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Multifunctional Magnetic Nanomaterials

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Abstract— Magnetic nanomaterials are the category of nanomaterials that capable to be influenced externally with controllable size and, in the presence of magnetic field. The magnetic nanomaterials are in focus of most of the research recently because of the potential benefits exhibited by these materials. In this paper the applications of magnetic nanomaterials such as biomedicine (tissue specific targeting), cell tracking, drug delivery, medical imaging, protein purification, waste water treatment, genetic engineering, data storage, etc. are discussed. The paper also gives an exposure to various magnetic nanomaterials and theoretical views of magnetism on nanomaterials, some ideas as future prospects are proposed based on the applications and the materials discussed.

Keywords: magnetic nanoparticles, biomedical applications,

I. INTRODUCTION

Magnetic nanoparticles are the main category of nanomaterials which can be influenced using magnetic field gradients consist of magnetic elements such as iron, nickel and cobalt and their more chemical compounds. Magnetic nanoparticles size are typically 5–500 nanometers. Magnetic nanobeads are the magnetic nanoparticle clusters which are composed of a number of individual magnetic nanoparticles with size of 50–200 nanometers. Magnetron is a spinning electric-charged particle, which create a magnetic dipole and they are associated in groups in ferromagnetic materials. A magnetic domain defines to a volume of ferromagnetic material in which all magnetons are aligned in the same direction by the exchange forces. When the size of a ferromagnetic material is reduced below a critical value, it becomes a single domain [2].

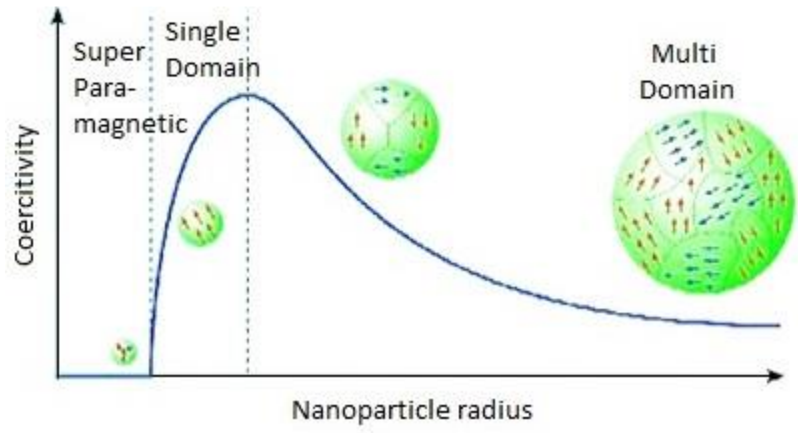

Fig 1: Figure of the relation between coercivity and nanoparticle radius. [2]

When the particle size is reduced, the coercivity increases to a maximum and then decreases toward zero as shown in the figure 1. When the size of single domain particles decreases further below a critical radius, the coercivity reaches zero and these particles show superparamagnetic behaviour. The superparamagnetic particles have zero coercivity and no hysteresis because thermal fluctuations of superparamagnetic particles are quite strong to demagnetize previously saturated magnetism. Nanoparticles show magnetic behaviour in the presence of an external magnet and when the external magnet is removed, they revert back to nonmagnetic state. There is no active behaviour of the particles in the absence of the magnetic field. Frenkel and Dorfman were the first to predict that a particle of ferromagnetic material, below critical particle size (<15 nm), would consist of a single magnetic domain, i.e., a particle that is in a state of uniform magnetization at any field. A number of magnetic nanomaterials are available in the forms of dry powders and surface functionalized powders e.g. Maghemite (MGH) (γ-Fe_2O_3), Magnetite (Fe_3O_4), Co-ferrite ($CoFe_2O_4$) and MnZn-ferrite ($MnZnFe_2O_4$) [2,4].

II. PROPERTIES OF MAGNETIC NANOMATERIALS

Magnetic nanoparticles show outstanding properties such as high field irreversibility, high saturation field, superparamagnetism and extra anisotropy behaviour etc. These properties are due to narrow and finite size and surface effects that controls the magnetic behaviour of nanoparticles. The ratio of the surface area to the volume of the particle increases when the size of the particle decreases. This ratio becomes significantly large causing a large portion of the atoms to reside on the surface compared to those in the core of the nanoparticles. For example, for a particle of size 1 μm in diameter, nearly 0.15% of its atoms are on the surface, while for a particle of 6 nm in diameter nearly 20% of its atoms are on the surface. The large surface-to-volume ratio of the nanoparticles is the main reason to the extra ordinary physical, chemical, and mechanical properties compared to those of the other bulk material having same composition.

Each possible application of the magnetic nanoparticles requires different nature of properties. For data storage applications, the particles are required to be stable, have switchable magnetic state to represent t bits of information and immune to temperature. For biomedical applications, the usage of particles that show super paramagnetic behaviour at room temperature is desired. The applications in medical therapy, biology and medical diagnosis require the magnetic particles to be stable in water. The nature of the magnetic components, the final size of the particles, their core and their coatings are the major factors to decide toxicity and the biocompatibility of the materials. Iron oxide nanoparticles such as magnetite (Fe_3O_4) or its oxidized form maghemite (γ-Fe_2O_3) are the most commonly employed nanoparticles for biomedical applications. The least used are highly magnetic materials such as cobalt and nickel because they are susceptible to oxidation and more toxic. The main advantage of using particles of sizes smaller than 100 nm is their higher effective surface areas, lower sedimentation rates and improved diffusion.

In vivo biomedical applications, magnetic nanoparticles used are non-toxic and non-immunogenic material, with small particle size so that they remain in the circulation after injection and can pass through the capillary systems of organs and tissues. They also have high magnetization behaviour so that their movement in the blood can be controlled with a magnetic field. [2]. The spins in an isolated particle are held in a particular direction via the magnetic anisotropy energy which is caused by spin-orbital interactions of the electrons. If the particles are not isolated, other interactions will be involved. The anisotropy energy per particle is given by:

$$E(\theta) = K\,V\,\sin\theta \qquad (1)$$

where V is the volume of the particle, K the effective anisotropy constant, and θ is the angle between the magnetization and the easy magnetization axis of the particle [3].

III. APPLICATIONS OF MAGNETIC NANOMATERIALS

The magnetic nanoparticles have been the focus of research now a days because of their outstanding properties which are employed in catalysis including biomedicine and tissue specific targeting, magnetically tuneable colloidal photonic crystals, magnetic resonance imaging, magnetic particle imaging, data storage, environmental remediation, nanofluids, microfluidics, genetic engineering, optical filters and defect sensor etc. Broadly, emphasis on the importance, some applications of the magnetic nanomaterials are given below.

A. Medical diagnostics and treatments

Magnetic nanoparticles can be used for the detection of cancer. Magnetic nanoparticles are used in experimental cancer treatment called magnetic hyperthermia or nanoparticle-delivered cancer drugs in which the nanoparticles heated in the presence of alternative magnetic field. Affinity ligands such as epidermal growth factor, folic acid, lectins, proteins and DNA etc. can be attached to the magnetic nanoparticle surface. This enables targeting of magnetic nanoparticles to specific tissues or cells. There is another important treatment of cancer to attach magnetic nanoparticles to free-floating cancer cells. A microfluidic chip with magnetic nanoparticles is inserted in the blood. The magnetic nanoparticles are attached inside due to an externally applied magnetic field. The magnetic nanoparticles can be recovered and the attached cancer associated molecules can be examined.

Magnetic nanoparticles conjugate with carbohydrates are used for detection of bacteria. Iron oxide particles have been used for the detection of gram negative bacteria. Researchers from Harvard Medical School and Massachusetts General Hospital have developed a magnetic nanoparticle based MRI technique for predicting whether and when subjects diabetes disease be developed. The schematic representation of the magnetically driven transport of drugs to a specific region is shown in figure 2. A catheter is inserted into an arterial feed of the tumour, and a magnetic field is passed over the target field. [1,7].

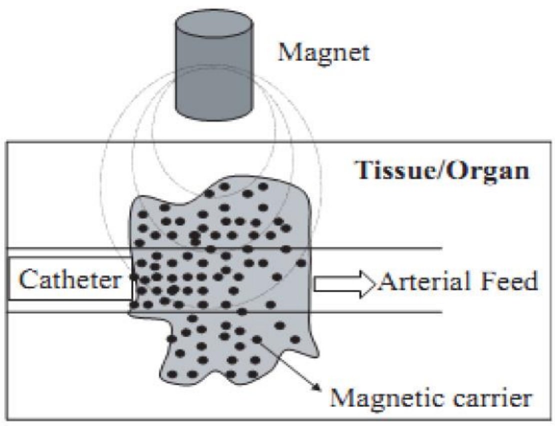

Fig 2. Magnetically driven transport of drugs to a specific region

B. Magnetic immunoassay

Magnetic immunoassay is a category of diagnostic immunoassay in which magnetic nanobeads are utilized as labels. This involves the binding of an antibody to its antigen, where the magnetic label is combined to one element of the pair. In the presence of magnetic field, nanobeads is detected by magnetometer. The signal measured by magnetometer is in proportion to the virus, toxin, bacteria and cardiac marker etc. quantity in the sample and can be analysed.

C. Waste water treatment

Magnetic nanoparticles have a great capacity for treatment of contaminated water due to their high surface area with respect to micron-sized sorbents. Magnetic nanoparticles are used as sorbents for the removal of metal ions. In this method, EDTA (Ethylenediaminetetraacetic acid) chelators of carbon coated metal nanomagnets, attached with heavymetals from the contaminated water. Magnetic nanoparticle clusters hold potential for waste water treatment because of good biocompatibility as compared to metallic nanoparticles. A very important aspect in metal toxin removal is the preparation of functional sorbents for similarity or selective removal of hazardous metal ions from waste water

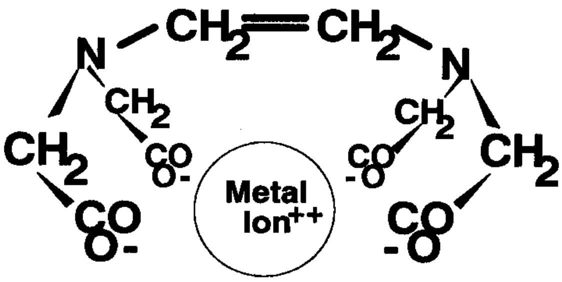

Fig 3. EDTA-Ethylenediaminetetraacetic acid chelator.

D. Genetic engineering

Magnetic nanoparticle carriers consist of three parts: magnetic core, surface coating, and functionalized outer coating as shown in figure 4. The carrier at the centre has the superparamagnetic behaviour. The functionalized outer coating may be biologically active drug molecule known as therapeutic agents or ligand for scavenging of metal ions. The therapeutic agents are encapsulated within a magnetic nanoparticle. The therapeutic DNA is used to correct a genetic defect. Magnetic nanoparticle can be used for in vitro gene transfection. Magnetic nanoparticles have strong impact for exploring gene therapy by applying targeted delivery of DNA into tissues and cells.

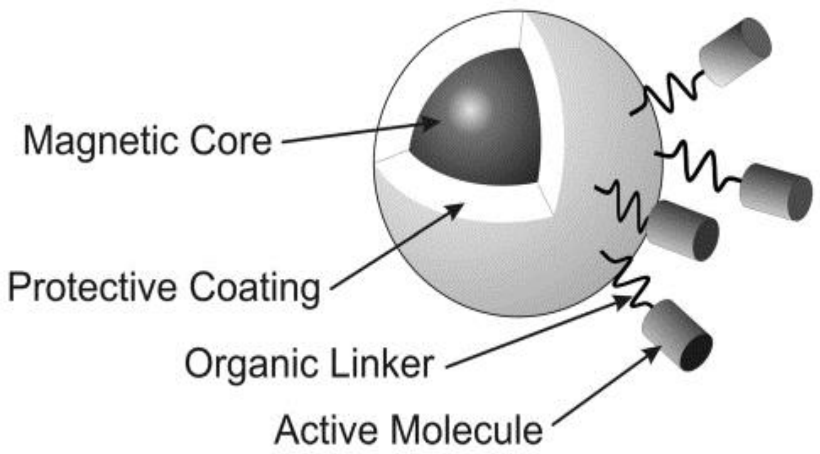

Fig 4. Structure of magnetic nanoparticle carrier [5]

E. Industrial applications

Magnetic nanoparticles have important uses in various branches of industry. Magnetic iron oxides are commonly used as synthetic pigments in ceramics, paints, and porcelain. Hematite and magnetite are used as catalysts for many important reactions, such as the preparation of NH_3, the desulfurization of natural gas, the high-temperature water-gas shift reaction, Fishere-Tropsch synthesis for hydrocarbons, dehydrogenation of ethylbenzene to styrene, oxidation of alcohols and the large-scale synthesis of butadiene [4,6,7].

IV. CONCLUSIONS

The aim of this review was to introduce applications of magnetic nanoparticles with their important physical properties. The surface effects and anisotropy are the reasons of having outstanding properties of nanoscale particles from the bulk scale.

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