Q&A: Expert discusses past and future of Nobel-winning quantum dots technology

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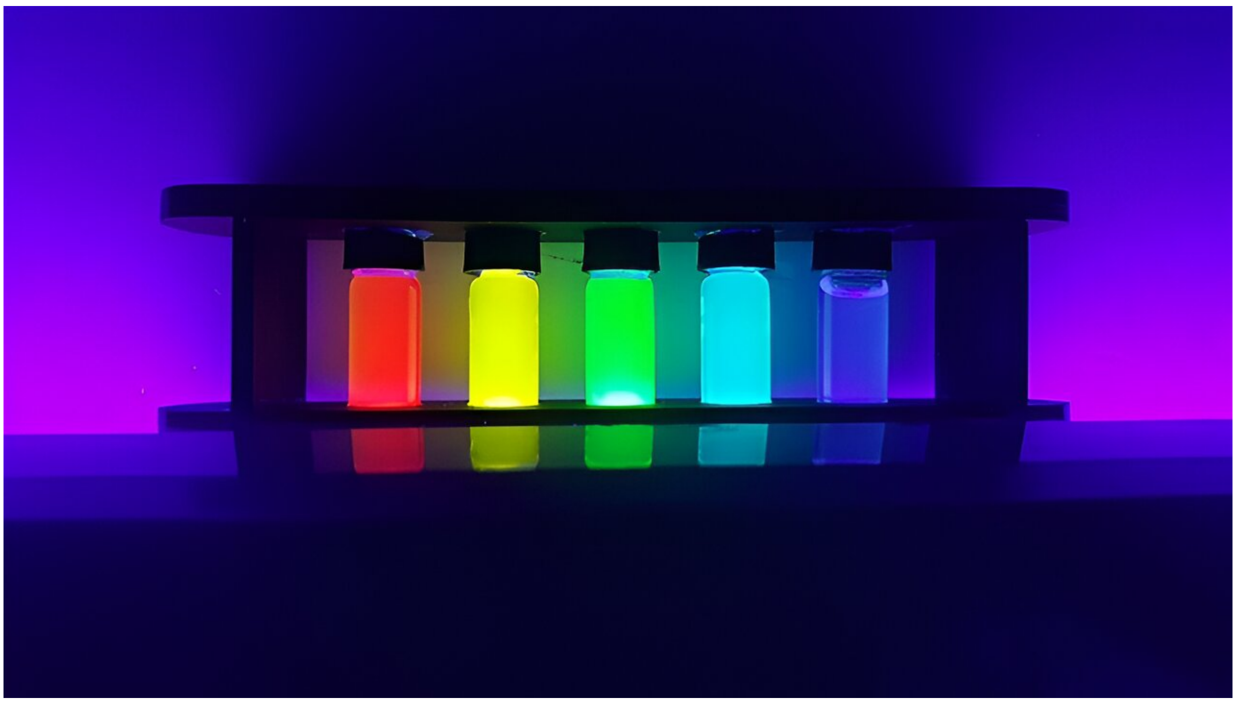

Quantum dots demonstration set. Credit: Physicsexperimentsorg/Wikimedia Commons, CC BY-SA

The world woke up on Oct. 3 to learn that Moungi Bawendi of MIT, Louis Brus of Columbia University, and Alexei Ekimov of Nanocrystals Inc. received the Nobel Prize in Chemistry for their discovery and synthesis of semiconductor quantum dots.

Quantum dots are not just any nanoparticles. Often described as artificial atoms, these nanometer-sized semiconductor crystals possess unique attributes largely governed by their size, which chiefly dictates how they interact with light.

To delve deeper, Penn Today met with Penn Integrates Knowledge Professor Christopher B. Murray. A former advisee of Bawendi, Murray had worked closely with him during his doctoral studies at MIT, authoring a seminal paper on quantum dots. With decades of experience, Murray offers an insightful look into the world of quantum dots and their far-reaching applications.

What is a quantum dot, and what about this discovery merits the Nobel Prize in Chemistry?

Quantum dots are semiconductor nanocrystals that showcase quantum mechanical behaviors due to their tiny size, which is usually between 2 to 10 nanometers. Given that they're semiconductors, they can move electricity around, like we see in more traditional "bulk" material semiconductors, but these dots stand out due to their quantized energy levels, which enable them to absorb and emit light of specific wavelengths that can be finely tuned just by using a single parameter, the particle's size.

For example, a Cadmium Selenium quantum dot can be tuned to represent nearly every color on the visible light spectrum by changing its size. This size variation affects the gap between its high-energy-level conduction band and low-energy-level valance band. Driving these unique optical and electronic properties is the quantum confinement effect: As the quantum dot gets smaller, its band gap increases.

Therefore, a quantum dot embodies the combination of this quantum confinement happening simultaneously in all three spatial dimensions. The crux here is that these systems are miniaturized to such an extent that every single particle is either comparable to or tinier than the typical range over which electrons usually spread out, or delocalize.

In the quantum universe, Heisenberg's uncertainty principle is a fundamental tenet. It says that the exact location and energy of a quantum particle cannot be pinpointed simultaneously. Knowledge of one aspect inevitably compromises the knowledge of the other, but, by encapsulating a particle within a confined geometry, or space, the energy-level separations within the system naturally react. Miniaturizing entities leads to a shift in their energy states, which is essentially the confinement aspect.

But the work that's been recognized with this Nobel Prize in Chemistry is a nod to the fact that these nanoparticles can be engineered using novel tricks—novel in the sense that much of the work done on semiconductors since their inception in the 1950s and 1960s has shown this to be done with compositional changes relying on large machinery, deposition tools, and fabrication infrastructure, whereas here it can be approached with a chemical synthesis.

Your work with Bawendi has been critical to advancing the field of nanotechnology and highly regarded by the larger scientific community. Could you tell us about the work and how it feels to see all this recognition and support culminate in a Nobel?

The project I took on as a graduate student was to develop methods to chemically synthesize quantum dots, purify them, and develop procedures to systematically characterize their structural properties, their chemical properties, and some of the basic optical features. My thesis was the primary content that was featured in a 1993 *Journal of the American Chemical Society* paper, along with one *Science* paper that came out a couple of years later that showed that self-assembly natural forces driving organization could organize these tiny semiconductor particles into and a whole host of other materials.

Additionally, under Moungi's leadership, my fellow graduates David Norris and Manoj Nirmal were using those materials for many more advanced spectroscopy studies mapping out their properties and helping to understand the potential of the systems. This earlier work really gave us the control of multiple systems and established a potentially scalable route for making quantum dots. It's also one of the areas of research my lab is still interested in today.

As you can imagine, I'm thrilled by the announcement. It's an incredibly exciting time for us, I'm so happy for Moungi and have sent messages to congratulate the winners and reconnect with co-workers. I'm sure their inboxes must be flooded with thousands and thousands of messages, seeing as professor Cherie Kagan and I have also been getting calls and visitors to our door. I was in Moungi's first group when he just started as a professor, and Cherie was in the very next cohort.

Could you speak about some of the changes you've seen in this space throughout your career, and also what are you looking forward to and hoping to contribute?

The transformation over the last 30 or so years has been massive. The studies in those earlier days were mostly motivated by possible applications in nonlinear optics and electro-optics in other areas, but they were mainly focused on fundamental discoveries of material properties: how we could we understand and then harness them and what was necessary to push their limits for characterization and performance.

That first wave gave rise to many more people who contributed immensely to both fundamental understanding and the development quantum dot-based technology. One of the most well-known applications is display technology. Quantum dots are currently used in quantum dot LED displays, enhancing color and brightness by converting the light emitted from a backlight in TVs. What's exciting about this is that this ever-expanding market is entering its next generation of displays, where we get the same bright colors and high performance but with less energy consumption and at a fraction of the size via direct electrical injection of charge carriers for color emission rather than an optical pumping of the quantum dots. It's a big leap forward.

But beyond this, it is their ability to absorb and re-emit specific wavelengths of light with high efficiency that makes them highly sought after in biomedical imaging. For instance, when attached to specific molecules, quantum dots can help detect cancer cells or other targets within the human body. In solar energy, quantum dots can be used to improve the efficiency of photovoltaic cells, capturing a broader spectrum of sunlight or converting that sun light into storable chemical fuels through photocatalysis. These are just a few examples, and the potential applications are vast.

Our work has continued to look at a range of applications. We're particularly excited by what emerges when you couple quantum dots or other nanoscale structures couple to each other. This analogy is that most of the first generation of quantum dot properties were exploiting atomic-like transitions, with their tunable properties; now we've moved to making molecules and extended solids and thin film devices, essentially connecting them together to make different types of materials that are hybridized.

This means that their energy levels overlap and still interact with one another but over larger length scales as the quantum mechanicals states now extend over multiple particles. When you couple the quantum dots in creative ways, you have a building set that's bigger than the atoms and ions we traditionally associate with the periodic table or molecular components but still at length scales that are small enough in each component that the underlying quantum characteristics can be exploited.

What we focus on is the idea that you can build new solid-state architectures with control and precision by taking the chemically derived building blocks and inducing them to self-assemble. So, when I first started in this nanoworld, we were trying to find ways to make a lot of the high quality (uniform) building blocks, which I liken to a bunch of Lego pieces. Now that we've got all these pieces, we're working on finding efficient ways to preprogram all these Legos to build the model plane or train that's printed on the box by themselves. That way, you could just dump all the pieces onto the ground, and they'd figure it out how to arrange themselves in interesting and useful patterns.

Once again, I must stress it's truly an exciting time for nanoscale materials chemistry as my colleagues and I look forward to the possibilities we have not even dreamed of yet.

Provided by University of Pennsylvania

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