Monodisperse spherical mesoporous nanocomposite mSiO$_2$/C-dots/Eu$^{3+}$ particles with broadband luminescence in the visible spectral range

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Abstract. A facile template synthesis has been developed to obtain monodisperse spherical mesoporous nanocomposite mSiO$_2$/C-dots/Eu$^{3+}$ particles of submicron size exhibiting bright broadband luminescence in the visible spectral range. The use of europium ions made it possible to increase the integrated emission intensity of the nanocomposite particles in the reddish-orange region. The particles have a specific surface area of 540 m$^2$/g, pore volume of 0.35 cm$^3$/g, and average pore diameter of 2.7 nm. The obtained particles are promising for application in nanomedicine as nanocontainers simultaneously serving as biomarkers.

1. Introduction
A large number of studies are being actively carried out on developing multifunctional nanoparticles for diagnostics and therapy of various diseases [1]. In particular, systems for delivery of medicinal preparations into tumors, based on mesoporous silica particles (MSPs) are developed and studied [2,3]. These particles exhibit attractive characteristics such as chemical stability, biocompatibility, non-toxicity [3,4]. We have recently developed a method for the fast synthesis of submicron monodisperse spherical mesoporous silica particles (MSMSPs) via the controlled coagulation of nanosized SiO$_2$/cetyltrimethylammonium bromide (CTAB) clusters composed of amorphous SiO$_2$ channels [5]. The MSMSPs have an ordered mesoporous structure, large specific surface area and pore volume [5], which enables a substantial amount of a medicinal preparation being transported to a target site and makes it possible to reduce the toxicity of the chemotherapeutic drugs being introduced [6]. The monodispersity of the particles (size scatter about 5%) provides them with identical hydrodynamic properties in the blood circulatory system and, consequently, enables control over the time needed for delivery of the cargo.

When using nanocontainers in drug delivery systems, it is important to monitor the process of their accumulation in the tumor tissue. For that purpose, the particles are functionalized, e.g., they are made luminescent by introduction of phosphors within the pores. A hard-template approach is traditionally used for the synthesis of target substances within MSMSP pores. The pores of a template can be filled with a precursor solution or a melt, with its subsequent decomposition and chemical transformation to the desired substance. Previously, we have produced metals [7], oxides [8], and carbon nanodots [9] by this method. The monodispersity of the template particles and the identical mesopore diameters predetermine the identical conditions of chemical processes occurring within MSMSPs. Therefore, the target material with the same size and composition is to be formed within the MSMSP pores.
In this study, we fabricated monodisperse spherical mesoporous nanocomposite particles having the form of MSMSPs containing carbon nanodots (C-dots) and europium ions (Eu\(^{3+}\)) within the pores. The nanocomposite particles possess a large pore volume and exhibit bright broadband luminescence in the visible spectral range.

2. Experimental

2.1. Synthesis of mSiO\(_2\)/C-dots/Eu\(^{3+}\) particles

Monodisperse spherical mesoporous silica (mSiO\(_2\)) particles were synthesized via basic hydrolysis of tetraethoxysilane (TEOS, 99\%, Acros Organics, Germany) by the soft-template method described elsewhere [5,10]. Cetyltrimethylammonium bromide (99+% Acros Organics, Germany) was used as a pore-forming soft template agent. The molar ratio of the reagents, TEOS:NH\(_3\):H\(_2\)O:C\(_3\)H\(_4\)OH:CTAB, was 1:60:370:230:0.2. The reaction was performed in the course of 1 h at 45 °C. To remove organics, the particles were washed with an alcoholic solution of HCl (0.01 M) and then calcined in a flow of O\(_2\) at a temperature of 400 °C for 5 h.

Carbon nanodots and Eu\(^{3+}\) ions were introduced into MSMSPs by the method of thermal decomposition of europium acetate and 3-Aminopropyltriethoxysilane (APTES) infiltrated into the pores [8]. A 1-g portion of MSMSPs was impregnated with a 50 wt % alcoholic solution of 1 g of APTES and 0.05 g of Eu(Ac)\(_3\). After 3 h, the particles were dried at 50 °C and annealed in air at 250°C for 5 h.

2.2. Structural and optical characterization

A microscopic analysis was made by atomic-force microscopy (AFM) on an NT-MDT SMENA microscope operating in the tapping mode. The hydrodynamic diameter of the particles was determined by the dynamic light scattering (DLS) method at a temperature of 25°C with a Zetasizer Nano ZS instrument (Malvern, UK).

An adsorption-structural analysis was made with an ASAP 2020 analyser (Micromeritics, United States) at a temperature of 77 K, with nitrogen as the adsorbate. The specific surface area was calculated by the Brunauer–Emmett–Teller (BET) method. The pore size distribution was found using the nonlocal density functional theory (NLDFT), as this was done in previous studies [5,10].

Photoluminescence (PL) spectra were examined at room temperature on a MDR-23 spectrometer with FEU-79 electron multiplier operating in the photon counting mode, equipped with He-Cd laser (\(\lambda_{\text{exc}}=325 \text{ nm}\)) as a source of light.

3. Results and Discussion

The formation of the MSMSPs during the synthesis is the result of the controlled coagulation of SiO\(_2\)/CTAB clusters which provides monodispersity of the particles [5,10]. In this study MSMSPs with an average diameter of 510 nm were used (figures 1,2). The specific surface area calculated from the nitrogen adsorption isotherm at a temperature of 77 K (figure 3) by the BET method was found to be 770 m\(^2\)/g. The mesopore diameter calculated by the NLDFT was found to be 3.1 ± 0.2 nm (figure 4).

Carbon nanodots and Eu\(^{3+}\) ions were obtained within the pores of MSMSPs by template synthesis. This method is based on introducing a precursor (organosilane and europium salt solution) into pores and their subsequent thermal decomposition resulting in formation of carbon nanodots. Both the template material (amorphous silica) and C-dots could possibly be doped by Eu\(^{3+}\) ions.

DLS data and AFM images of the mSiO\(_2\)/C-dots/Eu\(^{3+}\) particles demonstrate that the obtained nanocomposite particles remain spherical and monodisperse (figures 1,2). An average diameter of the particles was found to be 510 nm, which corresponds to the diameter of bare MSMSPs. The standard size deviation of the particles according to the AFM data does not exceed 5%. Thus, the infiltration of C-dots and Eu\(^{3+}\) ions into the pores does not affect the size and shape of the particles.
The BET specific surface area, the pore volume and the pore diameter of the nanocomposite mSiO$_2$/C-dots/Eu$^{3+}$ particles are 540 m$^2$/g, 0.33 cm$^3$/g and 2.7 ± 0.5 nm, respectively (figures 3,4). Apparently, the porosity of the mSiO$_2$/C-dots/Eu$^{3+}$ particles decreased compared to bare MSMSPs but still remains high. The high porosity of the nanocomposite particles enables additional functionalization of their pore surface, introduction of medicinal preparations into the pores, and the use of such particles as nanocontainers for toxic chemotherapeutic agents.

Figure 1. DLS size distribution of monodisperse spherical mesoporous nanocomposite mSiO$_2$/C-dots/Eu$^{3+}$ particles.

Figure 2. AFM image of monodisperse spherical mesoporous nanocomposite mSiO$_2$/C-dots/Eu$^{3+}$ particles.

Figure 3. N$_2$ adsorption and desorption isotherms for the particles at 77K: 1 – bare MSMSPs, 2 – monodisperse spherical mesoporous nanocomposite mSiO$_2$/C-dots/Eu$^{3+}$ particles.

Figure 4. Pore size distribution determined by NLDFT for: 1 – bare MSMSPs, 2 – monodisperse spherical mesoporous nanocomposite mSiO$_2$/C-dots/Eu$^{3+}$ particles.
Figure 5 shows a PL spectrum of an aqueous suspension of the mSiO₂/C-dots/Eu³⁺ particles. The particle concentration was 1 mg/ml, the excitation wavelength was 325 nm. The spectrum exhibit a broad band in the UV-Vis spectral range that corresponds to the emission of C-dots [8,11] and a group of emission lines [8,12] typical for europium (III). The narrow lines are associated with intracenter transitions in Eu³⁺: 5D₆ → 7F₉, where J = 0-4 (the corresponding transitions are shown in the spectrum) with a clearly pronounced peak at a wavelength of 612 nm (5D₆ → 7F₂). Prior to being analyzed by PL spectroscopy, the synthesized mSiO₂/C-dots/Eu³⁺ particles were stored in an aqueous suspension for a month and after that PL measurements were carried out. This evidences that the luminescent material we obtained is not susceptible to degradation in aqueous media. The PL intensity of Eu³⁺ ions is comparable to that of C-dots. Note that the introduction of europium ions made it possible to increase the integrated photoluminescence intensity of the obtained mSiO₂/C-dots/ Eu³⁺ particles in the reddish-orange region as compared to PL of mSiO₂/C-dots particles (figure 5). The luminescent properties of the nanocomposite particles allow one tracing their accumulation in a tumor when using as nanocontainers for toxic chemotherapeutic preparations. The chemical binding of Eu³⁺ ions to the pore walls and C-dots prevents its diffusion from the particles and penetration into the organism.

![PL spectra of aqueous suspensions](image)

**Figure 5.** PL spectra of aqueous suspensions (C=1 mg/ml) of monodisperse spherical mesoporous nanocomposite mSiO₂/C-dots (1) and mSiO₂/C-dots/Eu³⁺ (2) particles upon excitation at 325 nm with a He-Cd laser at 300 K.

Owing to the presence of empty pores available for filling and broadband visible luminescence, mSiO₂/C-dots/Eu³⁺ particles are promising for use as nanocontainers for targeted drug delivery systems with the ability to simultaneously control their localization in the body by fluorescence microscopy.

4. Conclusion

Monodisperse spherical mesoporous nanocomposite mSiO₂/C-dots/Eu³⁺ particles were obtained by a facile hard-template method. According to nitrogen porosimetry, the particles have large specific surface area (540 m²/g) and pore volume (0.35 cm³/g). The obtained nanocomposite particles are spherical, monodisperse and exhibit broadband luminescence in the visible spectral range. The use of europium ions made it possible to increase the integrated emission intensity of the nanocomposite particles in the reddish-orange region. This in the future will facilitate their visualization by photoluminescence spectroscopy, for example, in vitro. The results we obtained demonstrate that the mSiO₂/C-dots/Eu³⁺ particles synthesized in the study are promising as nanocontainers for delivery of
toxic chemotherapeutic preparations. The particles can be simultaneously used as a luminescent markers thereby serving as a multifunctional theranostic agent.

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