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Review Paper

Physical Fabrication of Metallic Nanoparticles: Methods, Mechanisms, Control Variables, Emerging Trends

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Abstract
Physical methods of synthesizing metal nanoparticles (MNPs) are of great importance because the synthesized nanomaterials can be very pure, free of bonds, and correct in terms of their structure. On the other hand, physical methods transform metals from a solid state to an atomic or plasma state using heat, electricity, plasma, and light. They then cool rapidly and agglomerate to form nanoparticles. This study focuses on the main techniques used to manufacture metal nanoparticles through physical methods with detailed scrutiny. Some techniques include inert gas condensation, magnetron sputtering, spark discharge, and laser ablation in liquids. We can discuss the fundamental physical mechanisms of nanoparticle formation, such as super saturation of vapor, homogeneous nucleation, coagulation, agglomeration, and surface diffusion. We can discuss the effect of process parameters on nanoparticle properties such as nanoparticle size, shape, crystal structure, composition, and surface chemistry. A comprehensive review of different techniques is provided, including their pros and cons, scalability, and effectiveness in different applications. There is also a discussion of new challenges that may arise in the future, such as real-time process control, synthesis of high-entropy multicomponent nanoparticles, and green chemistry in large-scale nanoparticle synthesis.

Keywords
Metallic, Nanoparticles, Materials, Physical Synthesis, Methods

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1. INTRODUCTION

Metal nanoparticles are one of the most researched nanomaterials due to their wide use in chemical catalysis, plasmonics, electronics, sensing, energy storage and conversion, and biological fields (Atikur and Grégory, 2024; Nabila et al., 2023; Inna et al., 2023; Aliya et al., 2021). Metal nanoparticles are characterized by high surface-to-volume ratios, variable band structures, and quantum size effects due to their nanoscale dimensions (Jhilirani et al., 2020; Ismail et al., 2025; Saba, 2015; Abdullah et al., 2025; Danbature et al., 2023). This is one of the main differences between metal nanoparticles and their bulk counterparts (Mohammad et al., 2019). The method of manufacturing metal nanoparticles is extremely important because the size, shape, composition, and surface state of metal nanoparticles affect their properties (Amir et al., 2018). The most commonly used methods for synthesizing metal nanoparticles are wet chemical reduction, sol-gel methods, and microemulsion techniques. These methods are easy and can be used in different ways (Zhang and Wada, 2021; Hameed et al., 2019; Zhu et al., 2001; Zhang et al., 2011; Abdullah et al., 2025; Danbature et al., 2023).

In general, these methods involve the use of reducing agents and/or stabilizers and/or surfactants that are adsorbed onto the metal nanoparticles. These reducing agents and/or stabilizers and/or surfactants can act as toxins or impurities (Matej et al., 2017). Without changing the form of the nanoparticles, these kinds of species are still hard to get rid. Physical synthesis methods, on the other hand, only use physical processes to make nanoparticles from bulk metals (Gurunathan et al., 2009). This usually makes the surfaces cleaner, the purity higher, and the ability to reproduce better (Nadia et al., 2023; Ganjali et al., 2015; Kim et al., 2016). Physical synthesis technologies were made possible by advances in aerosol science, thin-film deposition, and plasma physics.

Early research on vapor-phase condensation laid the groundwork for the theoretical basis for making nanoparticles from supersaturated vapors (Ahmad et al., 2024; Atiaf and Qusay, 2020; Chewchinda et al., 2013). Improvements in vacuum technology, plasma sources, and high-power lasers have made it possible to create nanoparticles with specific properties using a number of physical synthesis approaches. There has been more research in this area because people are more interested in ligand-free catalysts, nanomaterials that can be used in devices, and sustainable production (Jasim, 2025; Hamed and Reza, 2024; Schwenke et al., 2011; Kulinich et al., 2013; Jasim et al., 2024b; Fazio et al., 2020; Hussein et al., 2024; Attallah et al., 2023). The importance of this work lies in reviewing studies related to the preparation and production of metallic nanomaterials by physical methods.

2. BASIC PRINCIPLES OF SYNTHESIS PHYSICAL NANOPARTICLES

The basic rules of thermodynamics, kinetics, and aerosol dynamics control the making of metallic nanoparticles utilizing physical synthesis methods (Cristoforetti et al., 2011). The process usually starts with creating metal atoms, clusters, or ions using methods including sputtering, evaporation, electrical discharge, or laser ablation. At initially, these things are in a vapor or plasma state at a high temperature. When the metal vapor cools down very quickly, which is normally when it reaches an inert gas or liquid, it becomes supersaturated (Jasim et al., 2024a; Quintana et al., 2002; Ahmed et al., 2024b; Franzel et al., 2012). Homogeneous nucleation occurs when clusters form on their own from the vapor phase. This occurs when the vapor phase is supersaturated (Ahmed et al., 2024a). Once stable nuclei have formed, growth continues through the condensation of atoms in the vapor phase and the agglomeration of clusters. The importance of these processes varies based on the amount of vapor, the temperature, the pressure, and the duration of the vapor phase (Ganash, 2022). Coalescence is very important for figuring out what the final form of a particle will be. When particles collide at extremely high temperatures, they can merge completely into small, spherical nanoparticles. When it's colder, particles can adhere together to make agglomerates that look like fractals and have a lot of holes (Ganash, 2022; Gondal et al., 2012; Ismail et al., 2025; ElFaham et al., 2021; Alheshibri, 2023; Sabri et al., 2024). Surface diffusion and sintering can change the structure of particles a lot more during and after they are made. In order to change the properties of nanoparticles in physical production methods, you need to know how these processes work and how to change them.

3. GAS-PHASE CONDENSATION METHODS

Inert Gas Condensation (IGC) is one of the oldest and most explored ways to make metallic nanoparticles . This method entails heating a metal source within a chamber characterized by low pressure and an inert environment, such as argon or helium. (Figure 1) (Mendivil et al., 2015; Pandya and Kordesch, 2015). Resistive heating or electron-beam evaporation are the most common ways to do this. The metal vapor cools down and becomes supersaturated when it comes into contact with the inert gas. This starts the process of homogeneous nucleation (Pandya and Kordesch, 2015; Al-Nassar and Hussein, 2019; Mostafa et al., 2017). A lot of important things affect the size and spread of particles in IGC. These factors are the pressure of the inert gas, the rate of evaporation, the flow of gas, and the amount of time spent in the condensation zone (Swihart, 2003). Particles hit each other more often and cool down faster when gas pressures are higher. This usually makes the primary particles smaller. But

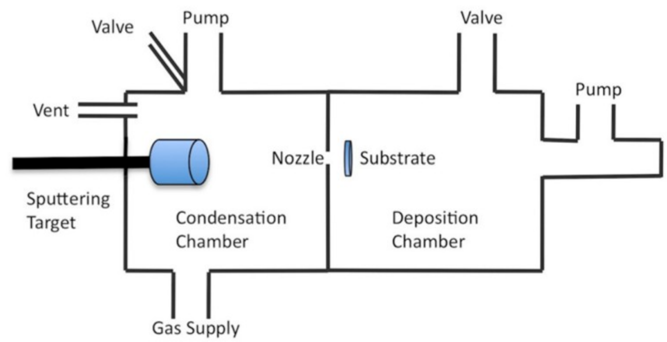

Figure 1. Scheme of Inert Gas Condensation (LGC) Method (Friedlander, 2000)

when water evaporates faster, the vapor becomes more concentrated, which makes it easier for larger particles to form (Simchi, 2007; Buffat and Borel, 1976; Burda, 2005; Link and El-Sayed, 1999). IGC can make nanoparticles that are very pure from many different metals and alloys, such as reactive metals, transition metals, and noble metals (Xia, 2009). You can buy nanoparticles as powders or put them right on surfaces. But there are problems with particles sticking together while they are being collected and reactive metals oxidizing when they touch air.

Magnetron Sputtering Gas Aggregation Magnetron sputterin g -based gas aggregation sources are a modern extension of inert gas condensation principles. In these systems, ions with a lot of energy hit a target and knock metal atoms off of it. Then, the atoms are put in a chamber where they are crushed (Figure 2) (Kratochvil et al., 2015; Haberland, 1992). Atoms that have been sputtered hit atoms of inert gas, which makes them heat up and turn into clusters and nanoparticles. One of the best things about gas aggregation sources is that they work well with direct deposition of nanoparticles. A beam drives gas-phase nanoparticles toward a substrate, which enables you make nanostructured films and composite materials (Haberland, 1992; Schmidt-Ott, 1988; Grammatikopoulos, 2023). You can use mass filters or differential pumping stages to pick the size of the particles, which are usually quite small, between 1 and 20 nm (Park, 2003). Gas aggregation sources are useful for making nanoparticles that are alloys or have more than one portion since they can work with more than one sputtering target at a time (Johnson, 2011). Still, it's hard to make a lot of things at once because the system is complicated and the throughput is low.

3.1 ELECTRICAL DISCHARGE METHODS

When electricity breaks down between two metal electrodes in a gas that is flowing, spark discharge generators (SDGs) make nanoparticles. A very hot plasma channel occurs every time there is a discharge. This channel soon breaks down and vaporizes the material on the electrode) Figure 3 (Mueller et al., 2012). When the metal vapor from the SDGs cools down, it becomes nanoparticles. The properties of these nanoparticles are greatly

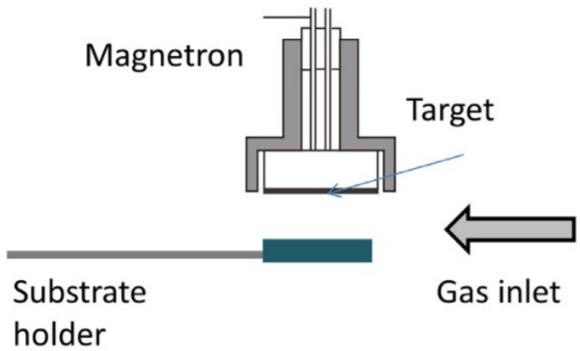

Figure 2. Magnetron Sputtering Gas System (Kratochvil et al., 2015)

affected by the electrical circuit characteristics, such as resistance, capacitance, inductance, discharge energy, and repetition rate (Mueller et al., 2012; Vernieres, 2020; Vazquez-Pufleau, 2023; Rizvi, 2012). The cooling speeds, oxidation behavior, and particle agglomeration all change according on the gas flow rate and composition (Amendola and Meneghetti, 2009; Zhang, 2017; Barcikowski and Compagnini, 2013; Fazio, 2020). People like SDGs because they are easy to use, don't use chemicals, and can be made bigger by running them in parallel. But SDGs often make clusters that look like fractals instead of nanoparticles that are perfectly spherical. These kinds of structures can be useful in some situations, but in other situations, they may need to be worked on more, like by sintering (Xiao, 2016; Wegner and Pratsinis, 2003; Gedanken, 2004; Thornton, 1974).

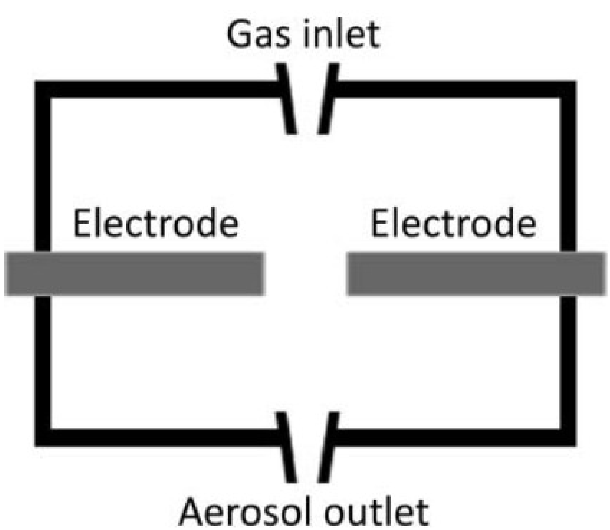

Figure 3. The Basic Components of the Spark Discharge Generator Chamber (Xiao, 2016)

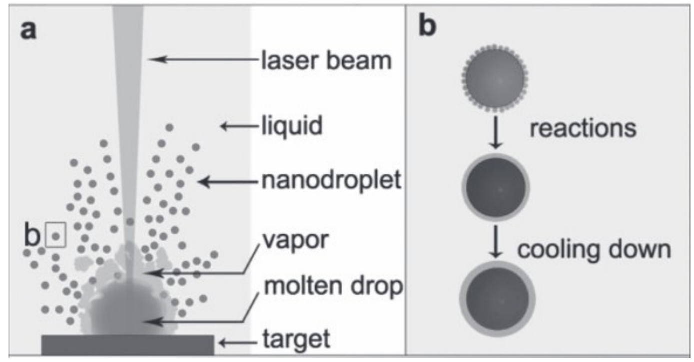

Figure 4. Schematic Diagrams of Metal Nano Droplet Ejection and Nanostructure Formation in the LAL Process Using a Low-Energy Millisecond Laser. a) Formation of Nano Droplets. b) Reactions of an Ejected Metal Nano Droplet with Ambient Liquid (Zeng et al., 2012)

4. LASER-BASED PHYSICAL SYNTHESIS

Laser ablation in liquids (LAL) or pulsed laser ablation in liquids (PLAL) is a flexible way to make colloidal metallic nanoparticles (Tolman, 1949). This method fires a pulsed laser beam at a solid metal target that is in a liquid (Figure 4) (Zeng et al., 2012). The laser and the substance interact so powerfully that they create a plasma plume that the liquid around it keeps in place. After that, the particles cool very quickly and turn into nanoparticles. LAL has the unusual benefit of making nanoparticles without using chemical reducing agents or surfactants. This results in colloids that don't have ligands or are extremely weakly stabilized (Shi et al., 2025; Gökce et al., 2015). The laser's wavelength, pulse duration, fluence, repetition rate, and the properties of the liquid media all affect the size and structure of nanoparticles (Ahmed et al., 2025; Sun and Xia, 2002; Eustis and El-Sayed, 2006). It was challenging to make LAL bigger because it didn't work very well. But new advances in high-repetition-rate lasers, scanning technologies, and flow-through ablation cells have made it considerably easier to do so (Heath, 2009; Hirscher, 2011; Zhang, 2010; Jain, 2006).

5. CONTROL PARAMETERS AND PROCESS OPTIMIZATION

In general, the efficiency and quality of nanoparticle preparation, in terms of structure and size, depend primarily on the ability to control the initial formation conditions and particle growth during the process. Although there are differences in energy sources and preparation media in Laser Ablation in Liquids (LAL), Spark Discharge Generators (SDG), and Gas-Phase Condensation (GPC) techniques, they share a fundamental principle: the generation of high-energy initial atoms or clusters, followed by controlled cooling leading to condensation and nanoparticle growth (Pratsinis, 2016).

In LAL technology, the laser energy source is the most important factor in controlling the process. Laser energy and pulse duration directly affect the amount of material removed and the

Table 1. Comparison Between Three of Physical Technologies

Properties	LAL	SDG	GPC
Preparation Medium	Liquid	Gas	Gas
Volume Control	Medium	Poor	Excellent
Volume Distribution	Wide	Very Wide	Narrow
Purity	Very High	Medium–High	High Very
Yield	Low	Medium	Medium
Industrial Applicability	Limited	Good	Relatively Good
Direct Precipitation	No	Yes	Yes
System Cost	High	Low	High

temperature of the resulting plasma Higher energy or longer pulses result in larger particles and a higher chance of re-melting, while lower laser energy or shorter pulses result in better size distribution. The liquid medium serves a dual purpose as a cooling agent and a limit to particle growth. The selection of the type of liquid and its viscosity has a direct impact on the cooling rate and agglomeration rate. There is a delicate balance needed in this process to achieve fast cooling rates without affecting the structural integrity of the particles (Liu, 2016).

In SDG technology, the control process is mainly concerned with the characteristics of the electrical discharge and the gas medium. The potential difference and the frequency of sparks influence the extent of the material vaporized from the electrodes, which in turn influences the temperature of the discharge, hence the size of the particles. The distance between the electrodes and the inert gas flow rate control the residence time of the particles in the cooling zone, which influences the growth of the particles, with a longer residence time resulting in larger size distribution. The optimized process is mainly concerned with the stability of the discharge, the elimination of non-uniform wear of the electrodes, and the gas flow to prevent agglomeration and ensure uniform cooling (Li, 2021).

In contrast with this, GPC technology provides the highest degree of control over the process of generation and growth. The pressure and type of gas used control the number of collisions between the vaporized atoms and gas molecules, hence controlling the rate of loss of kinetic energy and the size of the clusters formed. Residence time in the condensation chamber is another important factor in controlling the size of the particles formed. Precise control over the length of the condensation zone and the velocity of the clusters can result in a narrow range of particle sizes. The use of cooled walls in the condensation chamber is an important factor in optimizing the process of growth and flocculation (Qiu, 2020).

If one compares these three methods from a control and process optimization point of view, it becomes apparent that in LAL, a complex interrelationship between laser and liquid medium is present, allowing for a certain degree of control in terms of size. SDG, on the other hand, uses electrical discharge stabilization and gaseous medium control, allowing for a moderate degree of control in terms of particles produced. GPC offers the most flexibility and precision in control, as all stages of formation and growth can be adjusted almost independently, making it best suited for applications requiring homogeneous nanoparticles with precisely defined properties (Dehm, 2018).

A simplified comparison of the characteristics of the three physical technologies can be made as shown in Table 1.

6. APPLICATIONS OF PHYSICALLY SYNTHESIZED METALLIC NANOPARTICLES

The practical applications of many metallic nanoparticles prepared using the aforementioned physical methods depend heavily on their high purity and structural properties, as well as the nature of the medium in which they are prepared. LAL, SDG, and GPC techniques enable the production of nanoparticles without the use of chemicals, making them ideal for advanced applications. Nanoparticles prepared using LAL are characterized by high purity and stability in liquid media, making them suitable for medical and biological applications such as drug delivery, phototherapy, inhibition of various bacteria and fungi, and cancer cell therapy. They are also used in catalysis and optics, including photo sensing and water treatment. SDG nanoparticles, on the other hand, present a continuous method for their dry production, making them more useful in industrial applications like flexible electronics, conductive inks, heterogeneous catalysis, and aerosol studies. As GPC-mediated particle manipulation allows for precise control of particle dimensions and structural compositions, these particles are best for use in Nano electronics applications, multilayer films, and optical and magnetic materials (Niederberger and Garnweitner, 2006; Ahmed et al., 2024a).

7. EMERGING TRENDS AND FUTURE CHALLENGES

The appearance of new trends in the last decade, particularly regarding the appearance of hybrid techniques based on the combination of chemical and physical techniques for the synthesis of metallic nanoparticles, has allowed for an enhancement in the quality, stability, and functionality of the nanoparticles. It has allowed us to control the size and shape of the nanoparticle through the crystalline nature of its structure and to create nanoparticles for specific applications in the medical, electronic, and energy industries. The increasing number of applications in fields such as renewable energy, smart sensors, personalized medicine, and nanostructured membranes shows the versatility of nanoparticles (Jasim, 2025). Meanwhile, there is an increasing need for the development of sustainable production techniques that will minimize the use of chemicals in the production of high-purity and safe metallic nanoparticles. The future challenges will include ensuring the integrity of the nanoparticles through the challenges of stability and aggregation when they are subjected to practical situations, moving from the laboratory setting to the actual industrial setting, the long-term effects on the environment and the human population that may arise due to the use of metallic nanoparticles, and the effective integration of the nanoparticles in devices while maximizing their unique properties (Ismail et al., 2025).

8. CONCLUSIONS

This study explores several physical methods for synthesizing metallic nanoparticles, including laser ablation in liquids, electrospray techniques, and gas-phase condensation. The results show that these methods can successfully produce high-purity nanoparticles while minimizing reliance on chemicals, leading to significant environmental benefits. Furthermore, each technique offers distinct advantages in terms of particle size and shape control, as well as scalability. While some methods offer greater operational flexibility, others allow for continuous production or more precise control of crystal structure. However, despite the significant progress made in this field, challenges related to process efficiency and productivity remain. This underscores the need for further improvement to support future research and practical industrial applications.

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