https://doi.org/10.1038/s41563-024-01807-1

Quantum dots make it big at last

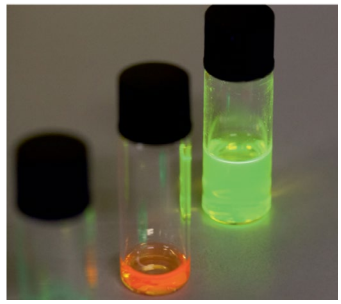
The 2023 Nobel Prize in Chemistry acknowledged work that paved the way to a nanotechnology worthy of the name.

At *Nature*'s international conference on nanotechnology in 1992, IBM scientist Don Eigler challenged the idea that nanotechnology actually existed at all. Despite the exciting advances taking place in nanoscience, Eigler said, there were as yet no true technologies to show for it.

But at the same meeting, Louis Brus of AT&T Bell Laboratories in New Jersey described one field of research that looked pregnant with promise of applications. Brus had devised ways of making colloidal semiconductor particles just a few nanometres across using 'wet chemistry'. Such entities were expected to act as quantum dots, meaning that their properties – such as optical absorption and emission spectra – were dominated by quantum-mechanical effects. The extremely small size meant that the energies of the uppermost electron bands were shifted relative to their values in the bulk material, by an amount dependent on the particle size itself. In this way, the colours of light the nanoparticles emitted (see image) could be tuned by controlling the particle size.

There were at that point still ample challenges to be met before these nanomaterials could become a viable technology, for example in optoelectronic display devices. Making samples with well-defined particle sizes wasn't easy, and clever chemistry was needed to stabilize the particle surfaces and eliminate surface electronic states that might trap charge carriers and quench emission. It was work in progress, Brus reported[1].

Just over 30 years later, that work has come to fruition with the award of the 2023 Nobel Prize in Chemistry to Brus and two other pioneers of quantum-dot nanoscience. Quantum dots are now the commercial products of an industry with an estimated global worth of around US$4 billion in 2021. They are being used not just in display screens, but in medical imaging techniques, quantum information processing, and more.



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Brus was honoured for his trailblazing work in preparing size-specific quantum dots by chemical means. When he began those efforts in the late 1980s, the potential for tailoring optical properties in nanoparticles through quantum size effects had already been demonstrated by his fellow laureate Aleksey Yekimov, working at the S. I. Vavilov State Optical Institute in the Soviet Union. From 1979, Yekimov studied the optical properties of colloidal particles in silicate glasses. His team observed that the particles' absorption excitations were blue-shifted as they became smaller[2]. Quantum size effects were already known in thin films (two-dimensional quantum wells), and Yekimov deduced that the same effect was at play in these 'zero-dimensional' systems.

Unaware of that work, in 1982 Brus and co-workers at Bell Labs made cadmium sulfide nanocrystals just a few nanometres across in solution, stabilizing them against aggregation using polymers, and reported a similar blue-shifting of the absorption relative to the bulk that they attributed to the quantum size effect[3]. The third laureate, Moungi Bawendi of the Massachusetts Institute of Technology, transformed the practical potential of the field in the early 1990s by developing methods for very precise control of particle size and shape, as well as improving the optical quality. His approach involved a well-controlled nucleation and growth process in a hot, non-aqueous solvent followed by size-dependent precipitation[4].

Such precise control of optical emission makes quantum dots attractive for full-colour display screens. In principle, thin layers of these particles can be electroluminescent, the emission being excited by injecting an electric current in a light-emitting diode configuration. But such devices are still only experimental, and commercial flat screens that use quantum dots are purely photoemissive: conventional semiconductor or organic light-emitting diodes are used to stimulate fluorescence from an overlayer of the nanoparticles. Typically, televisions using this technology deploy blue light-emitting diodes along with quantum dots that fluoresce with spectrally pure red and green light.

Some sophisticated uses of the optical behaviour of quantum dots in sensing and information processing may require greater control of their positioning and self-assembly. Surface ligands used to passivate the particles can be chemically modified with molecular tags that guide the assembly process: single-stranded DNA tags, for instance, may enable highly specific positioning by base-pairing to complementary strands on a substrate or on other particles. In this way, functionalized nanocrystals can be programmed to self-assemble into a wide range of structures[5]. Biomolecular tags also enable individual quantum dots to be targeted to specific molecules or cells in vivo for multiwavelength fluorescent imaging, cell tracking, immunoassays and other biomedical uses. With potential too in solar energy conversion and photocatalysis, the applied value of quantum dots is evidently still in its infancy. But it leaves no question that, three decades after Eigler's remark, nanotechnology has truly arrived.

And yet, with all this excitement around applications of quantum dots, it is perhaps easy to overlook one of their most striking features: they offer a direct and even beautiful visual confirmation of the truth of quantum mechanics. The glowing rainbow of hues that can be elicited from the same material purely through control of size is a glorious reminder of the counterintuitive idea that, at the smallest scales, physics may trump chemistry as the determinant of material behaviour.

Published online: 2 February 2024

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