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What are synthetic nanoparticles?

Summary

Synthetically produced nanoparticles play an important role in nanotechnology. They are the basis for many applications currently being used on a large scale, and they have a great potential in the development of new materials. The diversity of synthetic nanoparticles is considerable. They are distinct in their properties and applications. In addition to their size, synthetic nanoparticles vary in chemical composition, shape, surface characteristics and mode of production. This dossier provides an overview of the various characteristics of nanoparticles.

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Introduction

Nanoparticles are not solely a product of modern technology, but are also created by natural processes such as volcano eruptions or forest fires. Naturally occurring nanoparticles also include ultrafine sand grains of mineral origin (e.g. oxides, carbonates). In addition to commercially produced nanoparticles, many are unintentionally created by the combustion of diesel fuel (ultrafine particles) or during barbecuing.

Synthetic nanoparticles find use in many applications. This includes dispersions[1] in gases (e.g. as aerosols), as ultrafine powder, for films, distributed in fluids (dispersed, for example ferrofluids) or embedded in a solid body (nanocomposites). The present dossier focuses on those nanoparticles present in a solid state. Liposomes, micelles and vesicles, which are soluble nano-scale organic compounds and also fall into the category of nanoparticles, are omitted here.

Definition

The term "nanoparticle" is a mixture of the words "nanos" (Greek: the dwarf) and "particulum" (Latin: particle). In the scientific context, "nano" primarily refers to a specific order of magnitude, namely 10^{-9}. This can refer to a volume, a weight or a unit of time, whereby a nanometer (nm = 10^{-9} meters) corresponds to one millionth of a millimeter. To illustrate this more graphically, a nanometer has the same relation to a meter as the diameter of a hazelnut to the diameter of the Earth.

In the framework of nanotechnology, the term "nano" refers almost exclusively to particle length. This means that those objects that extend in two dimensions from 1 to several 100 nm are designated as nanoparticles. This, however, also includes filamentous objects such as nanotubes. This dossier therefore uses the definition of the EU-Commission SCENHIR[2], which is restricted to those objects whose extension in all three dimensions lies between 1 and 100 nm. Those that extend in only two dimensions on the nm-scale are termed nanotubes and particulate objects; those with only a single dimension under 100 nm are termed nanopellets.

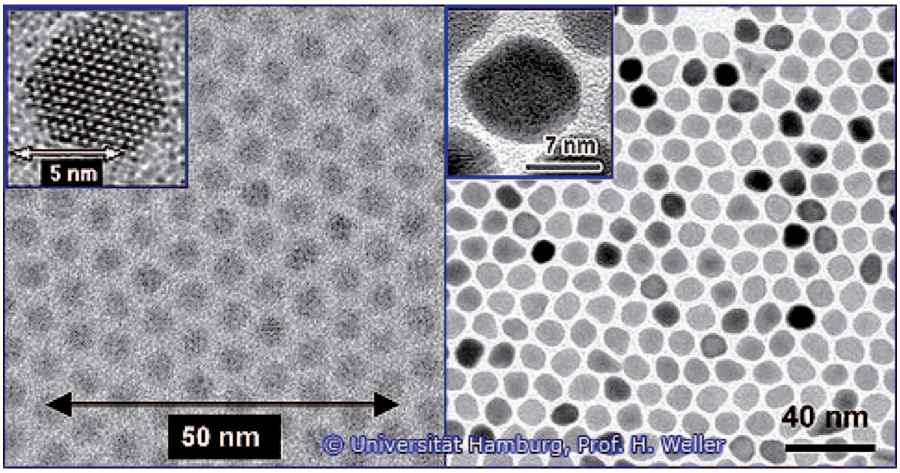

Figure 1: Electron microscopical images of various nanoparticles[3]

Characteristics of nanoparticles

A decisive feature that makes nanoparticles technically interesting is their surface-to-volume ratio. This ratio increases with decreasing particle diameter. A nanoparticle is composed of a few to several thousand atoms. This means that a significant portion of the atoms are located on the particle surface. At a particle diameter of 10 nm, 20 % of the approximately 30 000 atoms[4] of the entire particle are positioned on its surface; at a particle diameter of 5 nm, the value increases to 40 % of the approximately 4000 atoms, and at 1 nm diameter, almost all of the about 30 atoms are on the surface. The surface atoms, as opposed to those inside the material, have fewer direct neighbors and therefore contain so-called unsaturated bonds. These are responsible for the higher reactivity of the particle surface.

Increased reactivity is the basis for numerous applications. One idea, for example, is that precisely controlling particle diameter will yield a new generation of catalysts with high selectivity; such catalysts will accelerate only those chemical processes that produce the target product from the raw materials. This high reactivity would also reduce the melting point, so that using nanoparticular raw materials[5] would reduce the "firing" temperature in the case of ceramics. More importantly, the composites (solids composed of various materials) would shrink less during the hardening process, a particularly important feature in dental prosthetics for example.

Even though the surface of an individual particle naturally decreases along with its diameter, the specific surface area of a powder increases as the size of its component particles drops – under the precondition that the same amount by weight is being considered. This explains why nanostructured materials are interesting for filtration and catalysis. Nanoporous materials exhibit a large specific surface area on which the filtered substances can be deposited. They also have a high reactivity, which promotes adsorption or their catalytic effect.

Varying nanoparticle size not only modifies reactivity but can also alter the optical characteristics such as transparency, absorption, luminescence and scattering. Although particles measuring only a few nanometers in diameter lie far below the wavelength range of visible light (380 to 780 nm), they can absorb light of specific wavelengths (Figure 1).

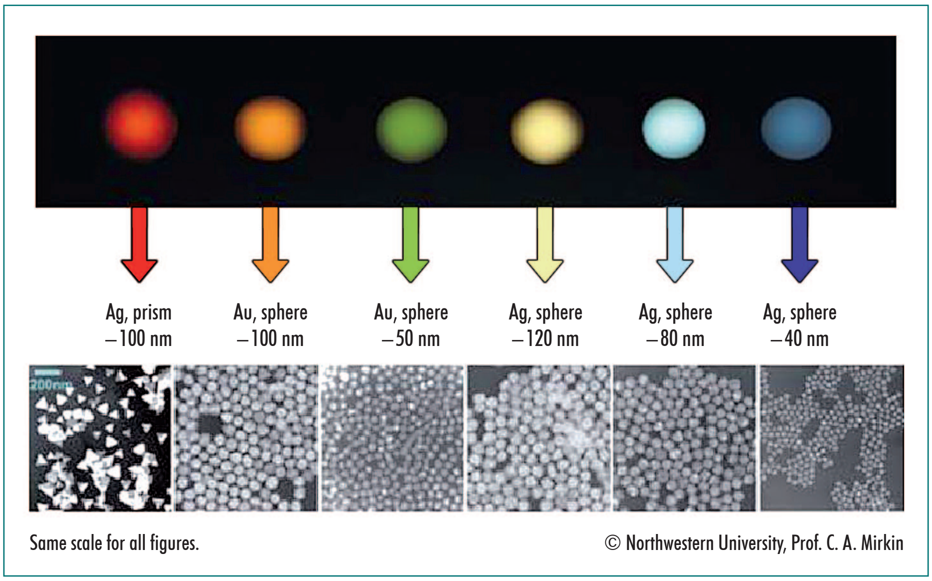

Figure 2: Rayleigh scattering images and electron microscopic images of nanocrystals of various shape (spherical, prism-shaped), size (40-120 nm) and composition (gold-Au, silver-Ag). Rayleigh scattering refers to the scattering of electromagnetic waves on spherical particles whose diameter is smaller than the wavelength of the scattered waves.[6]

These effects can only be understood on a quantum mechanics level. In the case of quantum dots, which are composed of so-called semiconductor materials, particle size can be used to adjust the wavelength of the fluorescence, for example. These optical features make nanoparticles especially interesting for applications in optoelectronics, cosmetics and medical diagnostics.

An important feature for the magnetic behavior of particles with a diameter in the nanometer range is that they magnetized permanent magnets in one direction. Nanoparticles therefore provide an opportunity to increase the storage capacity of magnetic data storage devices, which is determined by the number of magnetizable elements. Finally, the magnetic characteristics of nanoparticles are relatively insensitive to temperature fluctuations.

Forms of nanoparticles

Nanoparticles can have different chemical compositions. They can be composed of metals, semiconductor materials, compounds such a metal oxides (inorganic nanoparticles) or of carbon or carbon-containing compounds such as polymers (organic nanoparticles).

In the research and commercial sectors, synthetic nanoparticles are often grouped into the following categories based on their chemical and physical characteristics: carbonic, metal oxides, semiconductors or metals (Table 1).

Carbon-based nanoparticles can be produced in the form of spherical nanoparticles (fullerenes) or cylindrical nanotubes. Carbon Black is used to describe industrial soot, which is purposefully synthesized under controlled conditions and is physically and

Table 1: Types of artificially produced nanoparticles based on carbon and metals and their modifications

Carbonic	Metal oxides	Semiconductors	Metals
fullerenes nanotubes Carbon Black	silicon dioxide (SiO_2) titanium dioxide (TiO_2) aluminum oxide (Al_2O_3) iron oxide (Fe_2O_3) or (Fe_3O_4), zinc oxide (ZnO)	cadmium-tellurite (CdTe) silicon (Si) indium phosphide (InP or InGaP)	gold (Au) silver (Ag) iron (Fe) cobalt (Co)

chemically precisely defined. This contrasts with chimney and diesel soot, which are not clearly defined combustion byproducts of coal or hydrocarbons. The degree of the organic and inorganic contamination is therefore very high in these types of soot, in contrast to Carbon Black, in which the carbon content typically exceeds 96 %.

Nanoscale metal oxides such as titanium dioxide (TiO_2) and zinc oxide (ZnO) are already used on a larger scale in consumer goods such as cosmetics, paints and varnish. Zircon-(ZrO_2) and aluminum oxide-(Al_2O_3) nanopowders are used as components in technical ceramics to improve both hardness and breaking strength. Metallic nanoparticles primarily find use in catalysis, while semiconductor nanocrystals are used in laboratory diagnostics and medical diagnostics based on their optical features.

Nanoparticles can be single particles, aggregates or agglomerates. Aggregates are loose, reversible particle attachments formed by strong attractive interactions of the individual particles. In solutions, such aggregates can be dissolved into individual nanoparticles. Agglomerates, in contrast, are irreversible accumulations of particle elements; they cannot be dispersed into individual particles. Certain production methods and modifications of the particle surface can be employed to control aggregate formation, which is typically desirable for processing the particles. Larger composites of nanoparticles often have characteristics that differ from those of solitary particles.

Depending on composition and application, nanoparticles are applied with an untreated or modified surface. Untreated nanoparticles often arrange themselves next to one another and form aggregates or agglomerates (for example Carbon Black). Accordingly, their shape can be very heterogeneous and take on various forms, which strongly influence their characteristics. Depending on the production method and manufacturing conditions, nanoparticulate materials exhibit different forms and structures: spheres, needles or tubes, pellets and fibers. Isolated, individual nanoparticles can be produced by specifically modifying their surfaces. This can for example involve a chemical treatment such as a spacer (ligand) between the particles, which prevents their clustering.

Untreated metallic nanoparticles are usually chemically highly reactive and quickly oxidize in air. In many applications this calls for appropriate protective strategies to prevent the untreated nanoparticles from decomposing during or after synthesis. These stabilizing methods involve coating the nanoparticles, typically with organic compounds such as surfactants, carbon and polymers. One form of stabilization uses an inorganic shell consisting of silicate. In many cases these protective shells do more than merely stabilize the nanoparticles: depending on the field of application, they can be used for a further functionalization, for example with other nanoparticles or with ligands. The surface chemistry of the nanoparticles can determine their stabilization, dispersal and functionalization.

Nanopartcles find use, beyond in the loose form, also in nanocomposites. Nanocomposites refer to composite materials in which at least one component is present in the form of nanoparticles, nanopellets or nanotubes. The second component, the matrix, often consists of polymers. Composites are the best materials to combine the often unique features of nanoparticles with those of the composite matrix.

Application of nanoparticles

The fields of application for nanoparticles are wide ranging. They play a major role in materials development. The great expectations we place on today's modern nanoparticle-containing materials is based on the hope that the different material properties such as conductivity, weight, stability, flexibility, heat resistance etc. can be specified independently from one another.

Numerous nanotechnology products have been on the market for some time now. In the chemical sector this includes Carbon Black (soot particles), for example in printing black; in the automobile sector this includes scratch-resistant paints, filler in tires and anti-reflective layers. In the Life Sciences, nanoparticles are used for biochips as well as for so-called markers. They are also used in sunscreens and cosmetic products. In medical diagnostics, nanoparticles are increasingly being used as contrast media; they are also a tool in cancer therapy.

Recently, nanoparticle applications have been introduced on the market in paints, polymer-nanocompsoites and nanopigments.

Concepts and prototypes exist for regenerative medicine (for example in tissue cultures), highly efficient hydrogen storage systems, self-healing materials, and coatings that switch their color using sensor technology. Moreover, current efforts are being devoted to developing products to treat diseases and to affect a controlled release of medications.

Notes and References

1 Dispersions are mixtures consisting of at least two materials that are insoluble or only partly soluble in each other and do not form chemical bonds. The medium (the matrix) of a dispersion can be liquid, gas or solid.

2 SCENIHR (Scientific Committee on Emerging and Newly Identified Health Risks), 2008. The existing and proposed definitions relating to products of nanotechnologies, Brussels: European Commission.

3 www.chemie.uni-hamburg.de/pc/weller.

4 Nanopartikel-Materialien der Zukunft, Albert Rössler, Georgios Skillas, Sotiris E. Pratsinis; Chemie in unserer Zeit, 2001, 1, 32-41.

5 Whether energy can be saved overall, however, depends considerably on the energy consumption in producing the nanoparticular materials.

6 chemgroups.northwestern.edu/mirkingroup.

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Die Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR) der europäischen Commission hat seine abschließende „opinion“ über die „Wissenschaftliche Basis für die Definition des Ausdruckes ' Nanomaterial“ veröffentlicht.

Die Hauptmitteilungen der wissenschaftlichen „Stellungnahme“ sind, dass die Definition eines Nanomaterials auf seiner Größe basieren sollte und nicht auf seine Eigenschaften. Weiters, dass es keine wissenschaftliche Rechtfertigung für die Bevorzugung einer spezifischen Größenbegrenzung von 1 bis 1000 Nanometer gibt.[1]

[1] http://ec.europa.eu/health/scientific_committees/emerging/docs/scenihr_o_032.pdf.

Addendum for Dossier No. 002, Version: February 2011

The European Commission's Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR) has published its final opinion on the 'Scientific Basis for the definition of the Term 'nanomaterial''.

The key messages of the Scientific Opinion are that the definition of a nanomaterial should be based on its size and not on its properties. Further on that there is no scientific justification for preferring any specific size limit to any other in the range from 1 to 1000 nanometers.[1]

[1] http://ec.europa.eu/health/scientific_committees/emerging/docs/scenihr_o_032.pdf.