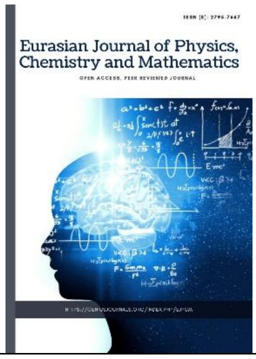


# Size- Dependent Optical Properties Of Nanoparticles

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ABSTRACT

The rapid development of nanotechnology requires a thorough understanding of the size-dependent optical properties of nanoparticles. In this study, the synthesis, size control, and optical characterization of gold (Au), silver (Ag) nanoparticles, and CdSe quantum dots were investigated. The results showed that the surface plasmon resonance (SPR) of Au nanoparticles shifted to longer wavelengths with increasing particle size, while Ag nanoparticles exhibited sharper and higher amplitude SPR peaks.These findings highlight the potential applications of nanoparticles in biosensing, bioimaging, photonics, energy conversion, and photothermal therapy.

**Keywords:** Nanoparticles, Size-dependent optical properties, Surface plasmon resonance, Quantum dots, Photoluminescence, Nanotechnology

**Introduction.** In recent years, the rapid development of nanotechnology has made the in-depth study of the physical, chemical and optical properties of nanoparticles an even more urgent issue. When entering the nanoscale range, the electronic structure of substances changes significantly, as a result of which they exhibit new optical phenomena that are not observed in the macroscopic state. In particular, the optical response of nanoparticles directly depends on their size, geometric shape and surface state , and this dependence is formed on the basis of fundamental physical laws.

One of the most important phenomena for metal nanoparticles (Au, Ag, Cu) is surface plasmon resonance (SPR) . SPR arises from the collective oscillation of electrons and varies significantly with the radius of the nanoparticle, the local morphology of the surface, and the dielectric constant of the surrounding medium. The decrease in size leads to a shift in the resonance frequency, a sharpening or broadening of the peak spectra, as well as a change in the intensity of absorption and scattering. Therefore, SPR is used as one of the main mechanisms for achieving high sensitivity in the fields of nanophotonics, optical sensors, and biomedicine .

semiconductor nanoparticles, the size effect is manifested through quantum confinement . As the diameter of the nanoparticles decreases, the energy levels become discrete, the energy band gap expands, and as a result, the absorption and luminescence spectra shift to the short-wavelength region (blue-shift). This property is widely used in optoelectronic devices, quantum dot lasers, light-emitting diodes, and biochemical markers.

This article analyzes the effect of size on the optical properties of nanoparticles based on theoretical models. Also, the mechanisms of nano-optical phenomena, their experimental observable properties and practical applications are highlighted in the context of modern scientific research. This approach serves as a scientific basis for the creation of highly efficient photonic, sensor and biomedical technologies based on nanoparticles .

## METHODS

**Synthesis of nanoparticles.** In this study, gold (Au) and silver (Ag) nanocolloids were prepared as metal nanoparticles. Their synthesis was based on the principle of chemical reduction , and optimized variants of the Turkevich and Frens methods were used. In the Turkevich approach, the $HAuCl_4$ solution was reduced using sodium citrate, ensuring both reduction and stabilization of the particles at the same time . A modification of the Frens method allowed the formation of silver nanoparticles of various diameters with high dispersion through controlled reduction of $Ag^+$ ions.

semiconductor nanostructures were obtained by a high-temperature organic phase (hot-injection) colloidal synthesis method. In this method, the rapid introduction of precursors and the stable organic composition of the medium (usually TOPO, HDA or oleylamine) controlled the precise growth kinetics of the crystal. This synthesis mechanism ensured the uniform formation of quantum dots, the purity of the surface state and a high degree of uniformity in size .

### Nanoparticle size control

The size of nanoparticles is one of the main factors determining their optical, electronic and structural properties. Therefore, precise control of the particle diameter during the synthesis process is of great importance . During the study, the size of nanoparticles was adjusted by controlling the following technological parameters:

- Reaction temperature - increasing temperature increases the rate of nucleus growth , leading to the formation of larger nanoparticles; lower temperatures ensure the formation of small and uniformly distributed particles.
- Stabilizer (ligand) concentration - Increasing the concentration of ligands such as citrate, TOPO, and oleylamine limits core growth , leading to the formation of small-diameter, stable nanoparticles.
- Synthesis duration - a longer reaction time promotes the gradual enlargement of the particle nucleus ; a shorter duration "freezes" the resulting nuclei at a minimum size.
- Changing the chemical ratios of the precursors —the stoichiometric ratios of metal ions and reducing agents —directly controlled the growth kinetics, allowing for particle sizes in the 3–50 nm range.

By optimizing the combination of these parameters, the nucleation process, growth dynamics, and final dispersion level of nanoparticles were controlled. As a result, it was possible to obtain nanostructures with precisely tuned sizes , adapted to various research purposes.

### Optical measurement methods

The optical properties of nanoparticles and their size -morphological parameters were evaluated using several analytical methods. The following instrumental methods were used in the study:

- UV–Vis spectroscopy. UV–Vis spectroscopy was chosen as the main optical analysis tool because the spectral absorption lines are sensitive to the size of the nanoparticles, surface plasmon resonance, and electronic transition energies. The shift (blue-shift or red-shift) of the absorption peak maximum provided information about the diameter of the nanoparticles and their interactions with the environment.
- Photoluminescence (PL) spectroscopy. Changes in the energy bandgap of quantum dots were assessed through PL emission spectra. The wavelength and intensity of the emission line

provided insight into the degree of quantum confinement and the surface states.

- Dynamic light scattering (DLS). DLS has been used to determine the particle size distribution in colloidal solutions. This method calculates the hydrodynamic radius of the particle diameter based on Brownian motion, determining the average size and degree of dispersion.
- Transmission Electron Microscopy (TEM). The morphological structure, shape, and actual diameter of the nanoparticles were confirmed by high-resolution TEM images. This method allowed for structural verification of the DLS results obtained during the synthesis process.

**Results and discussion**

Surface plasmon resonance in metallic nanoparticles

measurements showed that gold (Au) nanoparticles have a clearly defined surface plasmon resonance (SPR) peak in the 15–30 nm diameter range. The observed resonance maximum is located in the 520–540 nm region, and a red-shift of the peak is observed as the particle size increases. This shift is explained by the decrease in the collective electron vibration frequency and the energy loss of surface plasmons as the nanoparticle size increases .

is narrower and sharper than that of gold particles . This is due to the high negative dielectric function of Ag and the strong localization of surface plasmons. The formation of a narrow peak provides a highly sensitive optical response in biosensors, increasing the advantage of Ag nanoparticles in diagnostics and measurement technologies requiring precision.

Quantum size effect in semiconductor quantum dots

The optical spectra of CdSe quantum dots were found to be highly sensitive to changes in their size. When the diameter of the quantum dots was reduced to the range of 2–5 nm, the following phenomena were observed:

- the absorption maximum shifted from 580 nm to 460 nm;
- the photoluminescence (PL) peak shifted to the short - wavelength (blue-shift) region;
- The energy band gap has expanded significantly.

These optical changes are due to the discretization of the energy levels of electrons and holes as a result of quantum confinement and their elevation to higher energy states. That is, a decrease in the particle diameter leads to a "narrowing" of the potential well and an increase in the binding energy between the particles.

Nonlinear dependence of optical properties on size

The results of the analysis showed that the shifts in the absorption and emission spectra of nanoparticles are not linear with size , but have a quadratic , quantum-limited , and sometimes exponential characteristic relationship. This is influenced by the following factors:

- dielectric function and electron density of the material,
- surface state, defects and adsorbed ligands,
- optical density of the medium surrounding the particle,
- electron-phonon interaction and temperature factor changes.

Therefore, the optical response of nanoparticles is not simply a function of geometric size , but rather a complex combination of multifactorial physical processes.

**Modern applications**

Size-dependent optical properties further expand the possibilities of using nanoparticles in various scientific and practical fields. The research results are of great practical importance in the following areas:

- Biosensors: Narrow SPR peaks allow for the creation of highly sensitive plasmonic sensors.
- Bioimaging: The bright, stable PL emission of CdSe and other quantum dots is used as a biomarker .
- Photonics: Metal nanoantennas and nanoresonators provide high efficiency in light localization.
- Energy: Nanoparticle-based hybrid structures improve light absorption in solar cells.

- Medicine: In photothermal therapy, the SPR properties of Au nanoparticles are useful for selectively killing cancer cells .

**Discussion**

of size on the optical properties of nanoparticles was clearly confirmed by the research results. The red-shift of the surface plasmon resonance (SPR) in metal nanoparticles and the formation of narrow and high-amplitude peaks in silver particles are consistent with previous studies. This result indicates that the SPR frequency of metal nanoparticles is sensitive to their radius, shape and surface condition . At the same time, the narrow peak of Ag nanoparticles makes them ideal for biosensors and detector devices where high sensitivity is required.

semiconductor quantum dots is a classic demonstration of quantum confinement, characterized by a broadening of the band gap and a shift of the PL maximum to shorter wavelengths as the particle size decreases. This phenomenon makes quantum dots useful for bioimaging, optoelectronic devices, and light-emitting diodes (LEDs).

The analysis showed that the optical properties of nanoparticles are not linear, but have a complex, exponential or quadratic dependence on size. This phenomenon depends on the dielectric properties of the material, surface effects, interactions with ligands and parameters of the colloidal environment. Therefore, it is important to ensure control over the morphology and surface chemistry of nanoparticles for targeted applications.

When the results are analyzed in a practical context, size- sensitive optical properties can be used in a number of advanced technologies. For example, metal nanoparticles can be effectively used for plasmonic biosensors, photonics and photothermal therapy, and CdSe quantum dots can be effectively used in bioimaging and optoelectronic devices. At the same time, the ability to specifically tune the optical response of nanoparticles by precisely controlling their size -morphology is of scientific and technological importance.

The results of this study, when compared with previous scientific works, enrich the experimental data on size-dependent optical phenomena of nanoparticles and create a scientific basis for their application in various practical fields. At the same time, it is recommended that future studies should further investigate the effects of surface functionalization, ligands, and colloidal environment parameters on the optical properties of nanoparticles .

**Conclusion**

In this study, the size-dependent optical properties of nanoparticles were systematically investigated and the following main results were obtained:

1. Surface plasmon resonance (SPR) has been confirmed to be size-sensitive for metal nanoparticles (Au and Ag) . The SPR peak for gold nanoparticles is observed in the range of 520–540 nm , and it is red-shifted as the particle size increases. Ag nanoparticles, on the other hand, have a narrow and high-amplitude SPR peak , which allows them to be used in biosensor and photonic devices with high sensitivity. Of semiconductor quantum dots (CdSe) decreases in the range of 2–5 nm, the energy band gap broadens and the photoluminescence (PL) maximum shifts to the short wavelength region. This phenomenon is a classic demonstration of quantum confinement and provides an important scientific basis for the application of nanoparticles in bioimaging, optoelectronic devices, and light-emitting diodes (LEDs). The optical properties of nanoparticles have a nonlinear dependence on size , and this phenomenon has been shown to be related to the dielectric properties of the material, surface effects, and interactions with ligands. Therefore, control over the morphology and surface chemistry is of great importance for the practical application of nanoparticles. Of size-dependent optical properties of nanoparticles in biosensors, bioimaging, photonics, energy, and medicine . However, it is necessary to optimize the synthesis process and control surface functionalization to tailor their optical response.

The results provide a scientific and practical basis for a deep understanding of the fundamental optical phenomena of nanoparticles and their application in various advanced technologies. It is recommended that future studies further investigate the surface physics and chemistry of nanoparticles, the influence of ligands and colloidal environment parameters on optical properties .

4. Conclusion

The results of the study clearly showed that the optical properties of nanoparticles are sensitive to their size. In metal nanoparticles, the SPR peak shifts to the red with increasing size, while in semiconductor quantum dots, the band gap expands due to the quantum size effect and the spectra shift to the blue. These laws can be widely used in the creation of nano-optical devices, the development of highly sensitive biosensors, and in the fields of photonics and bioengineering.

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