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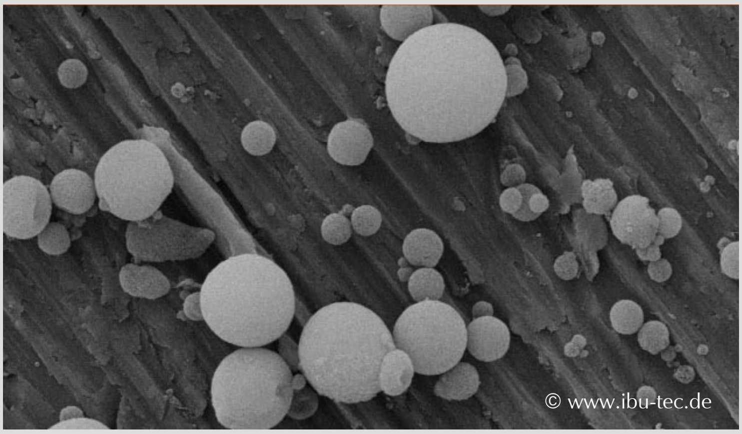
Synthetic Nanoparticles

Focus on environmental and health aspects



by

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Contents

Introduction

What are the aims of this report?

The report provides an overview of the two subject areas nanotechnology and synthetic nanoparticles that is intelligible to everybody. Its aim is to provide those participating in the "Dialogue on the evaluation of synthetic nanoparticles in work and environmental areas" event on 11 and 12 October 2005 with preparatory material. The report does not claim to be exhaustive.

What is nanotechnology?

To date there is no universally applicable definition of nanotechnology. In the following we will be referring to the definition of the Federal Ministry of Education and Research (BMBF): "The subject matter of nanotechnology is the production, study and application of functional structures whose dimensions are in the region of less than one hundred nanometres." (BMBF 2002)

Size …

A nanometre (nm) is defined as the millionth part of a millimetre or 10^{-9} m. In comparison, the diameter of a hair is approximately 50,000 nm; and that of a hydrogen atom approximately 0.1 nm.

…and new functionalities /properties …

Fundamental for nanotechnology is the fact that new functionalities or properties[1] result from the nanoscale character of the components. These new functionalities result for the most part from the altered ratio of surface atoms to volume atoms and from the quantum-mechanical behaviour.[2]

… and innovative manufacturing options.

Moreover, nanotechnology is distinguished by innovative manufacturing options it offers. These include, in particular, improved control possibilities in the manufacturing process and self-organisation of nanoscale materials. In self-

[1] New properties and/or functionalities can relate to: scratch resistance, colourfulness, transparency, conductivity, strength etc.

[2] Cf. also VDI TZ ZTC 2004; BMBF 2004

organisation, under certain ambient conditions, nanoscale materials join to form new structures.

Top-down and bottom-up

"The particular potential of nanotechnology lies in the combination of a top-down approach [Note: by means of progressive miniaturization] with a bottom-up approach [Note: combining individual components]. The key new factor distinguishing nanotechnology is the controllable manipulation of atoms and molecules on the nanoscale This will increasingly enable the construction of functional nanostructures atom by atom and consequently the creation of materials and components with hitherto unknown properties." (BMBF 2002)

What are synthetic nanoparticles?

Artificially manufactured particles smaller than 100 nm

Nanoparticles are understood to be both natural and artificially manufactured particles smaller than 100 nm. By synthetic nanoparticles, we mean artificially manufactured particles smaller than 100 nm in size, which have changed properties and/or functionalities. They are referred to as engineered nanoparticles or nanosized particles. The terms "ultrafine particles" (especially used by toxicologists), "nucleation mode particles" or "engineered nanostructured material" are also used. (cf. Oberdörster et. al. 2005)

The properties already known with respect to atoms or molecules, such as electrical conductivity, magnetism, colour, mechanical hardness or a particular melting point can change depending on the size or structure of the particles. Cadmium telluride particles (CdTe), for example, fluoresce in different colours depending on the size of the particles (2 to 5 nm).

Property changes

Three basic property changes were observed:

1. a changed quantum-mechanical behaviour, e.g. in relation to colour, transparency, hardness, magnetism and electrical conductivity
2. an enlarged surface leading to changes in the melting and boiling point, the chemical reactivity and the catalytic effect and
3. a changed molecular recognition capability, which, combined with an increased recognition ability, adaptation ability, repair ability and self-organisation, opens up new biological applications.

Current status and future development of nanotechnology

In which areas are research and development in nanotechnology being carried out?

Research and development areas of nanotechnology are, for example

- **Analytics**

  Topics: improving sensor properties and instruments for analysis, nano-analysis using nano-chemical sensors

- **Electronics**

  Topics: chip production, manufacture of improved storage media

- **Optoelectronics**

  Topics: new circuit design principles, making quantum effects usable for the production of new kinds of transistors, new kinds of semiconductor light sources (diodes and laser)

- **Optics**

  Topics: ultra high precision processing of optical components, lithography for producing ever smaller electronic components, optical components with function surfaces (aspheres) for data projectors, cameras, spectacle lenses, scanners

- **Biotechnology and medicine**

  Topics: use of nanoparticles in the fight against tumours, nanostructured and functionalised surfaces and membranes, improved diagnosis and more targeted use of active agents; neuro-active implants

- **Material sciences**

  Topics: ultrafine nanolayers, nanocrystals, nanostructures for microelectronic components, fuel cells, scratch-proof surfaces, water and dirt repellent surfaces; antireflective properties, photoactive radiation

Competence Centres BMBF

The BMBF has established a total of 9 Competence Centres in order to form a network of players:

- Competence Centre 'Ultrathin Functional Films' (Dresden)
- NanoChem (Saarbrücken)
- Ultra high precision surface processing (Braunschweig)
- Competence Centre for Nanoanalytics (Münster)
- HanseNanoTec (Hamburg)
- ENNaB – Excellence Network NanoBioTechnology (Munich)
- NanOp – Competence Centre for the Application of Nanostructures in Optoelectronics (Berlin)
- NanoBioTech (Kaiserslautern)
- NanoMat (Karlsruhe)

In addition, there is a series of further networks and research institutions. For more details visit www.nano-map.de (in English).

What are the market and employment potentials of nanotechnology?

What is the nanotechnology turnover?

The actual turnover depends very much on the definition of when a product was produced using nanotechnology (components or production methods).

Wide range of turn-over expectations

VDI-TZ ZTC (2004) compiles estimates from different analysts. These estimates range from USD 900 million for the world market volume of nanotechnological products in 2005 to a trillion USD for the world market volume of nanotechnically influenced products in the year 2015. The same authors expect an exponential growth of the world market in nanotechnological products.

According to a study by the US market research institute LuxResearch, products in which nanotechnology is used make up only 0.1 percent of global goods production. By 2014 this share will rise to around 15 percent.[3]

It is currently not possible to give an exact number with regard to jobs depending directly or indirectly on nanotechnology. The BMBF expects a substantial rise in jobs and an associated need for qualified staff (BMBF 2004).

How is nanotechnology being funded?

BMBF and BMWA funding

The Federal Ministry of Education and Research (BMBF) funds projects under its Nanotechnology Funding Programme. In addition, there is indirect support through institutional funding of scientific organisations. The Federal Ministry of Economics and Labour (BMWA) also funds some projects.

An overall picture of the total amount of nanotechnology funding in Germany in the years 2002 to 2005 can be seen below:

Nanotechnology support in Germany	**2002**	**2003**	**2004**	**2005**
BMBF project funding	73.9	88.2	123.8	129.2
BMWA project funding	21.1	24.5	24.5	23.7
Institutional funding[4]	143.1	144.2	144.8	145.4
Total amount (in mio. €)	**238.1**	**256.9**	**293.1**	**298.3**

(VDI TZ ZTC 2004)

Industry also invests in research and development in the field of nanotechnology. There is no data available on this.

Compared to other European countries, Germany provides one of the most substantial amounts of funding.

"A comparison of the expenditures in Europe, the USA and in Japan results, roughly estimated – and without going into the funding details – in similarly high funding volumes. " (VDI-TZ ZTC 2004)

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[3] Press release from Allianz AG dated 7 June 2005
http://www.pressetext.at/pte.mc?pte=050608055 dated 31 July 2005

Therefore, VDI-TZ ZTC comes to the conclusion that Germany currently occupies a favourable position in international competition.

What products are there?

The use of nanoscale materials can be traced back to Chinese pottery as far as 2000 years ago. The use of carbon black particles in rubber tyres has also long been the international standard.

First products available

An increasing number of innovative products containing nanotechnical materials or produced using nanotechnological methods have been entering the market recently.

Which products are already on the market?

The following overview shows some of the products already available:

- Sun cremes with higher UV protection and for the more sensitive skin contain oxide particles
- Cosmetics with nanoparticles
- Nanoscale ink particles for copiers and printers
- Paints and coatings that absorb UV rays
- Scratch-proof car paints
- Textiles that are water and dirt repellent
- Textiles that have improved sun protection owing to oxide particles
- Safety clothing that prevents the build-up of static
- Improved antireflection coating and greater scratch resistance in spectacle lenses
- Optimised electronic chips, hard disks, RAM memory, diode lasers, displays, accumulators

[4] Institutional funding refers to funding by DFG, MPG, HGF, FhG and WGL

- More efficient use of energy in light diodes in display boards, rear lights and torches
- Golf clubs and tennis racquets containing carbon admixtures with greater stability and improved playing properties
- Admixtures of nanoparticular materials in babies' nappies to enhance moisture absorption, in cling film for greater tear strength and gas permeability

(among others BMBF 2004).

What products might we see in the future?

There is a multitude of ideas and potential uses. The following compilation contains ideas as well as products and processes that have already reached the trial stage.

- **Car industry**: intelligent systems that react to driving behaviour and environmental stimuli; mirrors and windows that adjust automatically to outside conditions; improved tyre adhesion on different road surfaces; paintwork colour changeable at the touch of a switch; scratch proof synthetic materials for the interior cladding
- **Mechanical and plant engineering**: new manufacturing and plant technologies; improved machines and plants through use of functional layers; improved metrology and sensor technology
- **Energy technology**: new means of energy storage such as fuel cells; highly efficient solar cells and innovative materials that convert heat into electricity
- **Medicine**: methods for diagnosing and treating cancer and diabetes; nanoparticles as contrast medium, for localised destruction of tissue (e.g. tumours) and to transport agents (medication); bio-chips for medical diagnosis
- **Information and communication**: multifunctional devices in small formats; three-dimensional holographic displays; devices enabling online-diagnostics with automatic alarm function

- **Optics**: lighting techniques based on optoelectronic components (e.g. large surface light diodes); optical lenses manufactured in any desired shape with nanometre precision (e.g. for data projection devices, in lithography and medical engineering).

(various sources including BMBF 2004).

Which products have a positive effect on the environment?

With the vast number of possible applications benefits for the environment are repeatedly highlighted:

- Improved extraction of drinking water, improved soil and air decontamination using nanotechnological methods
- More efficient use of energy e.g. through the solar cells having a higher utilization factor, improved utilization factor in lamps (OLED Organic Light Emitting Diode)
- Improved energy storage and transport e.g. through hydrogen storage tanks, optimised lithium-ion batteries, improved fuel cell technology, hybrid cars
- Preserving resources by using new materials e.g. by using lighter materials in the car industry, thinner layers
- Preserving resources by using fewer materials e.g. with paint pigments
- Reducing the use of substances harmful to the environment e.g. by using self-cleaning surfaces or by replacing harmful substances

The stages of development range from ready for the market (paintwork and lamps with optimised efficiency) to early stages of development (air and soil decontamination).

Potentials for environmental relief

IÖW Research

The Institute for Ecological Economy Research IÖW conducted a study on "sustainability effects through the production and application of nanotechnological products" on behalf of the BMBF. Carrying out a life-cycle analysis of products already in use, prospective positive ecological effects and potentials were set against potentially problematic effects. The ecological efficiency of Nano-Varnish, process innovation within the styrol synthesis, nano-innovations within the display sector, nanoapplications within the lights sector and risk potentials of nanotechnology application were examined in five case studies.

Not automatically holding potential for environmental relief

"The comparison of the life-cycle analyses shows that nanotechnology applications do not automatically hold a potential for immediate environmental relief. At the same time, though, a high level of potential for environmental relief could be shown for most contexts of application with the chosen method of the intercomparison study of functionalities."" (Steinfeld et. al. 2004)

The potentials for risk and hazard that are not piccovered by the life-cycle analysis are discussed using nanoparticles as an example. In addition, the IÖW authors note that the assessment depends on the known material and energy data and does not allow any estimate to be made concerning products still under development.

Assessment of nanoparticles with regard to environment and health

Classification of nanoparticles

VDI-TZ ZTC (2004) introduces a classification of nanomaterials under the categories of dimension, phase structure and manufacturing process.

Dimensions of nanosystems

Nanosystems can be nanoscale structured in one or several dimensions:

- One-dimensional nanostructured systems, e.g. ultrathin films
- Two-dimensional nanostructured systems, e.g. nanowires, quantum wires
- Three-dimensional nanostructured systems, e.g. quantum points, nanopowder, functional supramolecural systems.

Phase structure

They can consist of one (single-phase solids) or several (multi-phase solids) solid phases or of different phases (multi-phase systems, solid-liquid, liquid-gaseous, solid-gaseous). In addition, classification can be made according to the manufacturing process (mechanical or in gaseous or liquid phases).

Which nanoparticles are we talking about?

The word nanoparticle stands for a compound of a few to several hundred atoms or molecules.

Which nanoparticles are already in use?

The most important nanoparticles in use are:

- carbon black,
- metal oxides such as silicon dioxide SiO_2, titanium dioxide TiO_2, aluminium dioxide Al_2O_3, zinc oxide ZnO and iron oxide (Fe_2O_3, Fe_3O_4),

- semi-conductors such as cadmium telluride CdTe and gallium arsenide GaAs and
- metals such as gold and silver.

Carbon black, also known as furnace black is used, for example, as a strengthening filler for tyres. Nanoscale TiO_2 is used in sun cremes to reduce UV permeability. TiO_2 and ZnO is used for example in cosmetics.

Carbon nanotubes

Single or multi-walled tubes

Carbon nanotubes (CNT) are tubes with a diameter measuring one to 50 nanometres. They are generally only a few micrometres long, individual tubes can also be longer. Carbon nanotubes can have one wall (single-walled carbon nanotube SWCNT) or several walls (multi-walled carbon nanotube MWCNT). The ends can be open or closed, the wall can be a closed ring or a spiral structure.

They are characterised by a particularly high tensile strength and, according to structure, are conductive or semi-conductive. In low temperatures, some structures also have supraconductor properties. Because of their semiconductor property, they are also used to make transistors for computer chips. They are also used in the manufacture of displays.

Nanotubes made from different materials

In addition to the carbon nanotubes there are also nanotubes made from other materials such as metal nitrides, sulphides or halide.

Fullerenes

Fullerenes are macromolecules consisting exclusively of carbon atoms. Particularly well researched are fullerenes in the form C_{60}, C_{70}, C_{76}, C_{80} etc. C_{60} is also called Buckminster fullerene or Buckyball. Fullerenes are expected to be used in medical applications.

Quantum points

Quantum points are 5 nm high and 100 nm big pyramid-shaped formations. They are made up of several thousand atoms and around 100 billion quantum points can be fitted onto one square centimetre. Under appropriate boundary conditions, these quantum points arrange themselves independently and in regular patterns. They form, for example, the basis for new laser systems. (BMBF 2002)

When do we talk of risks?

In actuarial terms, the scale of the risk is calculated by the potential damage in relation to the probability of its occurrence. Risk experts differentiate between

Difference risk, danger, hazard, hazard potential

- risk as the probability of an adverse effect occurring under certain conditions,
- danger as a state, circumstance or event where there is sufficient probability of considerable damage to persons or the environment,
- hazard as the presence of a danger and
- hazard potential as the potential of a substance to cause damage (cf. Risk Commission 2003)

This hazard potential only becomes a hazard in the event of a specific occurrence, such as exposure of a substance in a minimum quantity.

Risk assessment criteria

The German Advisory Council on Global Change WBGU (1998) names the following criteria for risk assessment:

- **Probability of occurrence**: how probable is it that a risk will occur?
- **Reliability of the assessment of the probability of occurrence**: how well can the occurrence of an event be assessed?
- **How far-reaching are the consequences of the damage**: what is the extent of the projected damage?
- **Reliability of the assessment of the extent of the damage**: how reliably can the extent of the damage be assessed?
- **Ubiquity**: what is the extent of the spread?
- **Persistency**: how fast is recovery?
- **Irreversibility**: to what extent can the damage caused be reversed?

- **Delayed effect**: how long does it take before the damage occurs – acute to long-term effects
- **Potential for mobilisation**: to what extent does the damage result in changes in attitude or behaviour in the population

Concept transferable to synthetic nanoparticles?

The extent to which these criteria can be applied to synthetic nanoparticles still has to be clarified. In this context the question remains as to whether the risks can be summarized in specific hazard classes.

What health and environmental hazards posed by nanoparticles are known?

Open questions

To be able to assess the risks for human health, the following questions must be answered:

- Which synthetic nanoparticles in what size impair health in what way?
- Which properties of the nanoparticles and which reactions in the human body are influential here?
- How can the dose-effect relationship be quantified?
- What quantities/ concentrations/ surface size of synthetic nanoparticles are normally released in what actions (manufacture, processing, utilization, disposal/recycling)? What quantities/ concentrations/ surface size are released in the worst-case scenario?

(cf. also Oberdörster 2005). Comparable questions can be used to assess the risks to the environment.

So far, these questions can only be answered in part and only for certain particles. At the present moment, it is also unclear whether these studies must be carried out separately for all the particles or whether it is possible to divide the nanoparticles into risk classes.

Open questions concerning potential hazards to the environment

There are still questions to be resolved with respect to the environment:

- How do synthetic nanoparticles enter the environment (intentional – unintentional releases; life cycle: production-processing-product-recovery; release scenarios)

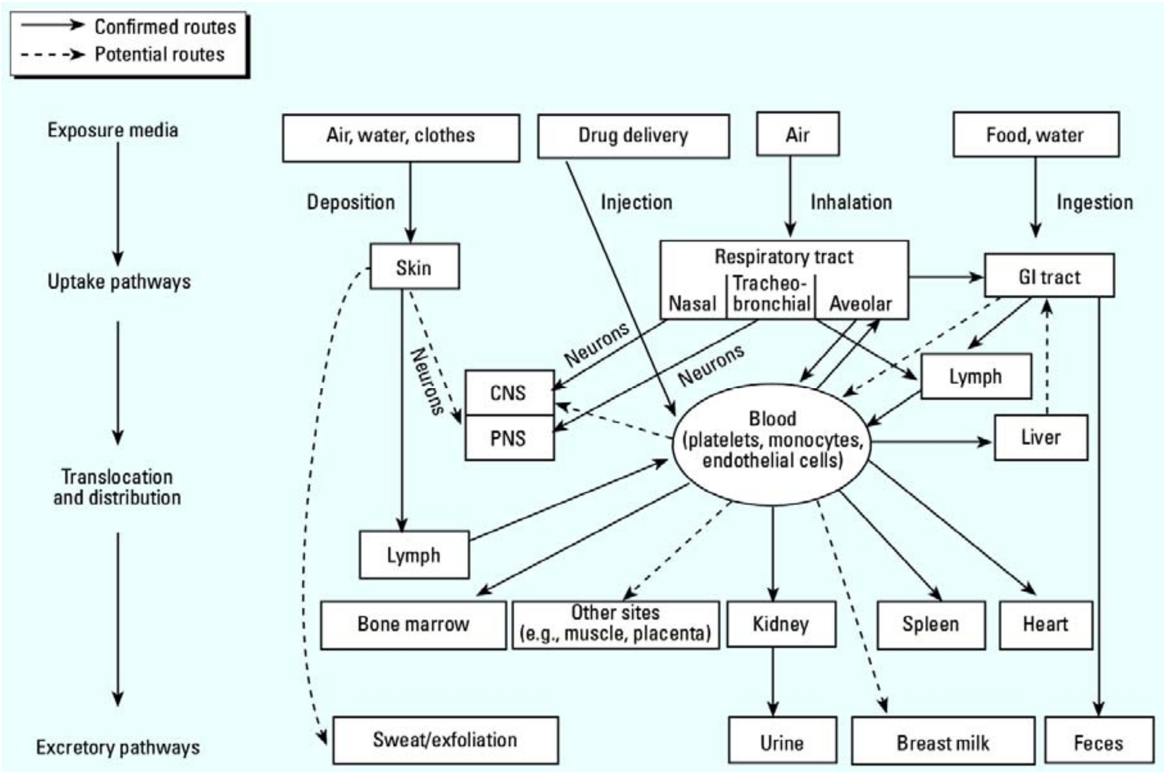
- How do the nanoparticles behave in the environment? (settling, agglomeration, deagglomeration, deposition, degradation, solubility)
- What impact do they have on the food chains?
- Which synthetic nanoparticles can act as transport media for other harmful substances? Or through what other substances are synthetic nanoparticles dispersed?
- To what extent can the results of the research into ultrafine particles (UFP) be extrapolated? (cf. also Swiss Re 2004)

Results for UFP

Oberdörster et. al. (2005) compile the results of previous studies on ultrafine particles (UFP) in their outline article where they discuss

- the toxicology of ultrafine particles for humans and the environment
- possible exposure and uptake pathways for humans, animals and the environment
- the different uptake routes (inhalation, injection, dermal and by ingestion)
- the behaviour of nanoparticles with respect to uptake, translocation, distribution and effects in the body and
- the questions that must be answered jointly by industry, science and the public administration as part of a risk assessment.

Oberdörster et. al. (2005) summarise the confirmed and potential routes of nanoparticles in the graphic chart below under the title “Biokinetics of synthetic nanoparticles”.



What results have been received so far?

Initial results should be viewed sceptically

We will be presenting some study results shortly. Previous studies were criticised for, in general, not being reproducible (e.g. due to lack of reference materials). With regard to ultrafine particles, it is frequently the case that mixtures of very different sizes are studied and no differentiation is made between natural nanoparticles produced by incineration and those synthetically produced. Therefore, an extrapolation of data from the field of ultrafine particles on synthetic nanoparticles must be looked at with a critical eye.

- In a trial, water soluble C_{60}-fullerene caused disturbances in the brain and symptoms of stress in young largemouth bass[5].
- With an injection of polyalkylsulphonated C_{60}-fullerene (FC4S), the lethal dose 50 (LD50) for rats is at 600 mg/kg bodyweight. Oral administration proved not to be toxic. (Chen et al. 1998)

[5] http://pubs.acs.org/cen/news/8213/8213bass.html dated 31 July 2005. The results of Eva Oberdörster have not as yet been confirmed by other scientists.

- Oberdörster makes the hypothesis that ultrafine particles are one of the causes leading to negative effects in sensitive persons. Studies carried out on rodents show that smaller particles in the same mass cause greater inflammatory effects than larger particles. Surface properties appear to play a role in this. (Oberdörster 2000)
- In another study, Oberdörster et al. observe that with rats significant amounts of carbon particles travel from the nose via the olfactory nerve to the central nervous system – and do so circumventing the blood-brain barrier. (Oberdörster et. al. 2004)
- Jens Schulz and colleagues from the company Beiersdorf studied the dermal absorption of nanoparticles such as TiO_2 and ZnO. No absorption via the skin was observed regardless of surface characteristic, size of the particles and particle form. Depositions of TiO_2 could only be found in the upper layers of the skin. (Schulz et. al. 2002)

  The initial results from the NANODERM project and from a study by BASF AG[6] confirm this evidence, but have found that if the skin is damaged the nanoparticles can penetrate into deeper layers of the skin.
- Kreuter carried out a study to determine whether the poly(butylcyanoacrylate) nanoparticles PBCA, now used to transport active agents, have toxic effects on the blood-brain barrier. In vitro and animal experiments suggest that there is no disturbance to the blood-brain barrier. (Kreuter et. al. 2003)
- In her outline work, Colvin touches on the toxic effects of carbon nanostructures (fullerene and carbon nanotubes) observed in some in vitro and animal experiments. (Colvin 2003)
- Warheit undertook the first toxicological peer-review study on single-walled nano carbontubes. Although rats died when subjected to high doses, this was due to mechanical blocks in the upper respiratory tract. (Warheit 2004) He considered it still too early to make any statements on the dangers posed by nanoparticles. He felt there were too few stud-

[6] According to verbal statements made by Dr. Reinert, University of Leipzig, and Dr. Leibold, BASF AG.

ies available which could substantiate such statements; and those available related to TiO_2, carbon black and diesel exhaust particulates. Moreover, trials using rats were only transferable to a limited extent, and the toxicity of a substance depends on the surface coating as well as on the size and composition. (Warheit 2004b)

- Lam studied mice 7 and 90 days after administering single-wall carbon nanotubes or quartz and carbon black. According to these studies, SWNCT is more toxic than carbon black. On the other hand, critics work on the assumption that the metallic catalytic particles in the nanoparticles are responsible for the effects on health. (Lam et. al. 2004)
- Derfus et. al. showed that quantum points have cytotoxic effects under certain conditions. The effect can be altered by, for example, appropriate coatings. (Derfus et. al. 2004)

Is a risk assessment possible?

A conclusive risk assessment of the hazards posed by synthetic nanoparticles cannot be made yet. More studies are needed to examine

Questions need to be resolved

- the toxicology of nanoparticles,
- the routes of exposure,
- the uptake and excretory routes,
- the long-term effects of nanoparticles
- and the dose-effect relations (cf. also Oberdörster 2005).

What projects are currently dealing with the effects on health?

The European Commission is funding the following projects:

- Nano-Pathology (since 12/2001): Development of diagnostic methods and tools and determination of the pathological significance of nanoparticles.

- NANODERM (since 01/2003): Studies on the penetration of nanoparticles into the skin. Especially particles such as TiO2 <20nm that are used in household and bodycare products.
- NANOSAFE (04/2003 to 08/2004): Risk assessment in the production, application and use of nanoparticles in industrial processes and products.
- NANOSAFE 2 (since 04/2005): Development of techniques for recognising, tracking and characterising nanoparticles
- NANOTOX: Research into other toxicological effects of nanoparticles. Has now been merged with IMPART. IMPART deals with the understanding of toxicological effects on health and environment.

In addition, research on the subject is also being carried out in public and company-owned research laboratories.

Where is a perceived need for regulation?

Need for regulation must be clarified

The Office of Technology Assessment at the German Bundestag, TAB, recognises a need to clarify the regulation requirements. "Priority should be given here to the current nanotechnological applications and those that can be realistically expected." (TAB 2003)

Here the following regulations in particular are the focus of attention:

- German Immission Control Act, TA Luft
- Chemicals Act and REACH[7]
- Occupational Safety Acts
- Drugs Act and Law Governing Medical Products
- Foodstuffs and Consumer Goods Act
- Novel Food Regulation (EC).

[7] The proposed EU regulation on the "Registration, Evaluation, Authorisation and Restriction of Chemical Substances" REACH is currently under review.

No "Lex Nanotechnology"

The Royal Society report (2004) focuses strongly on the existing regulatory requirements and where there is still a need for such requirements. At the time of writing, no need for special nanotechnological regulations is perceived. In particular, the call for a moratorium by the ETC Group (2003) is rejected. However, they do see a need to amend existing regulations to take into account the new and changed properties of synthetic nanoparticles[8]. It is the responsibility of the industry to make their assessments of the hazards of nanoparticles available. The authorities should then check whether the regulations protect people and the environment effectively. One recommendation is to treat synthetic nanoparticles as new substances as defined by REACH. Moreover, the report also contains some recommendations on industrial safety, product safety and measuring methods.

… but need for regulation should be clarified jointly

Consensus on regulation requirements must be reached at international level

The need for regulation is being considered at every level – Germany, EU and OECD and in other countries as well (e.g. USA, Great Britain, Australia). The different activities should be coordinated and consensus reached on how to proceed.

Environmental and health dangers posed by synthetic nanoparticles – What action needs to be taken?

In addition to the need for regulation, the following need for action has been expressed:

- Systematic analysis of the dangers posed to environment and health by nanotechnological processes and products (TAB 2003, Swiss Re 2004)
- Studies on the dispersal behaviour of synthetic materials such as fullerene and nanotubes in all media (especially air) and potential long-term effects on environment and health (TAB 2003)
- Analysis and specification of emission sources of nanocomposites and nanoparticles as well as dispersal models (TAB 2003)

[8] In this context, various players consider it appropriate, for example, to widen the parameters of the environmental measurements, weight and concentration, to include the parameters surface and particle size .

- Studies on and models of uptake, translocation into and interaction with the human body (TAB 2003, Swiss Re 2004)
- Toxicological and epidemiological studies including persistence and bioaccumulation of synthetic nanoparticles (Royal Society 2004)
- Studies on the behaviour of nanoparticles in products during the entire life cycle from production and processing through utilization to disposal/recycling (TAB 2003; Royal Society 2004)
- Recommendations as to how synthetic nanoparticles should be dealt with until such time as the risks have been clarified (Royal Society 2004)
- Establishment of a national, interdisciplinary research centre to study the potential hazards of synthetic nanoparticles (Royal Society 2004)
- Establishment of a central information office for the general public (TAB 2003)
- Holding of public dialogue on the opportunities and risks posed by synthetic nanoparticles (Royal Society 2004, TAB 2003)

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