevent it.[1] One way to ameliorate the problem is to chemically passivate the dots, which reduces absorption losses such as the trapping of electrons and holes at surface defect sites. And by packing the dots closely together, the team could prompt them

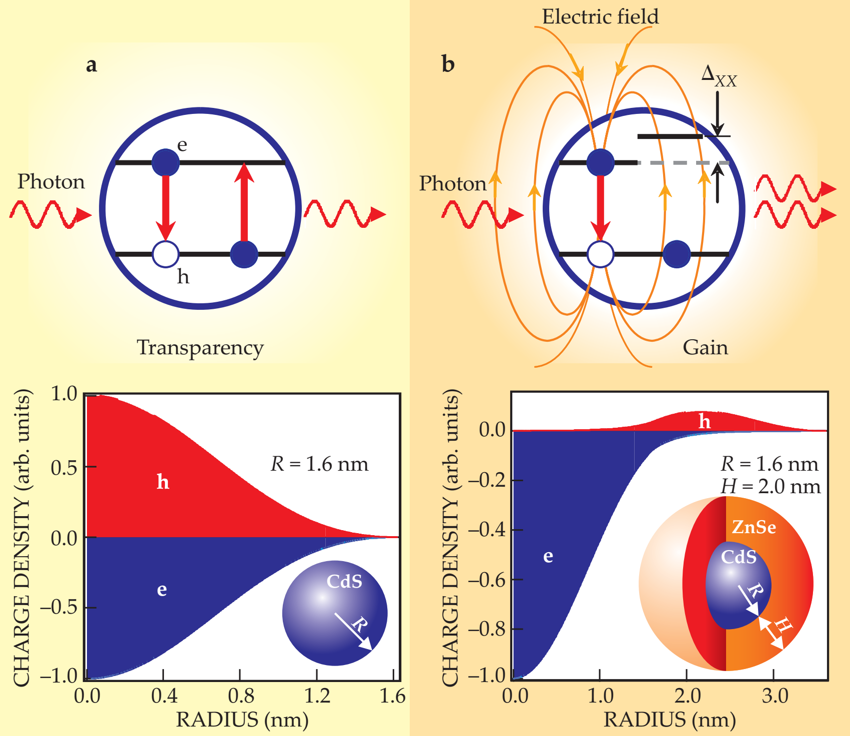

Figure 1. Single-exciton gain. **(a)** The light-emitting transition in conventional, homogeneous quantum dots can be described in terms of a two-level system in which each QD contains two electrons. The photon created from the stimulated recombination of an electron–hole pair, or exciton, is about as likely to be reabsorbed by the other electron in the dot to form a second exciton (loss) as it is to pass unabsorbed (gain). The net effect is transparency. The degeneracy in transition energies of states with either one or two excitons arises from the almost identical spatial distributions of electron (e) and hole (h) wavefunctions, as illustrated in the charge-density plot. The charge densities nearly cancel, and the exciton–exciton interaction energy is small. **(b)** Preparing QDs as core–shell structures made of cadmium sulfide and zinc selenide physically separates the electron and hole components of each exciton. The localization of each component breaks the degeneracy by an amount Δ_{XX}, the Coulombic repulsion between like charges. The shift in energy required to excite a second electron can be thought of as a manifestation of the Stark effect: The electric field from one exciton changes the energy required to excite the second one. (Adapted from ref. 2.)

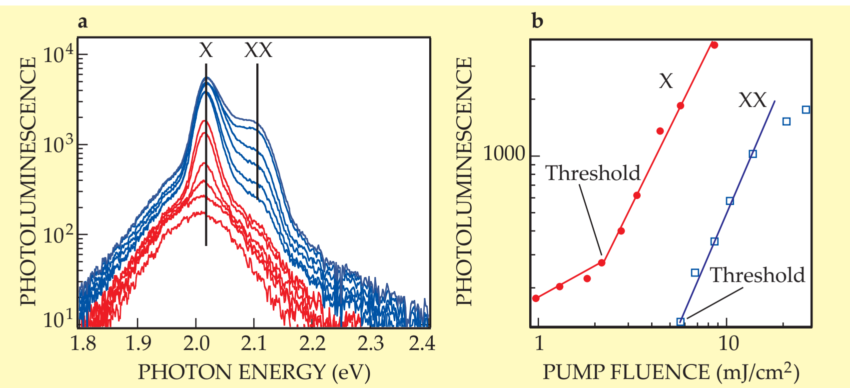

Figure 2. Optical gain in core–shell quantum dots. **(a)** Monitoring the photoluminescence in response to gradual increases in the pumping energy of ultrashort laser pulses reveals the evolution from an incoherent fluorescence signal to a narrow, coherent peak due to amplified spontaneous emission (ASE) from single excitons (X). Exciton–exciton repulsion shifts the emission from biexciton states (XX) to higher energy. If pumped intensely enough, those states also demonstrate amplified emission (blue curves). **(b)** The threshold pump fluence required to generate ASE from single excitons is significantly below the threshold for biexcitons. (Adapted from ref. 2.)

to emit light and collectively stimulate each other quickly enough to outpace Auger recombination and sustain population inversion. Even so, achieving optical gain still required optical pumping from intense and impractically short laser pulses.

Seven years later, Klimov and his Los Alamos colleagues now offer a more radical approach: Engineer the QD structure to amplify light using purely single-exciton states, which avoid Auger effects entirely.[2] To pull that off, the Los Alamos group chemically synthesized QDs that consist of a cadmium sulfide core coated with a zinc selenide shell.

Shell game

Heterostructures are, of course, not new. The University of Chicago's Philippe Guyot-Sionnest and Margaret Hines (now at Evident Technologies) found in 1996 that coating one semiconductor with another, typically with a larger bandgap, passivates the surface of a QD more effectively than molecular ligands alone can. But the core–shell structure, it turns out, can also be used to alter the energetics of electrons and holes at the interface of the two materials.

Whereas in a conventional, homogeneous QD, the electrons and holes are delocalized over the entire volume, the valence- and conduction-band levels of CdS and ZnSe tend to separate the positive and negative charges of each exciton created by a photon. Electrons get driven into the core and holes into the shell, an effect that can produce large local charge densities (see figure 1b).

The advantage of the approach is that localizing the electrons and holes in different parts of the QD breaks the degeneracy between single-exciton and biexciton energy levels. The imbalance arises from Coulombic repulsion between like charges. Solving the Schrödinger equation for the system, Klimov and company calculated that the repulsive energies can be engineered to be as high as 100 meV, comparable to the QD emission linewidth due to variations in dot sizes.

The challenge for chemist Sergei Ivanov was to minimize the size of the CdS core—the greater confinement increases repulsion energies—yet still grow a thick shell. As the shell's thickness increases, so does the separation between the electron and its companion hole, which weakens their attractive bond—again increasing the net Coulombic repulsion. To optimize the growth conditions, Ivanov created an alloy of the semiconductors at the core–shell interface by adding a little extra Cd into the mixture of Zn and Se precursors during the synthesis. The thin buffer layer of ZnCdSe at the interface cures the lattice mismatch between CdS and ZnSe and removes some of the strain and defects that otherwise limit the thickness and degrade the emission quantum yields.

Such custom-designed QDs alter what's required to achieve optical gain. Because exciting the biexciton state requires a higher photon energy than a single exciton emits, biexciton absorption can be completely eliminated. If the pump fluence—that is, incident energy density—is low enough to populate QDs with only single excitons, stimulated emission from those states competes only with absorption from unexcited nanocrystals. In that case only two-thirds of the core–shell QDs require an exciton to reach gain threshold, and the remaining one-third require none at all.

To quantify the relative advantage that operating in this single-exciton regime provides, the researchers monitored changes in the photoluminescence signal recorded from their core–shell QDs as a function of the pumping fluence from a femtosecond laser (see figure 2). The emergence of the narrow peaks on top of a broad fluorescence signal marks an evolution from incoherent fluorescence to coherent, amplified spontaneous emission at a threshold pumping fluence about three times lower than required using biexcitons.

A more impressive advantage of the core–shell QDs, according to the University of Rochester's Todd Krauss, is the long intrinsic lifetime of the single-exciton excited states, which can be more than 100 ns thanks to the weak electron–hole overlap.[3] Compare that with the 50-ps decay time typical for the multiexciton states of conventional QDs. As the ratio of threshold fluence and optical-gain lifetime, the pump-intensity threshold for lasing can therefore be orders of magnitude lower in core–shell QDs.

That fundamental difference, argues Klimov, clears the way for incorporating QDs into devices that rely on cheap, low-intensity, continuous-wave lasers—rather than expensive, ultrafast ones—to stimulate emission. Although it may yet take work to improve quantum yields and reduce scattering and absorption losses, the next step may be as simple as placing the dots in a resonant cavity to create a laser.

Mark Wilson

References

1. V. I. Klimov, A. A. Mikhailovsky, S. Xu, A. Malko, J. A. Hollingsworth, C. A. Leatherdale, H.-J. Eisler, M. G. Bawendi, *Science* **290**, 314 (2000).
2. V. I. Klimov, S. A. Ivanov, J. Nanda, M. Achermann, I. Bezel, J. A. McGuire, A. Piryatinski, *Nature* **447**, 441 (2007).
3. D. Oron, M. Kazes, U. Banin, *Phys. Rev. B* **75**, 035330 (2007).

Radar reveals Mercury's molten core

The answer to a long-standing question about Mercury's interior sheds new light on the formation of the planet and the origin of its magnetic field.

Mercury's rotation rate oscillates with a greater amplitude than it would if the planet's core were entirely solid. That is the conclusion of a team of researchers, comprising Jean-Luc Margot from Cornell University; Stan Peale from the University of California, Santa Barbara; Raymond Jurgens and Martin Slade from the Jet Propulsion Laboratory in Pasadena, California; and Igor Holin from the Space Research Institute in Moscow. They base their finding on recent radar measurements and the decades-old data from the *Mariner 10* probe.[1]

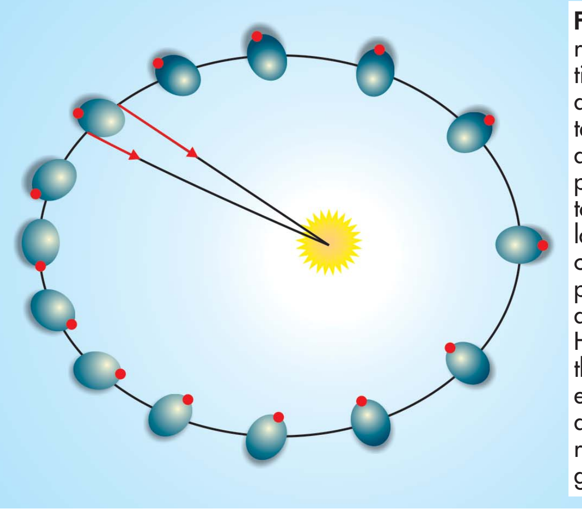

Figure 1. As Mercury rotates about its axis three times for every two trips around the Sun, the gravitational forces (red arrows) on parts of the planet create an overall torque. The resulting oscillation in the spin rate, called a forced libration, provides information about Mercury's interior. Here, the eccentricity of the orbit and the planetary profile are exaggerated for effect, and the red dots are included to guide the eye.

Mercury's structure is similar to Earth's: It contains a dense metallic core surrounded by a silicate mantle and a rocky crust. But seismic measurements provide additional information about Earth that's harder to come by in the case of other planets. It's known that the outer part of Earth's core is molten, due mostly to the heat produced by radioactive decay, whereas the inner core is kept solid under the gravitational pressure of the outer layers. Although Earth's mantle behaves like a fluid over the long time scales of continental drift, for faster processes the mantle is best characterized as a solid.

Earth's magnetic field isn't produced by the solid inner core, whose temperature is higher than the Curie temperature of iron and therefore cannot sustain a permanent magnetization. Instead, the convection of the molten outer core produces a self-sustaining planetary dynamo: The flow of the liquid metal through the magnetic field generates an electric current, which in turn enhances the field. (See PHYSICS TODAY, February 2006, page 13).

In 1974 *Mariner 10* detected a weak Mercurian magnetic field. That came as a surprise. Because Mercury is less than 6% as massive as Earth, it has a large surface-to-volume ratio. Planetary scientists expected that it would lose heat rapidly enough that the core would have solidified completely. A fully solid core makes a dynamo impossible but doesn't necessarily preclude a magnetic field. Mars and the Moon both have magnetic fields that emanate from their crusts, magnetized long ago by dynamos that have since ceased their activity. But the Martian and lunar magnetic fields are patchy and uneven, since some parts of the crusts have retained more of their magnetization than others. Mercury's field