CATALYTIC ACTIVITY OF CERIUM OXIDE NANOPARTICLES

[1]Irina BAZHUKOVA, [1]Inna ZVONAREVA, [1]Alexandra MYSHKINA, [1]Sergei BAZHUKOV, [2]Ilya GAVRILOV, [2]Viktor MESCHANINOV

[1]Ural Federal University, Institute of Physics and Technology, Yekaterinburg, Russian Federation, i.n.sedunova@urfu.ru

[2]Urals State Medical University, Yekaterinburg, Russian Federation

https://doi.org/10.37904/nanocon.2019.8696

Abstract

Cerium oxide (CeO_2) nanoparticles present an interesting material for various applications in biotechnology and medicine. The mechanism of CeO_2 nanoparticles biological activity is supposed to be related to the presence both Ce^{3+} and Ce^{4+} ions on the surface of the nanocrystal. We studied and compared the catalytic activity of CeO_2 nanoparticles synthesized by chemical and physical methods. The cerium oxide was found to demonstrate catalase-like and peroxidase activity. CeO_2 nanoparticles obtained by a chemical method showed more pronounced catalytic properties. In addition, this material catalyzed the decomposition of hydrogen peroxide by the enzyme horseradish peroxidase.

Keywords: Nanoparticles, luminescence, defects, cerium dioxide, catalytic activity, enzymes, catalase

1. INTRODUCTION

Cerium oxide (CeO_2) nanoparticles present a promising object for various applications, including biomedical research [1-3]. The CeO_2 nanoparticles are characterized by a high oxygen non-stoichiometry. The formation of oxygen vacancies leads to the reduction of cerium ions to the Ce^{3+} state on the particle surface. Such property correlates with the catalytic activity of cerium oxide nanoparticles and is probably responsible for their biological activity.

Many studies have reported on the multienzyme activity of cerium oxide nanoparticles, acting like superoxide oxidase [4] catalase [5] and oxidase [6] enzymes. CeO_2 nanoparticles catalyze the reactive oxygen species decomposition such as superoxide radical and hydrogen peroxide. Compared with natural analogues of enzymes, enzyme-like substances based on nanomaterials provide lower cost, the ability to change their catalytic activity and improved stability under harsh conditions. As shown in [7], CeO_2 nanoparticles possess enzyme-like catalytic activity and are stable over a wide range of pH values and temperatures, in contrast the natural enzyme horseradish peroxidase. Moreover, on the surface of nanomaterials there can be a larger number of catalytic centers as compared to natural enzymes, which have only one active center in the molecule [8]. The catalytic activity based on the cerium oxide nanoparticles ability to participate in the cycles of reduction and oxidation.

The majority of researches are devoted to the study of cerium oxide nanoparticles obtained by various chemical methods (co-precipitation method, hydrothermal synthesis, sol-gel technique, etc.). During chemical synthesis, the nanoparticles surface may be coated with an organic shell [9-10]. This shell helps to improve the aqueous sols stability and allows subsequent conjugation with biological molecules. In addition, the organic coating can protect the CeO_2 nanoparticles from oxidation, i.e., keep mixed valence states of cerium on the surface.

At the same time, the features of physical methods for producing this material are less considered. As we showed earlier, CeO_2 nanoparticles, obtained as a result of strongly nonequilibrium gas-phase synthesis

method conditions exhibit pronounced luminescent properties [11]. This fact allows us to assume the cerium ions of different valences presence on the nanoparticles surface.

The purpose of the present work is to study and compare the catalytic properties of CeO_2 nanoparticles produced by a gas-phase method and chemical technique.

2. EXPERIMENTAL

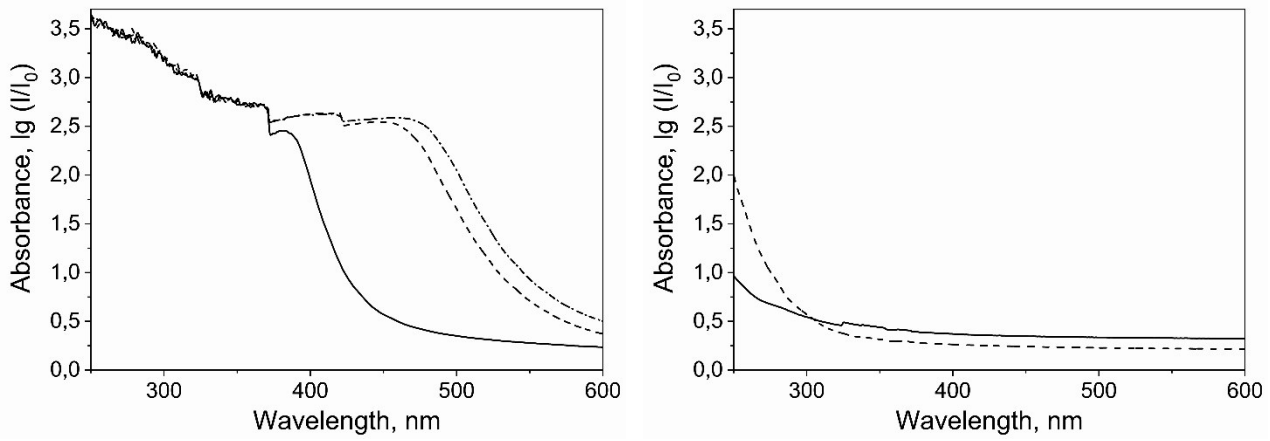
We studied two group of nanoparticles produced by different methods. The first group of CeO_2 nanoparticles was obtained by a pulsed electron beam evaporation in a low-pressure gas on a NANOBIM-2 installation. The details of nanomaterial synthesis correspond to paper [12]. The second group of CeO_2 nanoparticles was produced by chemical method according to paper [13] and coated with maltodextrin. We denote the first group as CeO_2 (P), the second group - CeO_2 (C).

We used the suspensions of nanoparticles for catalytic activity research. The nanoparticles were dispersed in distilled water in concentrations of 5 mg/ml. The sodium citrate was used as a suspension stabilizer for the first group of nanoparticles. The dispersion was thoroughly mixed and treated with ultrasound for 40 min.

The catalase-like activity of CeO_2 nanoparticles was studied by measuring the optical absorption of the suspensions before and after the addition of hydrogen peroxide (3%). The optical absorption spectra were recorded with a Helios Alpha spectrophotometer (λ=190-1000 nm) equipped with the Vision 32 software. The peroxidase activity of CeO_2 was determined using the TMB reagent (tetramethylbenzidine) by ELISA method.

3. RESULTS AND DISCUSSION

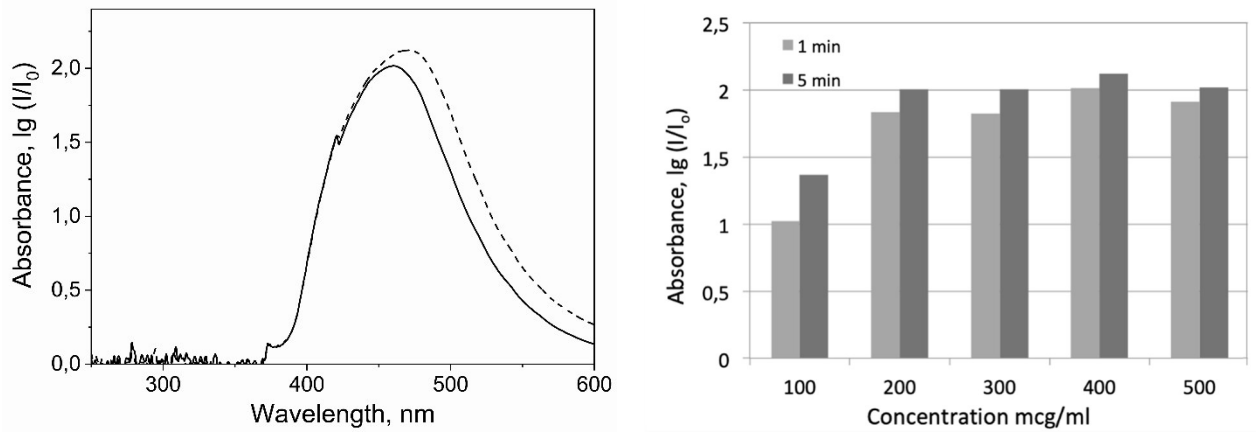
The catalase-like activity of CeO_2 nanoparticles was evaluated by the suspensions change in the optical absorption in the region of about 400-450 nm after the H_2O_2 addition (**Figure 1**). There is an expressed change in optical density for the CeO_2 nanoparticles produced by chemical method. At the same time, a similar effect is not observed for CeO_2 nanoparticles synthesized by a pulsed electron beam evaporation. A small decrease in the optical density of a CeO_2 (P) sample may be associated with effects of agglomeration and sedimentation.



(a) (b)

Figure 1 Change on optical absorption of CeO_2 nanoparticles during interaction with H_2O_2: the solid line - before H_2O_2 adding (pure), the dashed line - after H_2O_2 adding (in 1 min); the dash-dotted line - after H_2O_2 adding (in 5 min). a) CeO_2 (C), b) CeO_2 (P)

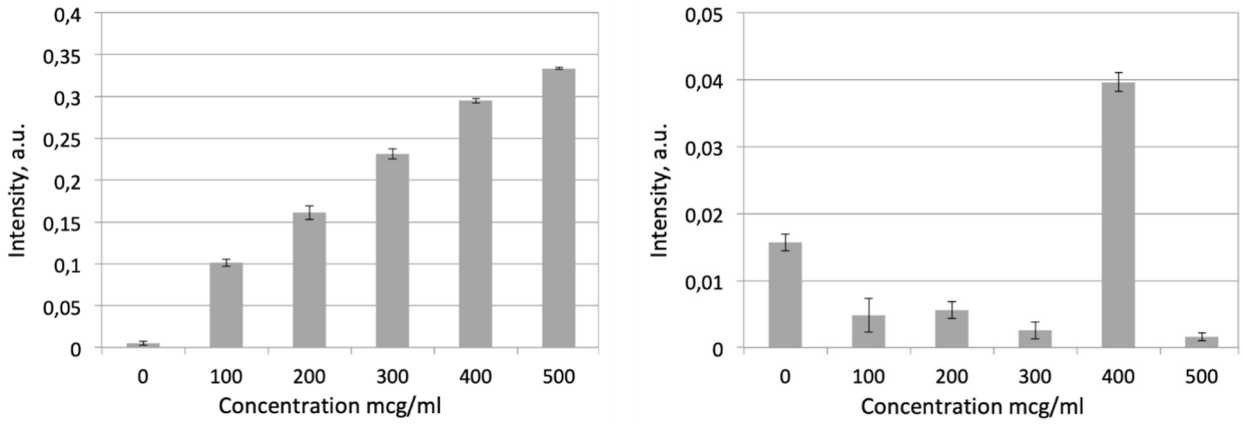
Figure 2a shows the CeO_2 (C) nanoparticles differential optical absorption spectra before and after adding H_2O_2 in 1 min and 5 min. Relative changes in the optical density of H_2O_2-containing samples were used for evaluation the catalase-like activity. The study results of the catalase-like activity dependence on concentration are presented in **Figure 2b**.



(a) (b)

Figure 2 a) Difference between optical absorption spectra of CeO_2 (C) nanoparticles before and after adding H_2O_2 in 1 min (the solid line) and 5 min (the dashed line); b) The relative change dependence in the optical density of CeO_2 (C) samples in the 450-500 nm region after the H_2O_2 addition to concentration

The results of study on the peroxidase activity are presented in **Figures 3-4**. **Figure 3** presents the study results of the CeO_2 effect on the tetramethylbenzidine (TMB) oxidation. The synergistic effect of CeO_2 nanoparticles and the enzyme horseradish peroxidase when interacting with TMB are shown in **Figure 4**.

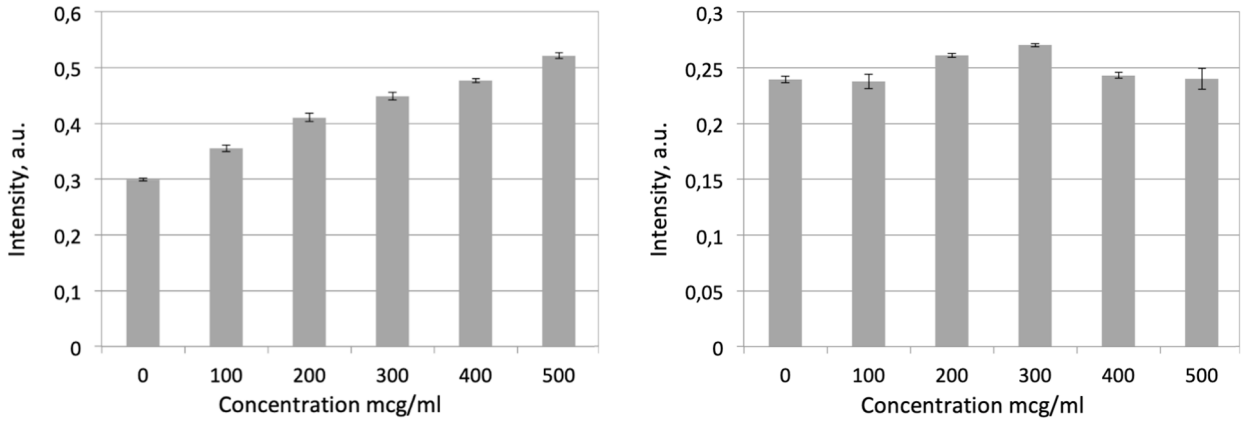


(a) (b)

Figure 3 Concentration dependence of the CeO_2 nanoparticles effect on the TMB oxidation: a) CeO_2 (C), b) CeO_2 (P)

The study's results of the CeO_2 nanoparticles catalytic activity show their catalase-like and peroxidase-like activity. The CeO_2 nanoparticles action mechanism as a catalase enzyme involves a two-step process: Ce^{4+} ion is first reduced by H_2O_2 to Ce^{3+} state, and a hydroperoxyl radical (HO•) is formed, then this radical is involved in the Ce^{4+} state in Ce^{3+} reduction. Common reaction products are Ce^{3+} ions, protons, water, and molecular oxygen [14]. Recent studies have shown the oxidation of Ce^{3+} into Ce^{4+}, induced by H_2O_2, leads to

the stable intermediate particles, such as peroxo- or hydroperoxoforms, associated with the nanoparticle surface [15]. The peroxidase-like activity mechanism also consists in the transformation of the hydrogen peroxide to water and molecular oxygen reduction [16].



(a) (b)

Figure 4 Concentration dependence of the CeO_2 nanoparticles and horseradish peroxidase synergistic effect on the TMB oxidation: a) CeO_2 (C), b) CeO_2 (P)

The observed enzyme-like activity is most appeared for the nanopowder obtained by the chemical method. This may be due to the fact the maltodextrin shell obstructs the natural CeO_2 oxidation processes and thus preserves the Ce^{3+} and Ce^{4+} ions presence on the particle surface. CeO_2 nanoparticles obtained by the gas-phase method have a rather high different valence cerium ions ratio [17]. However, strongly nonequilibrium evaporation conditions by an electron beam lead to a significant structural defects number, including on the nanoparticle surface [11]. The presence of structural defects leads to the formation of complex defects associated with Ce^{3+} ions and oxygen vacancies. This complicates the participation of Ce^{3+} ions in redox reactions and, probably, is a reason for the less expressed catalytic activity of these samples.

Note, the maltodextrin-coated CeO_2 nanoparticles exhibit catalytic activity that depends linearly on concentration. This is probably due to a sufficiently equable nanoparticles distribution in the sol. At the same time, the nanopowders obtained by the gas-phase method are characterized by the micrometer-sized elements presence as a synthesis result [12]. This can lead to a non-equitable nanoparticles' agglomeration distribution and a sol stability deterioration.

4. CONCLUSION

This paper presents a catalytic properties study of CeO_2 nanoparticles produced by a gas-phase method and chemical technique. Catalase-like and peroxidase-like activity of nanoparticles were detected. The most expressed catalytic activity is observed for nanoparticles obtained by a chemical method. Nanoparticles obtained by the gas-phase method are characterized by a non-equitable agglomerates distribution in size, and, accordingly, a lower sol stability. Probably, this may be the reason for the lower catalytic samples' activity obtained by this method. The CeO_2 nanoparticles and the horseradish peroxidase enzyme synergistic effect has been demonstrated. This allows to consider this object as a potential hydrogen peroxide biosensor in an enzyme-linked immunosorbent assay.

ACKNOWLEDGEMENTS

This work was supported by the Russian Science Foundation, project no. 18-72-00041. The authors are grateful to S.Y. Sokovnin and V.G. Ilves for CeO_2 nanoparticles, produced by gas-phase method, E.O. Baksheev and M.A. Mashkovtsev for CeO_2 nanoparticles, produced by chemical technique.

REFERENCES

[1] DAS S., DOWDING J. M., KLUMP K. E., MCGINNIS J. F., SELF W. and SEAL S. Cerium oxide nanoparticles: applications and prospects in nanomedicine. *Nanomedicine.* 2013. vol. 8, pp. 1483-1508.

[2] DHALL A. and SELF W. Cerium oxide nanoparticles: a brief review of their synthesis methods and biomedical applications. *Antioxidants* [on-line]. 2018. vol. 7., no. 8, pp. 97 [viewed 2019-10-01]. Available from: https://doi.org/10.3390/antiox7080097.

[3] RAJESHKUMAR S. and NAIK P. Synthesis and biomedical applications of Cerium oxide nanoparticles - A Review. *Biotechnology Reports*. 2018. vol. 17, pp. 1-5.

[4] GUAN Y., LI M., DONG K., GAO N., REN J., ZHENG Y. and QU X. Ceria/POMs hybrid nanoparticles as a mimicking metallopeptidase for treatment of neurotoxicity of amyloid-β peptide. *Biomaterials*. 2016. vol. 98, pp. 92-102.

[5] GAO W., WEI X., WANG X., CUI G., LIU Z. and TANG B. A competitive coordination-based CeO_2 nanowire-DNA nanosensor: fast and selective detection of hydrogen peroxide in living cells and *in vivo*. *Chemical Communications.* 2016. vol. 52, pp. 3643-3646.

[6] LIU B., HUANG Z. and LIU J. Boosting the oxidase mimicking activity of nanoceria by fluoride capping: rivaling protein enzymes and ultrasensitive F−detection. *Nanoscale*. 2016. vol. 8, pp. 13562-13567.

[7] TIAN Z., LI J., ZHANG Z., GAO W., ZHOU X. and QU Y. Highly sensitive and robust peroxidase-like activity of porous nanorods of ceria and their application for breast cancer detection. *Biomaterials.* 2015. vol. 59, pp. 116-124.

[8] LIU B., SUN Z., HUANG P.J. and LIU J. Hydrogen peroxide displacing DNA from nanoceria: mechanism and detection of glucose in serum. *Am. Chem. Soc.* 2015. vol. 137, pp. 1290-1295.

[9] ALPASLAN E., YAZICI H., GOLSHAN N. H., ZIEMER K. S. and WEBSTER T. J. pH-Dependent activity of dextran-coated cerium oxide nanoparticles on prohibiting osteosarcoma cell proliferation. *ACS Biomater. Sci. Eng*. 2015. Vol. 1, pp. 1096-1103.

[10] QI L., FRESNAIS J., MULLER P., THEODOLY O., BERRET J.-F. and CHAPEL J.-P. Interfacial activity of phosphonated-PEG functionalized cerium oxide nanoparticles. *Langmuir*. 2012. vol. 28. pp. 11448-11456.

[11] BAZHUKOVA I. N., SOKOVNIN S. Y., ILVES V. G., MYSHKINA A. V., VAZIROV R. A., PIZUROVA N. and KASYANOVA V. V. Luminescence and optical properties of cerium oxide nanoparticles. *Optical Materials*. 2019. vol. 92, pp. 136-142.

[12] ILVES V. G. and SOKOVNIN S. Y. Producing and researching the properties of nanopowders based on CeO_2 *Nanotechnologies in Russia*. 2012. vol. 7, pp. 213-226.

[13] SCHERBAKOV A. B., ZHOLOBAK N. M., IVANOV V. K., IVANOVA O. S., MARCHEVSKY A. V., BARANCHIKOV A. E., SPIVAK N. Y. and TRETYAKOV Y. D. Synthesis and antioxidant activity of biocompatible maltodextrin-stabilized aqueous sols of nanocrystalline ceria. *Russian Journal of Inorganic Chemistry*. 2012. vol. 57, no. 11, pp. 1411-1418.

[14] BALDIM V., BEDIOUI F., MIGNET N., MARGAILL I. and BERRET J.-F. The enzyme-like catalytic activity of cerium oxide nanoparticles and its dependency on Ce3+ surface area concentration. *Nanoscale*. 2018. vol. 10, pp. 6971-6980.

[15] DAMATOV D. and MAYER J. M. (Hydro)peroxide ligands on colloidal cerium oxide nanoparticles. *Chemical Communications.* 2016. vol. 52, pp. 10281-10284.

[16] JIAO X., SONG H. J., ZHAO H. H., BAI W., ZHANG L. C. and LV Y. Well-redispersed ceria nanoparticles: Promising peroxidase mimetics for H_2O_2 and glucose detection. *Anal. Methods*. 2012. vol. 4, pp. 3261-3267.

[17] VAZIROV R. A., SOKOVNIN S. Y., ILVES V. G., BAZHUKOVA I. N., PIZUROVA N. and KUZNETSOV M. V. Physicochemical characterization and antioxidant properties of cerium oxide nanoparticles. In *IOP Conf. Series: Journal of Physics: Conf. Series: 6th International Congress "Energy Fluxes and Radiation Effects*. Tomsk, 2018, pp. 032094.