

MORPHOLOGY OF METAL NANOPARTICLES AND ITS ROLE IN ANTIMICROBIAL EFFICACY

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ABSTRACT

This review article examines the relationship between the morphological features of metal nanoparticles, specifically silver, gold, and copper-based materials, and their antimicrobial activity. Currently, the proliferation of antibiotic-resistant bacteria and the spread of nosocomial infections necessitate the search for new disinfectants with nanotechnology playing a crucial role in addressing this issue.

The article provides an in-depth analysis of nanoparticle synthesis processes, particularly nucleation and crystal growth mechanisms. Methods for controlling nanoparticle shape through seed structure and the influence of the chemical environment are described.

The primary focus of the study is to determine the impact of nanoparticle size and shape on antibacterial efficacy. The results of the literature review indicate that smaller particles exhibit higher activity due to their increased surface area. The review concludes that optimizing nanoparticle morphology is key, as triangular nanoprisms exhibiting superior activity over spherical and rod-like particles due to their high-energy facets and sharp reactive edges.

INTRODUCTION

Nanoscience and nanotechnology represent an expanding research area, which involves structures, devices, and systems with novel properties and functions due to the arrangement of their atoms on the 1–100 nm scale (Rezić, 2022). This field focuses on the manipulation of materials at atomic and molecular scales (Ghorbani et al., 2011). The properties of metal nanoparticles are directly dependent on their physical parameters, such as their shape, size, and structure. For example, studies in Raman scattering show that the shape and structure of nanoparticles play a crucial role in affecting the spectral region (Ghorbani et al., 2011.). In catalytic reactions, for example, the efficiency of copper nanoparticles can be improved by reducing their size (Chandra & Kumar, 2016).

Although there are physical and biological methods for preparing nanoparticles, the chemical reduction method is the most common due to its reaction rate, simplicity, and cost-effectiveness (Iravani et al., 2014; Kulkarni & Muddapur, 2014).

Metal nanoparticles such as silver, gold, and copper are being widely investigated as antibacterial materials because they show activity against a broad range of pathogens, including drug-resistant bacteria (Prabhu & Poullose, 2012). Some studies report enhanced activity for rod-shaped AgNPs against *E. coli* and other bacteria, which has been linked to sharp features and reactive crystallographic planes. However, rather than showing a uniform advantage for rods, the literature indicates that the most active AgNP shape varies across other morphologies each outperforming others in different studies (Cheon et al., 2019).



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In recent years, the rise in hospital-acquired infections and medical costs has made the search for new disinfectants a pressing issue (Rutala & Weber, 2011). The purpose of this review is to investigate the antibacterial efficacy of metal nanoparticle shapes and to determine their potential as alternatives to current antimicrobial agents. However, for the targeted creation of nanoparticles with specified properties, detailed control of their formation at the earliest stages is necessary, namely, in the processes of nucleation and crystal growth.

EARLY STAGES OF NANOPARTICLE FORMATION

Nucleation is the earliest step of crystallization and remains one of the least directly accessible stages of nanoparticle formation. Experimental studies have long struggled to capture nuclei in real time because these species are extremely small, transient clusters, and conventional imaging often misses the interval between precursor conversion and the appearance of detectable particles (Xia et al., 2015). Even so, direct measurement of nucleation remains difficult because the smallest nuclei can fall below the spatial resolution of liquid-cell electron microscopy. Nevertheless, in situ liquid TEM is often used to reduce some of the artifacts associated with tip-based approaches (Erni et al., 2009). In gold systems, for example, beam-induced and electrodeposition-driven crystallization occur at different locations and produce different morphologies. A careful control of liquid thickness can suppress beam-induced products to negligible levels. Nanoparticle synthesis generally begins when a precursor is decomposed into reactive monomeric species that supply the building blocks for nuclei and subsequent nanocrystal growth. However, the current literature shows that this description is often incomplete (Xia et al., 2015). In the decomposition, the nucleation process follows the path proposed by Lamer and his colleagues (Figure 1) (Whitehead et al., 2021).

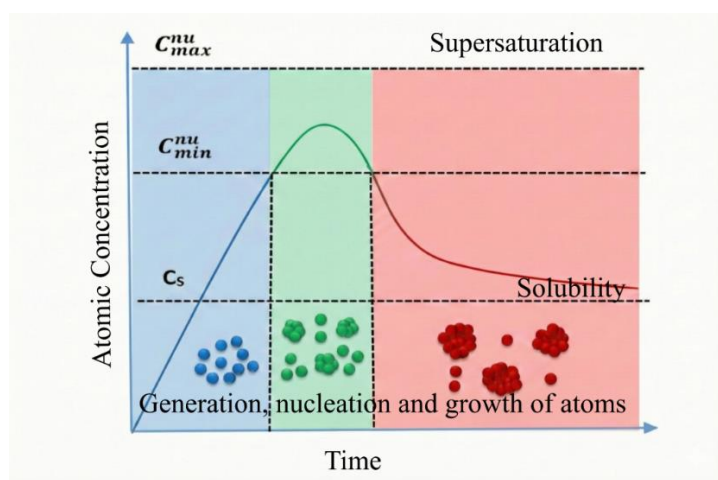


Figure 1. Atomic concentration and time, representing the process and growth

This process follows well-established solution-phase models for monodisperse and metallic nanoparticle synthesis, in which precursor decomposition under thermal or ultrasonic stimulation steadily generates the species that drive nucleation and subsequent growth. When the atomic concentration exceeds the saturation point, atoms begin to self-assemble into small clusters of nuclei via homogeneous nucleation. As the atomic concentration in the solution decreases, the nuclei grow steadily. When the atomic concentration falls below the minimum saturation level, nucleation events immediately cease (Xia et al., 2015). Ongoing precursor decomposition continuously supplies growth species, which feed nuclei and drive their enlargement into bigger nanocrystals until a dynamic balance is reached between dissolved species and atoms at the nanocrystal surface (Bai & Tian, 2013).

The early steps of nanoparticle formation are still under debate, because it is not yet settled whether precursors first become zero-valent atoms that later assemble into nuclei, or whether precursor-derived species begin nucleating before complete reduction. First-principles molecular dynamics offers a way to test these alternatives by tracking atomic motion in time through numerical solution of Newtonian dynamics with forces obtained from electronic-structure theory, and repeated trajectories can be used to build more realistic models of the underlying reaction pathway. It has been shown that the precursor can directly become nuclei without passing through a zero-valent state, and then attach to other growing nanocrystals or nuclei. For example, research demonstrates that a chlorine-stabilized platinum dimer with mixed oxidation states (platinum(II) and platinum(I)) forms directly from dichlorodiaquaplatinum(II) complexes via a single-electron transfer (Bai & Tian, 2013).

Nanocrystal syntheses often start from a metal salt in solution, but the chemically active precursor is not always a simple solvated ion; larger coordinated species can form in solution, and their speciation can control the kinetics and final structure of the nanocrystals. Mass spectrometry studies show that aqueous solutions prepared from commercially available AgNO₃ powders contain high concentrations of trimeric Ag aggregates (Chandra & Kumar, 2016).

A thorough characterization of the solutions and reagents used for nanoparticle synthesis is crucial. A thorough characterization of the solutions used in the synthesis is critical for establishing the underlying causes of the specific nanocrystal morphology formation.

Nucleation and growth kinetics fundamentally govern particle formation and final dimensions, as particle size correlates directly with the critical nucleus size (Bai & Tian, 2013). While electrospray mass spectrometry effectively detects small clusters and larger aggregates during nucleation, its scope is limited to cluster size determination (Chandra & Kumar, 2016). To resolve geometric and internal structures, mass spectrometry must be paired with collision-induced dissociation, photoelectron spectroscopy, or *ab initio* calculations. Additionally, *in situ* emission and absorption spectroscopies offer element-specific characterization, providing a valuable probe during thermal sample treatment.

MECHANISMS OF NANOPARTICLE FORMATION AND GROWTH

Beyond a critical size, structural fluctuations in a cluster become energetically unfavorable, leading to a stable atomic arrangement; this marks the formation of a seed. The seed serves as a bridge between the initial nucleus and the growing nanocrystal. These seeds can exist as single-crystalline, twinned, or multiply twinned structures, often coexisting within a single reaction (Chandra & Kumar, 2016). Regulating the population of these structural motifs allows precise control over final nanoparticle morphology. This structural distribution is governed by the relative free energies of different species and the nucleation kinetics of metal atoms (Chandra & Kumar, 2016).

Under thermodynamic control, the reaction predominantly yields the product with the highest relative stability. This equilibrium state can be predicted using the Wulff theorem, which determines the optimal morphology by minimizing the total interfacial free energy (γ) of the system for a given volume (Boukouvala et al., 2021). Here, the interfacial free energy represents the energy cost associated with forming a unit area of a new surface.

$$\gamma = \left(\frac{\delta G}{\delta A} \right)_{n_i, T, P} \quad (1)$$

Here, G represents the free energy, and A represents the surface area.

In a newly formed grain, the lack of chemical bonds on the surface breaks the crystal symmetry, causing atoms to shift inward. To counteract this displacement, a restoring force is required. The formula for this ideal surface can be derived using a simple model.

$$\gamma = \frac{1}{2} N_b \epsilon P_a \quad (2)$$

Wolf model. This implies that to minimize the total surface energy of these monocrystalline grains, they must adopt tetrahedral or octahedral structures to maximize the {111} faces. However, the surface area of a tetrahedron and an octahedron is larger than that of a cube of the same volume.

Therefore, the monocrystalline grains must be in Wolff polyhedra (or truncated octahedra) surrounded by a mixture of {100} and {111} faces. Owing to their spherical profile, these geometries achieve the smallest possible surface area, minimizing the total interfacial free energy. The formation of such seed shapes has been experimentally observed in the synthesis of various metallic nanocrystals. (Chandra & Kumar, 2016).

In contrast to thermodynamic equilibrium, under kinetic control researchers tune the population of seeds bearing single, multiple, or no twin defects by adjusting the precursor reduction/decomposition kinetics and oxidative etching conditions (Xia et al., 2015). When multiply twinned particles remain sufficiently small, the strain energy from twinning is offset by the low surface energy from extensive {111} faceting, so these structures are favored only within a limited size range. However, in theoretical analysis, the low surface energy of the {111} planes cannot compensate for the excessive deformation energy during the rapid growth of the grains. This leads to the transformation of the polycrystalline grains into monocrystals. Therefore, the polycrystalline grain must be limited to relatively small sizes to increase their performance. In practice, this is typically achieved by keeping the atomic addition and generation rates low. Since this slow generation allows small sizes to persist for a long time, it enables the prevalence of polycrystalline grains over monocrystals. Under similar kinetic conditions, a small amount of twin seeds may be formed (Chandra & Kumar, 2016).

Oxidative etching serves as a key technique for tuning the balance between aggregated and single-crystal seeds by converting elemental zero-valent metals into their corresponding cations (Chandra & Kumar, 2016). A considerable number of synthetic routes are conducted under ambient atmosphere, utilizing dissolved molecular oxygen. When a metal-coordinating ligand is present, it interacts with dissolved oxygen to generate a potent oxidizing complex capable of attacking newly formed nuclei and seeds. Because structural defects and grain boundaries within aggregated particles possess higher surface free energy relative to defect-free single crystals, these distorted regions exhibit increased susceptibility to oxidation. As a result, atoms at these active sites react with the oxidant, undergo oxidation, and subsequently dissolve back into the medium. Conversely, monocrystalline seeds resist such oxidative degradation due to the absence of grain boundary imperfections. Exploiting this inherent chemical selectivity allows for precise, regulated manipulation of distinct seed populations during synthesis. For instance, in the polyol synthesis method – which utilizes organic compounds containing multiple hydroxyl groups – the addition of trace amounts of chloride ions (Cl^-) to the reaction mixture during silver (Ag) synthesis leads to the complete removal of aggregated seeds, yielding exclusively single-crystal seeds. Substituting chloride with milder halide species, such as bromide (Br^-), offers moderate selectivity by selectively dissolving highly aggregated structures while preserving a mixture of single-twinned seeds and single crystals. The utility of oxidative etching has been verified across various noble metals, including gold and silver, where both suitable ligands and oxygen are essential components. Notably, even minor trace impurities or precursor residues present in commercial chemical reagents can unintentionally trigger oxidative etching, drastically altering the final distribution of seed geometries.

After the seed is formed, its size increases as metal atoms attach to it. Nevertheless, tracking nanoparticle expansion at the atomic scale poses significant challenges—and may even be unattainable—particularly during solution-phase synthesis. Research on chemical precipitates shows that when atoms are added to a surface, they circulate until they encounter a site where they can bind. Crystal growth is regulated by a competition between the increase in surface

energy, which favors dissolution, and the decrease in bulk energy, which favors growth. Thus, the dynamic interplay between dissolution and growth determines the evolution of embryos into nanocrystals (Silva et al., 2022). Using electron microscopy, the shapes and internal structures of nanocrystals can be resolved; for example, although animal cells are colorless and very small, it has been possible to determine their internal structure by improving staining methods. Seeds formed at different stages of the synthesis. Consequently, a one-to-one correspondence between the initial seeds and the final nanostructures has been confirmed across several precious metals. The nanoparticles grow homogeneously onto larger templates. Both stages occur in a single reaction vessel via the polyol process, which accounts for the gradual and manageable kinetics relative to chemical reduction using hydrazine (Chandra & Kumar, 2016).

Comprehensive understanding of the growth mechanism remains challenging because previous investigations relied on a restricted set of specimens. Typically, single-crystal seeds evolve into cubic, cuboctahedral, or octahedral geometries, dictated by the relative growth kinetics along the $\{100\}$ and $\{111\}$ directions. When directional growth is favored, cubic and cuboctahedral seeds elongate into rectangular prisms or octagonal rods, respectively. Seeds featuring a single twin plane give rise to symmetric bipyramids bounded by $\{100\}$ facets, which consist of two upright tetrahedra; under anisotropic growth conditions, these can stretch into nanobeams. For multiply twinned seeds, the stability of side-facing $\{100\}$ planes determines whether decahedra, icosahedra, or pentagonal nanowires/nanorods are produced. Seeds containing stacking fault defects usually develop into thin plates with $\{111\}$ basal faces and side surfaces comprising mixed $\{111\}$ and $\{100\}$ facets (Bai & Tian, 2013). Driven by their hexagonal symmetry, such grains initially yield thin plates with hexagonal cross-sections, which may eventually transform into triangular shapes as lateral $\{111\}$ facets disappear during prolonged growth. Additionally, structural defects, non-standard grains, excessive growth rates, and surface-capping agents can cause final morphologies to deviate significantly from standard geometrical profiles. The progression from initial seeds to final nanostructures is illustrated below (Figure 2).

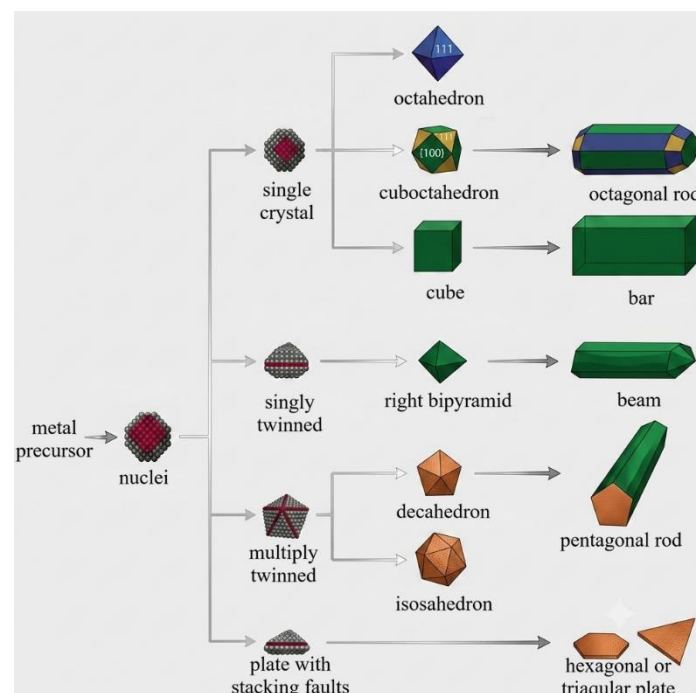


Figure 2. Single-crystal seeds give rise to cubes, cuboctahedra, or octahedra based on the growth rates along $\{100\}$ versus $\{111\}$ planes. Stimulating preferential growth along a single axis converts cubic seeds into rectangular bars and cuboctahedral seeds into octagonal cores

An effective method for controlling the shape of nanocrystals is the introduction of constraining agents. Surface confinement or chemical adsorption processes in solution significantly affect nanoparticle morphology, as the agents can inhibit the growth of certain facets, allowing for the regulation of surface areas (Bai & Tian, 2013).

Furthermore, Xia et al. showed that stacking and stacking faults disrupt the cubic symmetry, leading to the formation of anisotropic shapes (Xia et al., 2015). Stacking faults typically occur in close-packed lattices with hexagonal symmetry (Oliver et al., 2015). If the added atoms preserve the seed structure during crystal growth, this process is called epitaxial (Oliver et al., 2015).

SURFACE MORPHOLOGY AND CRYSTAL STRUCTURE

The crystal structure and surface morphology represent the atomic arrangement. High-resolution characterization techniques are widely utilized to evaluate surface topography at the nanoscale. Atomic force microscopy (AFM) provides direct three-dimensional spatial visualization of surface structures and grain features. The 3D surface topography obtained via AFM analysis illustrates the characteristic morphology and height profile of nanoscale crystalline domains (Figure 3). (Askeland-the-Science-and-Engineering-of-Materials, 2006).

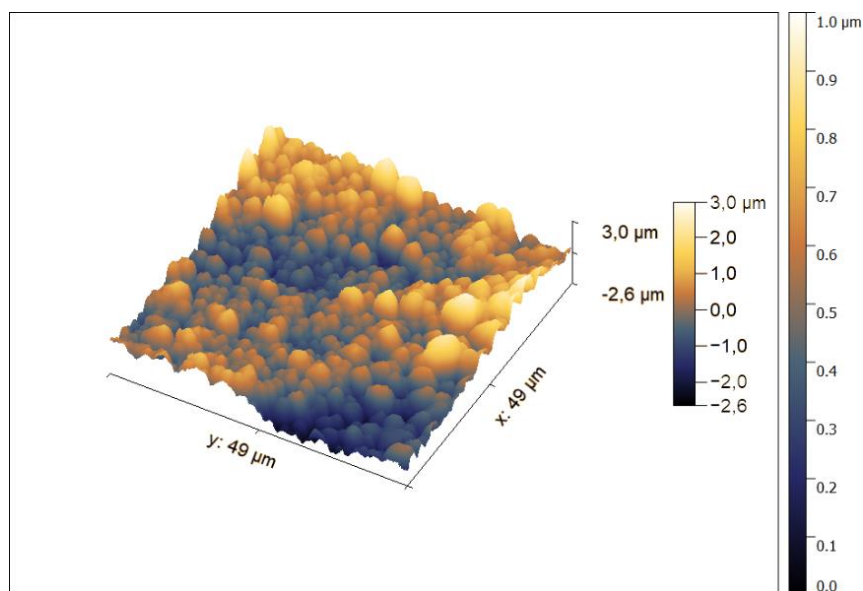


Figure 3. AFM topographic image displaying the surface morphology

CRYSTALLINE STRUCTURE AND UNIT CELL GEOMETRY

Polycrystalline solids are composed of many individual grains or crystallites, where each grain is considered a separate crystal with its atomic structure ordered over long distances. Since polycrystalline solids are isotropic, they lack periodicity. In amorphous materials, there is no long-range ordering. Then, many unit cells are grouped together to form a macroscopic crystal (Chawla, 2012). The figure below shows the basic structure of a unit cell of a 3-dimensional crystal lattice. The unit cell contains the faces a , b , and c in three directions, as shown in Figure 4.

A unit cell can be described by the vectors a , b , and c . Each of its faces has a length of $a(2r)$, where r is the radius of the atom at the lattice points. This distance is called the lattice constant. An important property of the unit cell is the nearest distance between the centers of these atoms, as they are held more tightly by the nuclear force than in other regions.

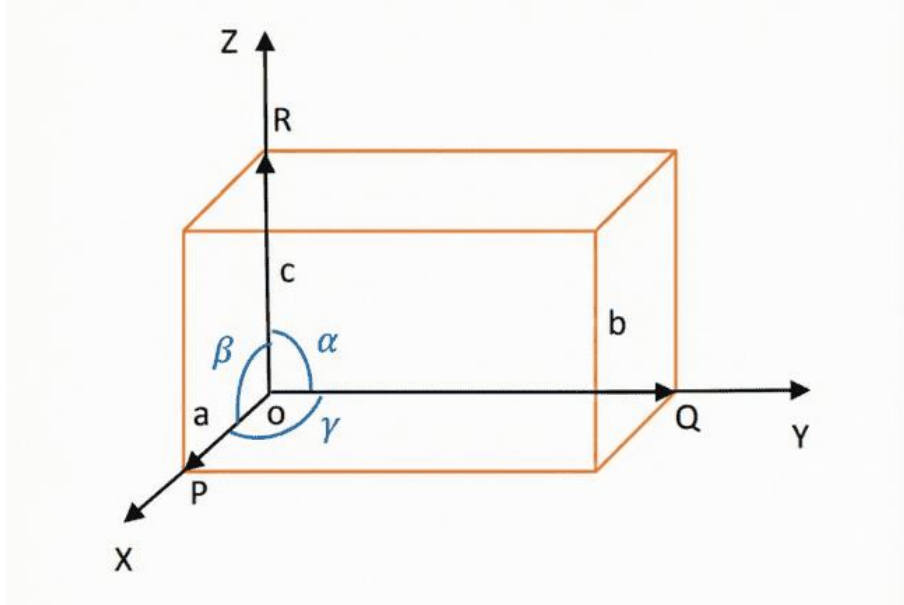


Figure 4. Unit cell lattice parameter

There are different lattice types for the unit cell, including simple cubic (SC), body-centered cubic (BCC), and face-centered cubic (FCC). The total volume of the unit cell is determined by the product of its edge lengths.

A unit cell is geometrically represented by the translation vectors a , b , and c . For cubic crystal systems, these vectors are equal in magnitude and perpendicular to one another, and their common length is designated as the lattice constant. The classification of cubic lattices are simple cubic (SC), body-centered cubic (BCC), and face-centered cubic (FCC) structures.

$$V_c = a \times b \times c \quad (3)$$

The atomic packing factor (APF) of the unit cell is determined by the equations shown below.

$$APF = \frac{N \times V_1}{V_2} = \frac{v}{V} \quad (4)$$

where, N – total number of atoms, V_1 – volume of one atom, V_2 – volume of a unit cell. Schematic examples of Miller index notation for crystal planes, such as (111), (100), and (110) (Figure 5).

For the simple cubic cell, the total number of atoms at all angles = $(1/8) \times 8 = 1$ atom. The radius of the simple cubic cell is $a = 2r$. The volume of the simple cubic cell = $a^3 = (2r)^3$.

For the body-centered cubic (BCC) cell, the total number of atoms per unit cell is $(1/8) \times 8 + 1 = 2$ atoms. The relationship between the lattice parameter a and the atomic radius r is given by the body diagonal: $a\sqrt{3} = 4r$, hence $a = 4r/\sqrt{3}$. The volume of the BCC unit cell is $V = a^3 = (4r/\sqrt{3})^3$.

Therefore, the atomic packing factor is the ratio of the volume of the unit cells and the principal atoms to the volume of a unit cell. Atomic packing factors depend on the atomic radius and the nature of the chemical bond and can be expressed as:

$$APF = \frac{2 \times \frac{4}{3} \pi r^3}{\left(\frac{4r}{\sqrt{3}}\right)^3} \approx 0.68 = 68\% \quad (5)$$

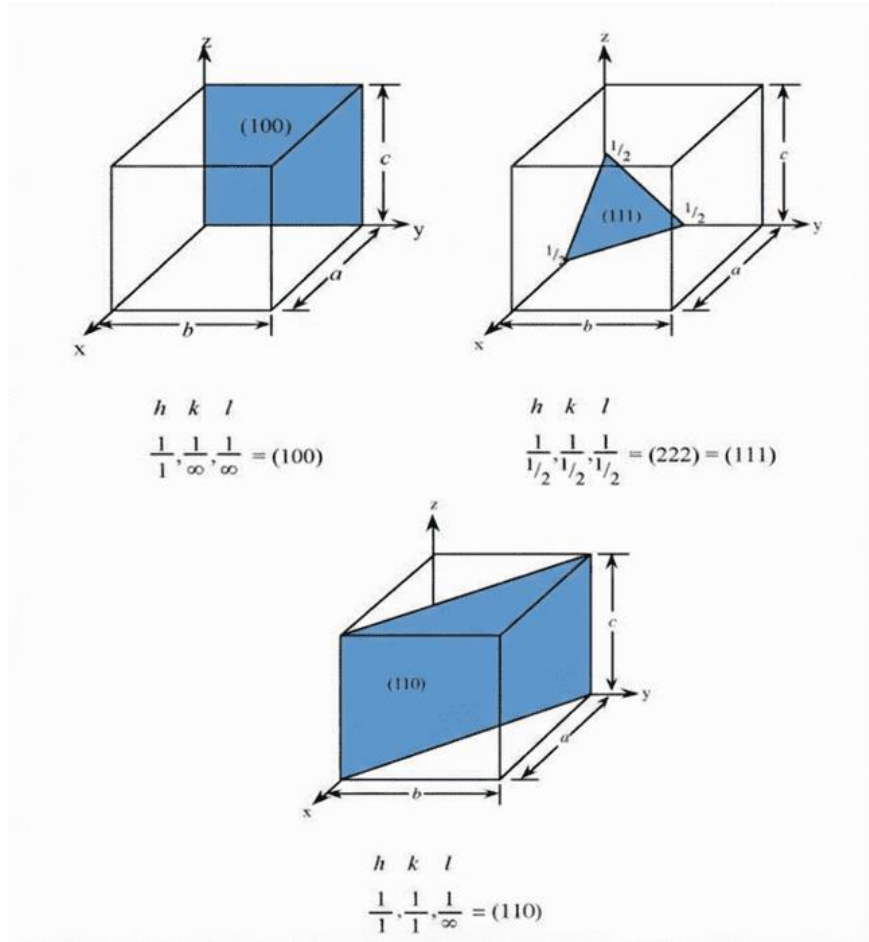


Figure 5. Examples of Miller index notation for crystal planes

The BCC unit cell has one atom at each of the eight corners and one in the center of the cell, as shown in Figure 6.

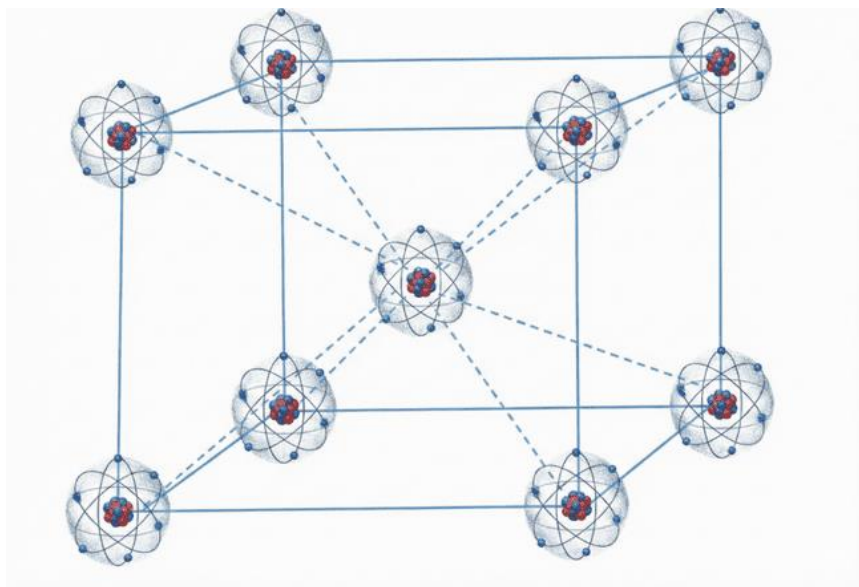


Figure 6. BCC structure

Lattice constants represent the spatial dimensions of unit cells within a 3D crystal matrix, serving as main metrics for evaluating structural compatibility across materials. Metals featuring a body-centered cubic lattice possess a less densely packed atomic arrangement than face-centered cubic systems. This specific lattice geometry yields higher rigidity and mechanical strength at the expense of ductility. Plastic deformation in BCC metals is inherently restricted because the structural coherence of the lattice renders the mutual sliding of parallel atomic planes significantly more difficult compared to close-packed metals such as gold. Thus, by controlling the kinetics and using targeting agents, particles with different morphologies can be produced. Below, we will examine how these morphological differences affect their antimicrobial efficacy using copper nanoparticles as an example.

ANTIBACTERIAL ACTIVITY OF COPPER NANOPARTICLES

Given the relentless rise in antimicrobial resistance and the dwindling efficacy of standard antibiotic regimens, nanoscale transition metals have garnered increasing scrutiny as alternative therapeutic agents (Ermini & Voliani, 2021). Copper-based nanomaterials—including pure metallic copper, cuprous oxide, and cupric oxide—are of particular interest. Their physicochemical profiles confer marked bactericidal properties, active against both Gram-positive and Gram-negative species (Elshaer & Shaaban, 2023). Silver nanoparticles are widely considered the reference standard in this domain. Yet copper presents distinct practical advantages. Production costs are substantially lower—approximately eight-fold relative to silver—and its antimicrobial action, mediated through multiple concurrent pathways, appears to match or even exceed that of its more expensive counterpart.

Given the complexity of the antibacterial response, the action of copper-based nanoparticles cannot be reduced to a single unifying principle; physical interaction and dissolution kinetics are both implicated (Ma et al., 2022). Generation of reactive oxygen species (ROS) is frequently regarded as the primary mechanism, wherein released copper cations cycle between the Cu^+ and Cu^{2+} oxidation states—reacting with cellular peroxides via Fenton-like pathways—to yield highly reactive hydroxyl radicals (Gudkov et al., 2024). Lipid peroxidation of the membrane follows: a loss of structural integrity, depolarization, and cytoplasmic leakage are the result. A distinct, parallel route concerns the internalization of intact nanoparticles, a process often termed the "Trojan-horse" mechanism. Once internalized, the acidic cytosolic microenvironment accelerates ion release, leading to a substantial intracellular accumulation of copper. Binding of these ions to sulfhydryl groups inactivates critical enzymes; simultaneously, disruption of iron-sulfur clusters via dismetallation further compromises cellular function—culminating, under many experimental conditions, in metabolic collapse. The relative contribution of these pathways, however, appears contingent upon the specific experimental design, and their precise interplay remains an open question.

In terms of antimicrobial activity, copper-based nanoparticles exhibit a pronounced dose-response relationship, contingent also upon exposure time and initial bacterial concentration (Lange et al., 2021). By comparison, earlier investigations into the viability of *Escherichia coli* and *Staphylococcus aureus* treated with CuNPs demonstrated complete cell inactivation—achieving up to a 5 Log_{10} reduction—within specific concentration thresholds. Yet, as energy dispersive X ray spectral analysis and surface characterization reveal, metallic CuNPs have a tendency to form passivating oxide layers upon exposure to ambient conditions or aqueous media; this surface transformation can, at least initially, moderate their ionic dissolution and, by extension, their antimicrobial potency relative to unoxidized noble metals. A key implication, therefore, is that the bactericidal performance of copper based systems is intrinsically governed by the oxidation state and chemical stability of the nanoparticle surface—a dynamic that is not without consequence for their practical deployment.

The oxidation state of copper nanostructures is increasingly recognized as a critical parameter governing both ion release kinetics and long-term biocidal durability—a relationship that is far from trivial. Pure metallic copper (Cu^0), though initially dissolving with considerable rapidity, is prone to passivation in physiological environments, a process that curtailed efficacy over extended durations. Cuprous oxide (Cu_2O) nanoparticles, in contrast, release monovalent Cu^+ ions, which, due to their higher reducing capacity, appear to exhibit antimicrobial activity superior to that of the divalent Cu^{2+} ions liberated from cupric oxide (CuO). A growing body of comparative evidence has borne this out. Studies have demonstrated, for instance, that Cu_2O thin films sustain robust bactericidal action against both *Klebsiella pneumoniae* and *Escherichia coli* for periods exceeding 144 hours, with no evidence of premature passivation under the experimental conditions tested. CuO nanostructures, however, are suggested to operate through a mechanism dominated by sustained reactive oxygen species (ROS) generation, with their ionic contribution playing a relatively lesser role. It should be noted, nonetheless, that the precise interplay between surface chemistry, ion dissolution, and the resulting oxidative stress remains an area of active investigation (Gonçalves et al., 2022; Gudkov et al., 2024).

The antibacterial efficacy of copper nanoparticles (CuNPs) is known to be subject to a complex interplay of dimensional and morphological determinants—a relationship that resists simplistic reduction to any single parameter (Raja et al., 2023). With respect to particle size, a reduction to dimensions below 50 nm has been repeatedly associated with a pronounced increase in the surface-area-to-volume ratio; this geometric amplification, in turn, is thought to facilitate more rapid contact with bacterial envelopes and to accelerate the concomitant release of copper ions into the surrounding milieu. Yet size alone, as emerging evidence suggests, does not fully account for the observed variability in antimicrobial performance. Of particular interest in this regard is the influence of particle morphology. Anisotropic nanostructures—triangular nanoprisms or rod-shaped particles exposing high-energy {111} crystallographic planes, for instance—have been shown, in comparative assays, to exhibit markedly superior bactericidal activity relative to their spherical counterparts (Pellosi et al., 2025). This enhancement is generally attributed to the elevated surface energy characteristic of the {111} facet, which not only promotes heightened chemical reactivity but also predisposes the nanoparticle to a distinctive mode of physical interaction. Often described in the literature under the rubric of the mechanical "blade effect," this mechanism involves the sharp edges or vertices of the anisotropic particles physically piercing the lipid bilayer, thereby compromising membrane integrity and lowering the minimum inhibitory concentration required for complete bacterial eradication. What emerges from these observations is a view of antibacterial activity in which precise architectural control assumes a position of equal importance to particle miniaturisation—a conclusion that carries significant implications for the rational design of next-generation nanocidal agents.

Crucially, the multi-target mechanisms of action associated with copper nanoparticles (Cu NPs) are considered to minimize the risk of acquired bacterial resistance—a feature of considerable therapeutic relevance. Sublethal exposure to copper-based nanomaterials, as demonstrated in certain experimental models, induces the transient expression of bacterial efflux pump genes, including the *copA* and *cusA* operons, which serve to mitigate ionic stress. However, such exposure reportedly does not lead to permanent genetic mutations in environmental or clinical microbial populations; nor does it appear to promote the horizontal transfer of antibiotic resistance determinants. Synergy has indeed been observed in the combination of Cu NPs with standard antibiotics. Studies point to a considerable reduction in the minimum inhibitory concentrations required to suppress resistant strains—a compelling advantage from a therapeutic standpoint (Ali Solangi et al., 2024). Practical translation is complicated, however, by several safety concerns. Uncontrolled exposure to Cu NPs has been associated with systemic cytotoxicity, pulmonary irritation, and oxidative stress—risks that

collectively underscore the need for rigorous optimization of dose, morphology, and surface coatings.

CONCLUSION

In the current context of the rise of antibiotic-resistant microorganisms and the spread of hospital-acquired infections, metal nanoparticles, especially silver-, gold-, and copper-based materials, play an important role as an effective alternative. A deep understanding of the mechanisms of nucleation and crystal growth enables the control of nanoparticle morphology at the molecular level and the production of shapes with the desired antimicrobial properties.

Not only the size but also the geometric shape of nanoparticles is a crucial factor in enhancing antimicrobial activity. In particular, triangular nanoprisms with a dominant {111} crystallographic plane and sharp edges exhibit much higher bactericidal properties compared to their spherical or rod-like counterparts. This efficacy is directly related to the high surface area of the triangular shapes and the presence of reactive edges, which makes them optimal for inactivating pathogens such as *E. coli*. However, for new antimicrobial agents to be widely introduced into medical practice, their efficacy must be accompanied by further comprehensive research into their potential toxic effects on the human body.

CONFLICT OF INTEREST: The authors declare that they have no conflict of interest.

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