

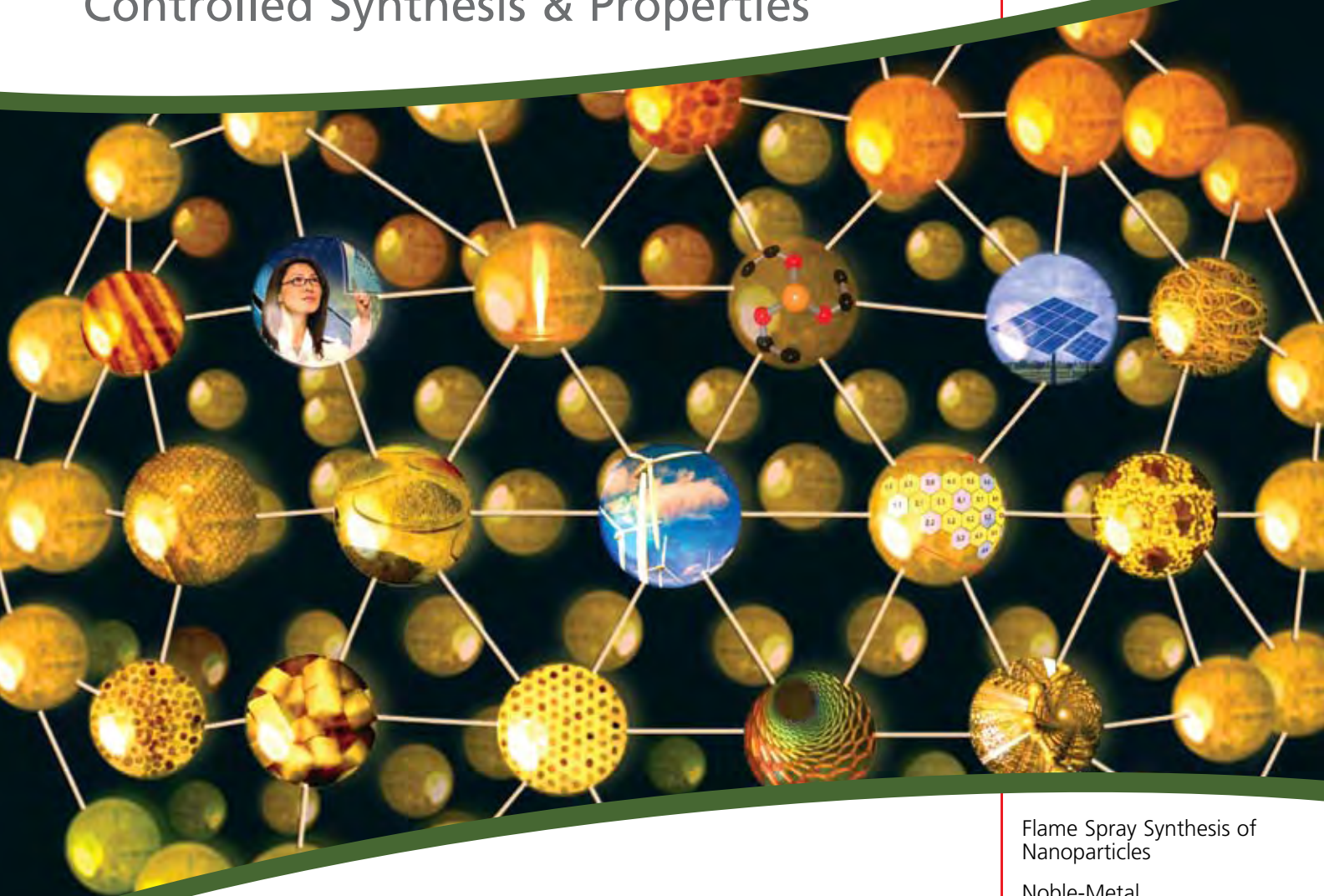
Material Matters™

Vol. 4, No. 1

ALDRICH
Chemistry

Nanomaterials

Controlled Synthesis & Properties



Morphing Materials into Meaning

Flame Spray Synthesis of Nanoparticles

Noble-Metal Nanostructures

Monodisperse Magnetic Nanoparticles

Nanostructured Mesoporous Carbon

Single-Walled Carbon Nanotubes

SIGMA-ALDRICH

Introduction

Welcome to the first issue of **Material Matters™** for 2009, which discusses a selection of synthetic methods used to create a variety of nanomaterials, specifically nanoparticles and nanotubes.

A nanomaterial can be broadly defined as any material in which one of its dimensions is less than 100nm. Over the last decade, nanomaterials, including their synthetic methods, have rapidly become one of the most active areas in scientific research, mainly on account of their unique properties in comparison to the traditional micron-sized material. Examples of material properties that change upon entering the nano-regime include conductivity (silicon becomes conductive), transparency (copper becomes transparent), reactivity (aluminium becomes combustible), physical state changes (gold becomes a liquid), and even attainments of chemical behaviors (platinum becomes catalytic).

By studying interactions at the nanoscale, scientists are uncovering fascinating events that aid in the understanding of properties that exist on a quantum level. This knowledge can then be harnessed to develop materials that have an immediate and heightened impact, which affect fields such as alternative energy, electronics and even integrated medicine. The availability of size as a new parameter that permits the tuning of physical and chemical properties has tremendously extended the potential capabilities within materials science.

The in-depth investigation into the properties of these materials is heavily reliant upon the rapid development of synthetic methods that can be used to generate novel nanostructures with reproducible, well-defined features. This issue aims to provide an insight into such controlled synthetic methods and the intriguing materials they can produce.

Researchers in the Department of Chemistry and Applied Biosciences at ETH Zurich describe flame spray synthesis, which is able to produce nanoparticles with a variety of coatings simply by modifying the process parameters. The next article discusses a number of *noble-metal* nanostructures with controlled morphologies that were made using a modified polyol process developed by researchers at Washington University in St. Louis. The synthesis of monodisperse magnetic nanoparticles by researchers at Brown University, is the subject of the next topic, which exemplifies the structures of the nanoparticles made also using a solution-based method. Researchers at the University of York in the UK demonstrate a three-stage heating preparation of mesoporous carbon materials that contain an array of pore diameters. Finally, SouthWest NanoTechnologies, Inc., elaborates on their CoMoCAT® catalytic CVD process, which provide, not only single-walled carbon nanotubes with very narrow diameter distributions but also the ability to scale up production of the highly sought after SWCNTs.

Continuing in the theme of **Material Matters™**, we begin the issue with a section entitled, "Your Materials Matter." Here, we highlight a material that has been brought to our attention by you, the scientific community. Each article in this issue is accompanied by the corresponding Sigma-Aldrich products that are nanomaterials or materials used in the described synthetic processes. The facing page lists the material categories that you will find in this issue. For a comprehensive library of products and all associated information, please visit Aldrich Materials Science at sigma-aldrich.com/matsci. We invite you to direct your comments and questions regarding **Material Matters™** or any materials of interest to matsci@sial.com.



Kaushik Patel, Ph.D.
Materials Science Initiative
Sigma-Aldrich Corporation

Material Matters™

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About Our Cover

Nanomaterials are a new class of materials that have been making a silent and, at times, a "not-so" silent revolution in the last decade. A central challenge of nanoscale science is the need for fundamental understanding of how nanomaterials grow and for control of the growth environment, in order to synthesize materials with new or greatly enhanced properties at attractive rates. The cover depicts an artistic rendition of the building block concept in going from synthesis, structure, morphology, to downstream applications—A precursor for magnetic iron oxide nanoparticles, iron(II) ethoxide (as discussed in the article on page 14), a flame to symbolize combustion based processes (presented in the article on page 2), different kinds of nanostructured morphologies and finally to their practical use, be it in solar panels, touch sensitive displays or light-weight, extreme strength nanocomposite-based wind turbines.

"Your Materials Matter."



Joe Porwoll

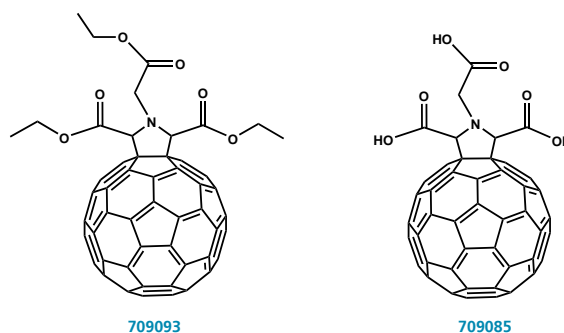
Joe Porwoll, President
Aldrich Chemical Co., Inc.

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Dr. Michael Diener of TDA Research Inc., kindly suggested that we offer the pyrrolidine-derivatized C₆₀ molecule with a tris acid functionality (**Aldrich Prod. No. 709085**). This water-soluble material serves as a superoxide quencher,¹ on account of the redox properties of the C₆₀ moiety. It shows almost 100% improvement in the O₂⁻ quenching activity, which is measured by the decreased levels in reduction of cytochrome c by O₂⁻, (IC₅₀ = 103.4 μM) over analogous water-soluble C₆₀ molecules (IC₅₀ ~ 200 μM).² Fullerene-based compounds therefore have the potential to be patent antioxidants to protect against oxidative stress.³ These materials are expected to play a major part in the fight against Alzheimer's, Parkinson's, AIDS and many other diseases in which oxidation mechanisms play major roles.

References:

(1) Okuda, K.; Hirota, T.; Hirobe, M.; Nagano, T.; Mochizuki, M.; Mashino, T. *Fullerene. Sci. Technol.* **2000**, *8*, 89-104. (2) Sun, T.; Xu, Z. *Bioorg. Med. Chem. Lett.* **2006**, *16*, 3731-3734. (3) Lin, A. M. Y.; Chyi, B. Y.; Wang, S. D.; Yu, H.-H.; Kanakamma, P. P.; Lu, T.-Y.; Chou, C. K.; Ho, L. T. *J. Neurochem.* **1999**, *72*, 1634-40.



Name	Cat. No.
C ₆₀ Pyrrolidine tris-acid	709085-100MG
C ₆₀ Pyrrolidine tris-acid ethyl ester	709093-250MG

Nanomaterials and Nanomaterials Synthesis Products Featured in this Issue

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Chemistry in Flames: From Oxide to Salt and Metal Nanoparticles



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How to Make Nanoparticles in Flames

Small-scale materials with particle diameters in the nanometer range have already been used for a long time. The Chinese used carbon black, derived from a combustion process for painting applications a long time before modern technology allowed its industrial production. Besides changing optical properties as described in the above example, nanoparticles can alter physical, optical, electronic or chemical properties of a material by decreasing the particle size. Gold, for instance, is well known for its chemical inertness. Haruta and coworkers showed in the late 80's that even gold becomes a highly active catalyst for CO and H₂ oxidation, if the gold particles are in the nanometer range (**Aldrich Prod. No 636347**).¹ In the past decades there have been thousands of scientific publications covering this area. Due to their changed properties and enhanced reactivity the number of publications discussing nanoparticles has grown exponentially.

There are manifold ways to increase surface area by decreasing the particle size of materials. Generally speaking, there are two approaches toward the synthesis of nanosized materials: *Top-down* approaches such as milling have been known and applied within living memory. Modern milling techniques like ball milling are generally straightforward and can yield nanoparticulate materials. *Bottom-up* techniques include plasma, laser, liquid phase or flame spray synthesis. These "self-assembly" preparation methods generally result in well controlled nanoparticles which are built from smaller building blocks allowing the synthesis of more complex materials or the fabrication of nanoparticles with a very narrow size distribution.

In spite of the often cited novelty of nanomaterials, three large scale commodities have been around for half a century. Large-scale production of these materials started in the early 20th century with the introduction of nanoparticulate carbon black (tire soot) into car tires and rubber. For the large-scale production of silica and pigmentary titania (white pigment) flame technology was further adapted. Both processes are based on the oxidation of chlorides (SiCl₄/TiCl₄) (**Aldrich Prod. Nos. 289388, 254312**) in high temperature flames.² Today, the annual production volumes of flame derived nanoparticles has reached several megatons per year. Major chemical companies have contributed significantly to an efficient process design. Unfortunately, the technology of metal chloride oxidation is only suitable for a very limited set of elements (silicon, aluminum, titanium, vanadium and zirconium). For all other elements—including most mixed element systems—other solutions had to be found. This handicap was overcome initially by Zachariah and Huzarewicz³ as well as Matsoukas and Friedlander⁴ by the use of aqueous precursors. Further optimizations lead to the use of organic precursors like metal alkoxides,⁵ acetates,⁶ triethanolamines,⁷

and metal carboxylates.⁸ The latter is most promising as nearly all elements are available as low-cost naphthenate - metal salts. Further, these metal-organic salts are quite stable in air, tolerate humidity and are freely miscible amongst each other. This allows the fabrication of mixed-oxide materials that have excellent chemical homogeneity⁹ and high batch-to-batch reproducibility (see **Figure 1**).



Figure 1. Using flame spray synthesis, the compositional variety of inorganic nanoparticles is nearly endless. Different oxidic, salt and metallic nanoparticles with similar particle size distribution are depicted (courtesy of Nanograde LLC.).

Laboratory set-ups of flame spray reactors usually operate in the region of 10-100 g/hr (see **Figure 2**) and small pilot plants were shown to be capable of production rates of 1 kg/hr.¹⁰ Today, by the use of liquid organic precursors, the aerosol community has gained access to most oxide materials, and these have been explored for applications in heterogeneous catalysis,^{9,11,12} sensors,¹³ lasing materials,⁷ computer chip manufacturing and numerous other industrial sectors.

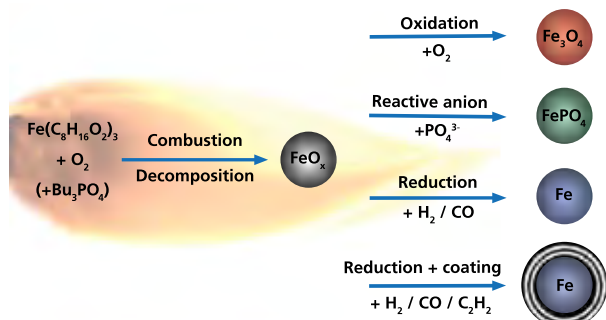


Figure 2. Depending on the metal loading the flames during the production of inorganic nanoparticles show different colors. Illustrated in this example is the combustion of metalorganic precursors containing copper, strontium, cerium and bismuth (from left to right).

Expansion to Salts and Metals: A Quantum Leap

By studying the chemical problems of the synthesis of complex inorganic materials in flame reactors, the range of accessible products can be successfully extended from oxides to most inorganic salts¹⁴ (see **Scheme 1**). Loher et al. demonstrated the use of a flame as a chemical reactor and that chemical reactions, usually performed in solid-state, can be adapted for the flame synthesis of nanoparticles. As a result of these advances, a number

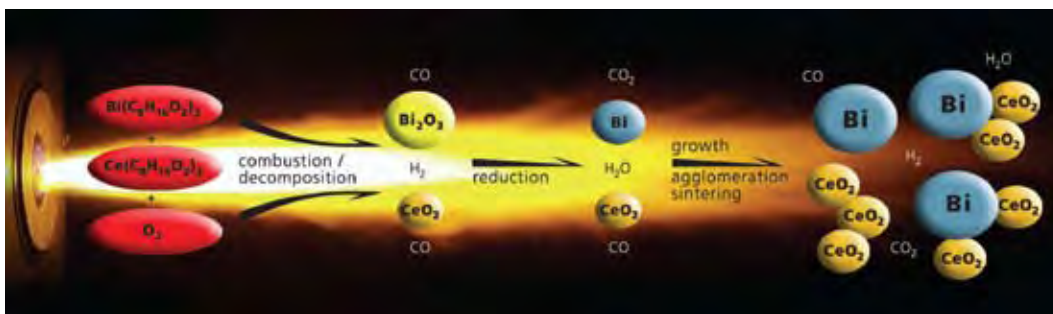
of everyday materials have become available in the form of nanoparticles, examples include: nano-gypsum,¹⁵ nano-salt¹⁶ and nano-tricalcium phosphate (Aldrich Prod. No. 693898).^{14,17,18} The latter has been incorporated in a number of biomedical materials and first *in vivo* tests demonstrated their successful application as biomaterials.¹⁸ A recent, preclinical study has demonstrated the advantageous re-mineralization properties of nanobioactive glass for damaged dentin (tooth repair).¹⁹



Scheme 1. Schematic illustration of the flexibility of flame spray synthesis is illustrated in this sketch. Depending on the process parameters, it is possible to produce oxide (oxidizing atmosphere), salt (addition of a reactive anion to the precursor solution), metal (oxygen starving conditions) or carbon-coated metal nanoparticles (introduction of acetylene).

Very recently, the concept of chemical aerosol engineering in flames has been extended to the synthesis of metal nanoparticles. The requirement of oxygen for combustion naturally led to production setups under oxidizing atmospheres. This circumstance, of course, impedes the synthesis of reduced materials, such as metal nanoparticles, as these would immediately react with oxygen, water or CO₂ in the flame atmosphere, forming metal oxides. To circumvent this instant oxidation of the metal nanoparticles, Grass et al. performed flame spray synthesis of a metal containing organic precursor in an oxygen-free, reducing atmosphere (See Scheme 2).^{20,21} This resulted in complete combustion of all oxygen present and the formation of metallic nanoparticles in the flame atmosphere.

Recently, a further synthetic step was taken to achieve controlled deposition of carbon on the metal surface of nanoparticles.²² In principle, the degree and rate of carbon deposition depends on temperature, gas composition and the metal surface. Controlled temperature profiles in the exit stream of flame reactors and additional feeding of hydrogen, carbon mono- or dioxide, methane or even acetylene provides an option to coat metals in situ with a carbon layer. Such core/shell metal/carbon materials, for example, can yield unexpected bulk properties. The suitability of 1 nm carbon-coated copper particles for temperature or pressure sensing was recently demonstrated. The same material dispersed in water has been proven for use in highly sensitive humidity sensor coatings.²³



Scheme 2. Reducing flame synthesis for the manufacture of metal/ceramic nanocomposite particles consisting of bismuth/ceria. The atmosphere of the flame (CO, H₂, H₂O, CO₂, N₂) is responsible for the reduction of bismuth oxide to metallic bismuth, but is not capable of reducing cerium oxide to metallic cerium (difference in reduction potential of bismuth and cerium).

Application Example: Self-Sterilizing Polymer Surfaces

One descriptive example of the flame spray technology is the development of highly active self-sterilizing polymer films. With this technology, it is possible to homogeneously deposit 1-2 nm scale silver nanoparticles on the surface of tricalcium phosphate carrier nanoparticles.²⁴ These metal-salt composite nanoparticles can be incorporated into a plastic film (see Figure 3). Such a film containing the composite nanoparticles was shown to be up to 1000 times more efficient as a killer of bacteria such as *Escherichia coli*, when compared to conventional silver preparations. One decisive factor appears to be that bacteria use the calcium carrier for their metabolism. The calcium phosphate particles, 20 to 50 nanometer in size, are absorbed by the micro-organisms and the subsequent dissolution of the calcium phosphate releases thousands of silver nanoparticles which are lethal to many bacteria. The synthesis of such complex composite materials without substantial changes in process design signifies the power of flame spray synthesis.



Figure 3. Composite nanoparticles with 1-2 nm silver nanoparticles homogeneously distributed on calcium phosphate carrier nanoparticles. Due to the small size and distribution on the surface of salt nanoparticles, these nanocomposites are up to 1000 times more efficient bacteria killers than conventional silver preparations.

In summary, flame spray synthesis allows the scalable fabrication of many mixed oxide, salt, metal, carbon-coated metal, silica-coated metal oxide or even metal-ceramic composite nanoparticles.²⁵ The synthesis is based on metal loaded liquid precursors and achieves accurate control over the composition and size of the nanoparticles. High batch-to-batch reproducibility, a highly homogeneous product and a wide product variety are only a few of the useful attributes of flame spray synthesis. With this technology, there are manifold opportunities to take the developed technologies to industrial products.

References:

(1) Haruta, M.; Kobayashi, T.; Sano, H.; Yamada, N. *Chem. Lett.*, **1987**, 405. (2) Osterwalder, N.; Capello, C.; Hungerbühler, K.; Stark, W.J. *J. Nanopart. Res.*, **2006**, 8, 1. (3) Zachariah, M.R.; Huzarewicz, S. *Combust. Flame*, **1991**, 87, 100. (4) Matsoukas, T.; Friedlander, S.K. *J. Colloid Interface Sci.*, **1991**, 146, 495. (5) Mueller, R.; Jossen, R.; Kammler, H.K.; Pratsinis, S.E. *Aiche J.*, **2004**, 50, 3085. (6) Tani, T.; Watanabe, N.; Takatori, K. *J. Nanopart. Res.*,

2003, 5, 39. (7) Marchal, J.; John, T.; Baranwal, R.; Hinklin, T.; Laine, R.M. *Chem. Mat.*, **2004**, 16, 822. (8) Stark, W.J.; Wegner, K.; Pratsinis, S.E.; Baiker, A. *J. Catal.*, **2001**, 197, 182. (9) Stark, W.J.; Grunwaldt, J.D.; Maciejewski, M.; Pratsinis, S.E.; Baiker, A. *Chem. Mat.*, **2005**, 17, 3352. (10) Stark, W.J.; Kammler, H.K.; Strobel, R.; Gunther, D.; Baiker, A.; Pratsinis, S.E. *Ind. Eng. Chem. Res.*, **2002**, 41, 4921. (11) Stark, W.J.; Pratsinis, S.E.; Baiker, A. *J. Catal.*, **2001**, 203, 516. (12) Strobel, R.; Stark, W.J.; Madler, L.; Pratsinis, S.E.; Baiker, A. *J. Catal.*, **2003**, 213, 296. (13) Athanassiou, E.K.; Mensing, C.; Stark, W.J. *Sens. Actuator A-Phys.*, **2007**, 138, 120. (14) Loher, S.; Stark, W.J.; Maciejewski, M.; Baiker, A.; Pratsinis, S.E.; Reichardt, D.; Maspero, F.; Krumeich, F.; Gunther, D. *Chem. Mat.*, **2005**, 17, 36. (15) Osterwalder, N.; Loher, S.; Grass, R.N.; Brunner, T.J.; Limbach, L.K.; Halim, S.C.; Stark, W.J. *J. Nanopart. Res.*, **2007**, 9, 275. (16) Grass, R.N.; Stark, W.J. *Chem. Commun.*, **2005**, 1767. (17) Brunner, T.J.; Grass, R.N.; Bohner, M.; Stark, W.J. *J. Mater. Chem.*, **2007**, 17, 4072. (18) Schneider, O.D.; Loher, S.; Brunner, T.J.; Uebersax, L.; Simonet, M.; Grass, R.N.; Merkle, H.P.; Stark, W.J. *J. Biomed. Mater. Res. Part B*, **2008**, 84B, 350 (19) Vollenweider, M.; Brunner, T.J.; Knecht, S.; Grass, R.N.; Zehnder, M.; Imfeld, T.; Stark, W.J. *Acta Biomater.*, **2007**, 3, 936. (20) Athanassiou, E.K.; Grass, R.N.; Stark, W.J. *Nanotechnology*, **2006**, 17, 1668. (21) Grass, R.N.; Stark, W.J. *J. Nanopart. Res.*, **2006**, 8, 729. (22) Athanassiou, E.K.; Grass, R.N.; Osterwalder, N.; Stark, W.J. *Chem. Mat.*, **2007**, 19, 4847. (23) Luechinger, N.A.; Loher, S.; Athanassiou, E.K.; Grass, R.N.; Stark, W.J. *Langmuir*, **2007**, 23, 3473. (24) Loher, S.; Schneider, O.D.; Maiefisch, T.; Bokorny, S.; Stark, W.J. *Small*, **2008**, 4, 824. (25) Teleki, A.; Akhtar, M.K.; Pratsinis, S.E. *J. Mater. Chem.*, **2008**, 18, 3547.

Nanoparticles—Prepared by Nanospray Combustion Process

For noble-metal nanoparticles, see page 11. For magnetic nanoparticles, see page 17.

Metallic Element Z: Symbol	Name	Composition	Form	Particle Size (nm)	Cat. No.
3: Li	Lithium titanate, spinel, nanopowder, >99%	Li ₄ Ti ₅ O ₁₂	-	<100 (TEM) <100 (BET)	702277-25G
12: Mg	Magnesium oxide	MgO	nanopowder	<50 (BET) <25 (XRD)	549649-5G 549649-25G
12: Mg	Magnesium aluminate, spinel	MgO·Al ₂ O ₃	nanopowder	<50 (BET)	677396-5G
14: Si	Silicon dioxide, alumina doped, 99.99% trace metals basis	(SiO ₂) _x (Al ₂ O ₃) _y , aluminum 7.5 wt. %	nanoparticles, 20 wt. % in H ₂ O	<50	701491-25ML 701491-100ML
20: Ca	Calcium oxide, 98%	CaO	nanopowder	<160 (BET)	634182-25G 634182-100G
20: Ca	Hydroxyapatite, 97+%	[Ca ₅ (OH)(PO ₄) ₃] _x	solid nanopowder	<200 (BET)	677418-5G 677418-10G
20: Ca	Hydroxyapatite	[Ca ₅ (OH)(PO ₄) ₃] _x	solid nanopowder	<200 (BET)	693863-5G
20: Ca	Hydroxyapatite	[Ca ₅ (OH)(PO ₄) ₃] _x	nanoparticles, 10 wt. % in H ₂ O	<200 (TEM)	702153-25ML
20: Ca	Calcium phosphate, amorphous	Ca ₂ O ₇ P ₂ · H ₂ O, Ca/P ~ 1/1	nanopowder	<150 (BET)	693871-5G
20: Ca	Tricalcium phosphate hydrate	Ca ₃ (PO ₄) ₂ · xH ₂ O	nanopowder	<100 (TEM) <200 (BET)	693898-5G
22: Ti	Titanium silicon oxide, 99.8% trace metals basis	(SiO ₂)(TiO ₂)	nanopowder	<50 (BET)	641731-10G 641731-50G
22: Ti	Titanium(IV) oxide, 97+%	TiO ₂	nanopowder	<100 (BET)	677469-5G
26: Fe	Iron-nickel alloy, ≥97%	Fe:Ni 55±5%:45±5%	nanopowder	<100 (BET)	677426-5G
28: Ni	Nickel cobalt oxide, 99% trace metals basis	NiO CoO	nanopowder	<150 (BET)	634360-25G 634360-100G
28: Ni	Nickel zinc iron oxide, 99+% trace metals basis	NiZnFe ₂ O ₄	nanopowder	<100 (BET)	641669-10G 641669-50G
29: Cu	Copper zinc iron oxide, 98.5% trace metals basis	CuZnFe ₄ O ₄	nanopowder	<100 (BET)	641650-10G 641650-50G
29: Cu	Copper iron oxide, 98.5% trace metals basis	CuFe ₂ O ₄	nanopowder	<100 (BET)	641723-10G 641723-50G
30: Zn	Zinc iron oxide, >99% trace metals basis	ZnFe ₂ O ₄	nanopowder	<100 (BET)	633844-10G 633844-50G
30: Zn	Zinc oxide, >97%	ZnO	nanopowder	<50 (BET)	677450-5G
39: Y	Yttrium iron oxide, 99.9% trace metals basis	Y ₃ Fe ₅ O ₁₂	nanopowder	<100 (BET) <50 (XRD)	634417-10G



Metallic Element Z: Symbol	Name	Composition	Form	Particle Size (nm)	Cat. No.
40: Zr	Zirconium(IV) oxide-yttria stabilized	ZrO ₂	nanopowder	<100 (BET)	544779-5G 544779-25G
40: Zr	Zirconium(IV) silicate, 98.5% trace metals basis	ZrSiO ₄	nanopowder	<100 (BET) <50 (XRD)	634395-25G 634395-100G
40: Zr	Zirconium(IV) oxide, dispersion	ZrO ₂	nanoparticles, 5 wt. % in H ₂ O	<100 (BET)	643122-100ML 643122-500ML
40: Zr	Zirconium(IV) oxide, dispersion	ZrO ₂	nanoparticles, 10 wt. % in H ₂ O	<100 (BET)	643025-100ML 643025-500ML
47: Ag	Silver-copper alloy	CuAg ₂₅ , Ag ~ 97.5% Cu ~ 2.5%	nanopowder	<100	576824-5G
47: Ag	Silver-tin alloy, 3.5% Ag basis ≥97%	Ag ₅ Sn ₂₅	nanopowder	<150	677434-5G
50: Sn	Tin(IV) oxide	SnO ₂	nanopowder	<100 (BET)	549657-5G 549657-25G
56: Ba	Barium ferrite, 99.5% trace metals basis	BaFe ₁₂ O ₁₉	nanopowder	<100 (BET)	637602-25G
58: Ce	Cerium(IV)-zirconium(IV) oxide, 99.0% trace metals basis	(CeO ₂)-(ZrO ₂)	nanopowder	<50 (BET)	634174-25G 634174-100G
58: Ce	Aluminum cerium oxide, 99% trace metals basis	AlCeO ₃	nanopowder	<50 (BET)	637866-10G 637866-50G
58: Ce	Cerium(IV) oxide, dispersion	CeO ₂	nanoparticles, 10 wt. % in H ₂ O	<25	643009-100ML 643009-250ML
62: Sm	Samarium strontium cobalt oxide, 99.9%	Sm _{0.5} Sr _{0.5} Co ₂ O ₄	nanopowder	<50 (BET)	677442-5G

Selected Nanoparticles

For a complete list of nanocomposites please visit sigma-aldrich.com/nanocomposites

Metallic Element Z: Symbol	Name	Composition	Form	Particle Size (nm)	Cat. No.
6: C	Carbon, ≥99% trace metals basis	C	nanopowder	<50 (BET)	633100-25G 633100-100G
6: C	Diamond, ≥97% trace metals basis	C	nanopowder	<10 (BET)	636428-1G 636428-5G
6: C	Diamond, ≥95% trace metals basis	C	nanopowder	<10 (BET)	636444-1G 636444-5G
22: Ti	Titanium(IV) oxide, mixture of rutile and anatase, 99.9% trace metals basis	TiO ₂	nanoparticles paste, 53-57 wt. % in diethylene glycol monobutyl ether/ethylene glycol	<250 (DLS) ~21 (primary particle size of starting nanopowder)	700355-25G
22: Ti	Titanium(IV) oxide, mixture of rutile and anatase, 99.9% trace metals basis	TiO ₂	nanoparticles, 33-37 wt. % in H ₂ O	~21 (primary particle size of starting nanopowder) <150 (DLS)	700347-25G 700347-100G
22: Ti	Titanium(IV) oxide, mixture of rutile and anatase, 99.9% trace metals basis	TiO ₂	nanoparticles, 45-47 wt. % in xylene	~15 (primary particle size of starting nanopowder) <100 (DLS)	700339-100G
13: Al	Aluminum oxide, dispersion	Al ₂ O ₃	nanoparticles, 20 wt. % in isopropanol	<50 (DLS)	702129-100G 702129-500G
49: In	Indium tin oxide, dispersion	In ₂ O ₃ 90% SnO ₂ 10%	30 wt. % in isopropanol	<100 (DLS)	700460-25G 700460-100G
39: Y	Yttrium(III) oxide, dispersion, ≥99.9% trace metals basis	Y ₂ O ₃	nanoparticles, 10 wt. % in isopropanol	<100 (DLS)	702048-100G
58: Ce	Cerium(IV) oxide, >99.95% trace metals basis	CeO ₂	nanopowder	<50 (BET)	700290-25G 700290-100G

General Metal Precursors

For noble metal precursors, see page 11. For magnetic metal precursors, see page 17.

Metallic Element Z: Symbol	Name	Structure	Cat. No.
12: Mg	Magnesium acetylacetonate dihydrate, 98%		129577-25G
12: Mg	Magnesium acetate tetrahydrate, 99.999% trace metals basis		229768-10G 229768-100G
13: Al	Aluminum-tri-sec-butoxide, 97%		201073-5G 201073-100G 201073-500G
13: Al	Aluminum ethoxide, 97%		235857-5G 235857-25G 235857-100G
13: Al	Aluminum tert-butoxide		235849-10G 235849-50G
13: Al	Aluminum isopropoxide, 99.99+% trace metals basis		229407-10G 229407-50G 229407-250G
14: Si	Hexamethyldisiloxane, ≥98%		205389-5ML 205389-100ML 205389-500ML
14: Si	Tetraethyl orthosilicate, 99.999% trace metals basis		333859-25ML 333859-100ML
14: Si	Trimethoxymethylsilane, 98+%		679232-50G
14: Si	Triethoxy(octyl)silane, ≥98% 99.99% trace metals basis		679305-50G
20: Ca	Calcium 2-ethylhexanoate, 98%		362964-5G 362964-25G
22: Ti	Titanium(IV) methoxide, 99.99+% trace metals basis	Ti(OCH ₃) ₄	463582-25G
22: Ti	Titanium(IV) ethoxide		244759-50G 244759-250G
22: Ti	Titanium(IV) propoxide, 98%		253081-100G 253081-500G
22: Ti	Titanium(IV) isopropoxide, 99.999% trace metals basis		377996-5ML 377996-25ML 377996-100ML
22: Ti	Titanium(IV) butoxide, 97%		244112-5G 244112-100G 244112-500G 244112-2KG
22: Ti	Titanium(IV) tert-butoxide		462551-25ML 462551-50ML
22: Ti	Titanium(IV) oxide acetylacetonate		330833-10G 330833-50G
29: Cu	Copper(II) nitrate hydrate, 99.999% trace metals basis	Cu(NO ₃) ₂ · xH ₂ O	229636-5G 229636-25G 229636-100G
29: Cu	Copper(II) acetate, 99.999% trace metals basis		517453-5G 517453-25G



Metallurgical Element Z: Symbol	Name	Structure	Cat. No.
29: Cu	Copper(II) 2-ethylhexanoate		337323-5G 337323-25G
30: Zn	Zinc nitrate hydrate, 99.999% trace metals basis	$Zn(NO_3)_2 \cdot 6H_2O$	230006-25G 230006-250G
30: Zn	Zinc acetate dihydrate, 99.999% trace metals basis		379786-5G 379786-25G
30: Zn	Zinc acetylacetonate hydrate, 99.995% trace metals basis		480991-5G 480991-25G
38: Sr	Strontium acetylacetonate hydrate		704512-5G 704512-25G
39: Y	Yttrium(III) 2-ethylhexanoate, 99.9% trace metals basis		347086-10G 347086-50G
40: Zr	Zirconium(IV) ethoxide, 97%		339121-5G 339121-25G
40: Zr	Zirconium(IV) propoxide solution		333972-100ML 333972-500ML
40: Zr	Zirconium(IV) tert-butoxide, 99.999% trace metals basis		560030-5G 560030-25G
40: Zr	Zirconium(IV) acetylacetonate, 98%		338001-25G 338001-100G
50: Sn	Tributyltin methoxide, 97%		229245-25G 229245-100G
50: Sn	Tin(IV) tert-butoxide, 99.99+% trace metals basis		494135-5G 494135-25G
50: Sn	Tin(II) acetylacetonate, 99%		697478-5G
50: Sn	Tin(II) 2-ethylhexanoate, ~95%		S3252-100G S3252-250G S3252-500G S3252-1KG
56: Ba	Barium 2-ethylhexanoate, 98%		361704-5G
56: Ba	Barium acetate, 99.999% trace metals basis		255912-10G 255912-50G
72: Hf	Hafnium isopropoxide isopropanol adduct, 99.9% trace metals basis		697508-5G
75: Re	Rhenium decacarbonyl, 98%	$Re_2(CO)_{10}$	245003-500MG 245003-5G