AMERICAN ACADEMIC PUBLISHER

INTERNATIONAL JOURNAL OF MEDICAL SCIENCES

ISSN NUMBER: 2692 - 5206 Volume 5. No 12. December ,2025

NANOMATERIALS AND QUANTUM DOTS: PHYSICAL-CHEMICAL PROPERTIES AT THE ATOMIC LEVEL

Salimboyeva Malikabonu Rustam kizi
Almalyk Mining and Metallurgical Technical School
Physics and Astronomy Teacher
Abdujabborova Xusniya Komiljon kizi
Almalyk Mining and Metallurgical Technical School
Senior Chemistry Teacher

Abstract: This article examines the fundamental physical-chemical properties of nanomaterials and quantum dots at the atomic scale, analyzing their unique quantum mechanical behaviors, surface phenomena, and potential applications in modern technology. Through comprehensive literature review and theoretical analysis, the study reveals how quantum confinement effects, surface-to-volume ratios, and atomic-level structural arrangements determine the exceptional characteristics of these materials, distinguishing them from their bulk counterparts.
Keywords: nanomaterials, quantum dots, quantum confinement, atomic structure, physical-chemical properties, nanotechnology

Аннотация: В данной статье рассматриваются фундаментальные физико-химические свойства наноматериалов и квантовых точек на атомном уровне, анализируются их уникальные квантово-механические свойства, поверхностные явления и потенциальные возможности применения в современных технологиях. Благодаря всестороннему обзору литературы и теоретическому анализу, исследование показывает, как эффекты квантового ограничения, соотношение поверхности к объему и структурные особенности на атомном уровне определяют исключительные характеристики этих материалов, отличающие их от объемных аналогов.
Ключевые слова: наноматериалы, квантовые точки, квантовое ограничение, атомная структура, физико-химические свойства, нанотехнологии

Annotatsiya: Ushbu maqolada nanomateriallar va kvant nuqtalarining atom miqyosidagi asosiy fizik-kimyoviy xususiyatlari o'rganiladi, ularning noyob kvant mexanik xatti-harakatlari, sirt hodisalari va zamonaviy texnologiyalardagi potensial qo'llanilishi tahlil qilinadi. Tadqiqotda keng qamrovli adabiyotlarni ko'rib chiqish va nazariy tahlil orqali kvant cheklash effektlari, sirt-hajm nisbatlari va atom darajasidagi strukturaviy tartiblar ushbu materiallarning o'ziga xos xususiyatlarini qanday belgilashi va ularni hajmdagi analoglaridan qanday ajratib turishi ochib beriladi.
Kalit so'zlar: nanomateriallar, kvant nuqtalari, kvant cheklash, atom tuzilishi, fizik-kimyoviy xususiyatlar, nanotexnologiya

INTRODUCTION

Nanomaterials and quantum dots represent a revolutionary class of materials whose properties are fundamentally determined by quantum mechanical effects operating at the atomic and nanoscale dimensions. These materials, typically ranging from 1 to 100 nanometers in size, exhibit physical-chemical characteristics that differ dramatically from their bulk equivalents due to quantum confinement, increased surface area, and modified electronic structures [1]. Quantum

AMERICAN ACADEMIC PUBLISHER
INTERNATIONAL JOURNAL OF MEDICAL SCIENCES
ISSN NUMBER: 2692 - 5206 Volume 5. No 12. December ,2025

dots, specifically semiconductor nanocrystals with dimensions comparable to the exciton Bohr radius, demonstrate size-tunable optical and electronic properties that have attracted considerable scientific attention since their discovery in the 1980s [2]. The exploration of atomic-level properties in these materials has opened unprecedented opportunities in various fields including optoelectronics, biomedicine, catalysis, and energy conversion [3]. Understanding the physical-chemical behavior at the atomic scale is essential for rational design and optimization of nanomaterial-based technologies. The quantum confinement effect, which occurs when the dimensions of a material become comparable to the de Broglie wavelength of charge carriers, leads to discrete energy levels rather than continuous energy bands, fundamentally altering electrical, optical, and magnetic properties [4]. Additionally, the extraordinarily high surface-to-volume ratio in nanomaterials results in a significant proportion of atoms residing at or near the surface, dramatically influencing chemical reactivity, thermodynamic stability, and catalytic performance [5]. This article aims to systematically analyze the atomic-level physical-chemical properties of nanomaterials and quantum dots through comprehensive literature review, examining the theoretical foundations and experimental observations that define these materials' unique characteristics.

METHODOLOGY AND LITERATURE REVIEW

The research methodology employed in this study consists of systematic literature analysis of peer-reviewed scientific publications, theoretical studies, and review articles focusing on the atomic-level properties of nanomaterials and quantum dots. The analysis framework encompasses three primary dimensions: quantum mechanical properties, surface phenomena, and structural characteristics at the atomic scale. Literature review reveals that the quantum confinement effect constitutes the most fundamental property distinguishing nanomaterials from bulk materials. According to quantum mechanical principles, when material dimensions approach the exciton Bohr radius, typically 2-10 nanometers for most semiconductors, the motion of electrons and holes becomes restricted in one, two, or three dimensions, resulting in quantized energy levels [1].

This quantum confinement directly influences the bandgap energy, which increases as particle size decreases, a relationship mathematically described by the effective mass approximation and confirmed through numerous spectroscopic studies [6]. The literature demonstrates that cadmium selenide quantum dots, for instance, exhibit tunable photoluminescence from red to blue wavelengths simply by controlling particle diameter from 5 to 2 nanometers, illustrating the direct correlation between size and optical properties [2]. Surface atomic arrangement and reconstruction represent another critical aspect extensively discussed in nanotechnology literature. At the nanoscale, surface atoms constitute a substantial fraction of total atoms—up to 50% for particles below 5 nanometers—and these surface atoms possess incomplete coordination spheres, resulting in dangling bonds, surface states, and modified electronic structures [5].

Research indicates that surface reconstruction, wherein surface atoms rearrange to minimize free energy, significantly affects catalytic activity, chemical stability, and electronic properties. Gold nanoparticles, traditionally considered chemically inert in bulk form, demonstrate remarkable catalytic activity at nanoscale dimensions due to the prevalence of low-coordination surface sites and quantum size effects [7]. The crystallographic structure at the atomic level determines many physical properties of nanomaterials. High-resolution transmission electron microscopy studies reveal that quantum dots can exist in various crystal phases, including wurtzite, zinc blende, and rock salt structures, with phase transitions occurring as size decreases due to surface energy considerations [3]. Defects at the atomic level, including vacancies, interstitials, and grain

AMERICAN ACADEMIC PUBLISHER
INTERNATIONAL JOURNAL OF MEDICAL SCIENCES
ISSN NUMBER: 2692 - 5206 Volume 5. No 12. December ,2025

boundaries, play disproportionately important roles in nanomaterials compared to bulk materials, affecting mechanical strength, electrical conductivity, and optical emission properties [8].

RESULTS AND DISCUSSION

Analysis of the literature and theoretical considerations reveals several key findings regarding atomic-level physical-chemical properties of nanomaterials and quantum dots. First, quantum confinement effects manifest in multiple observable phenomena including blue-shifted absorption spectra, enhanced oscillator strength, and prolonged exciton lifetimes as particle size decreases. The relationship between quantum dot diameter and emission wavelength follows predictable quantum mechanical models, enabling precise engineering of optical properties for specific applications such as display technologies and biological imaging [2]. Experimental observations consistently demonstrate that the energy gap increases proportionally to the inverse square of particle radius, confirming theoretical predictions from particle-in-a-box models and effective mass approximations [6].

Second, surface chemistry at the atomic level exerts dominant influence over nanomaterial stability and functionality. Surface passivation with organic ligands or inorganic shells proves essential for preventing oxidation, aggregation, and non-radiative recombination processes that would otherwise degrade performance. Studies show that the choice of surface ligands affects not only chemical stability but also charge transfer dynamics, dipole moments, and interfacial energy alignment in nanostructured devices [5]. Third, atomic-level structural analysis reveals that nanomaterials frequently exhibit polytypism and structural defects that are energetically unfavorable in bulk materials but become stabilized at the nanoscale due to surface energy contributions. These structural features create localized electronic states that can serve as either beneficial properties for applications like single-photon emission or detrimental trap states that reduce quantum efficiency [8]. Fourth, the high surface-to-volume ratio characteristic of nanomaterials results in thermodynamic properties that deviate substantially from bulk behavior, including reduced melting points, altered phase transition temperatures, and size-dependent lattice parameters.

Gold nanoparticles, for example, exhibit melting point depressions of several hundred degrees Celsius compared to bulk gold when particle diameter falls below 5 nanometers, a phenomenon explained by the Gibbs-Thomson equation accounting for surface energy contributions [7]. Fifth, electronic structure modifications at the atomic level lead to emergence of novel physical phenomena including superparamagnetism in magnetic nanoparticles, plasmonic resonances in metal nanostructures, and quantum tunneling effects in closely spaced quantum dot arrays. These quantum mechanical effects enable technological applications that are impossible with conventional materials, from ultra-sensitive sensors to quantum computing platforms [4]. The interplay between quantum confinement, surface effects, and atomic structure creates a complex but predictable framework for understanding and engineering nanomaterial properties, with size, shape, composition, and surface chemistry serving as the primary control parameters [9].

CONCLUSION

This comprehensive analysis of nanomaterials and quantum dots at the atomic level reveals that their exceptional physical-chemical properties emerge from the fundamental quantum mechanical principles governing matter at nanoscale dimensions. Quantum confinement effects, surface atomic arrangements, and structural characteristics collectively determine the unique behaviors that distinguish these materials from bulk counterparts. The size-dependent tunability of electronic, optical, and magnetic properties provides unprecedented control over material functionality, enabling revolutionary applications across multiple technological domains.

AMERICAN ACADEMIC PUBLISHER
INTERNATIONAL JOURNAL OF MEDICAL SCIENCES
ISSN NUMBER: 2692 - 5206 Volume 5. No 12. December ,2025

Understanding atomic-level phenomena—including quantum confinement, surface reconstruction, defect chemistry, and thermodynamic modifications—is essential for rational design and optimization of nanomaterial-based technologies. Future research directions should focus on achieving atomic-level precision in synthesis, developing comprehensive theoretical models that integrate quantum and surface effects, and exploring emergent properties in complex nanostructured systems [10]. The continued advancement of characterization techniques with atomic resolution will further deepen our understanding of these materials, potentially revealing new quantum phenomena and enabling next-generation nanotechnologies.

REFERENCES

1. Brus, L.E. (2007). Quantum crystallites and nonlinear optics. Applied Physics A, 53(6), 465-474.
2. Alivisatos, A.P. (1996). Semiconductor clusters, nanocrystals, and quantum dots. Science, 271(5251), 933-937.
3. Murray, C.B., Norris, D.J., & Bawendi, M.G. (1993). Synthesis and characterization of nearly monodisperse CdE (E = sulfur, selenium, tellurium) semiconductor nanocrystallites. Journal of the American Chemical Society, 115(19), 8706-8715.
4. Kayanuma, Y. (1988). Quantum-size effects of interacting electrons and holes in semiconductor microcrystals with spherical shape. Physical Review B, 38(14), 9797.
5. Roduner, E. (2006). Size matters: why nanomaterials are different. Chemical Society Reviews, 35(7), 583-592.
6. Efros, A.L., & Rosen, M. (2000). The electronic structure of semiconductor nanocrystals. Annual Review of Materials Science, 30(1), 475-521.
7. Haruta, M. (1997). Size-and support-dependency in the catalysis of gold. Catalysis Today, 36(1), 153-166.
8. Klimov, V.I. (2006). Mechanisms for photogeneration and recombination of multiexcitons in semiconductor nanocrystals: implications for lasing and solar energy conversion. Journal of Physical Chemistry B, 110(34), 16827-16845.
9. Kovalenko, M.V., Manna, L., Cabot, A., Hens, Z., Talapin, D.V., Kagan, C.R., & Heiss, W. (2015). Prospects of nanoscience with nanocrystals. ACS Nano, 9(2), 1012-1057.
10. Talapin, D.V., Lee, J.S., Kovalenko, M.V., & Shevchenko, E.V. (2010). Prospects of colloidal nanocrystals for electronic and optoelectronic applications. Chemical Reviews, 110(1), 389-458.