

## SPECTRAL-KINETIC PROPERTIES AND ENERGY TRANSFER IN NANOPARTICLES OF $Y_{0.5-x}Ce_{0.5}Tb_xF_3$ SOLID SOLUTION

A. S. Nizamutdinov,\* E. I. Madirov, E. V. Lukinova, A. G. Kiyamov,  
D. D. Andreeva, M. S. Pudovkin, S. L. Korableva, and V. V. Semashko

UDC 620.3;548.0

*Crystalline nanoparticles of  $Y_{0.5-x}Ce_{0.5}Tb_xF_3$ , doped with various concentrations ( $x = 0, 0.005, 0.01, 0.05, 0.1, 0.15,$  and  $0.2$ ) of  $Tb^{3+}$  ions were synthesized by co-precipitation. The crystal structure and chemical composition of nanoparticles were studied using transmission electron microscopy, scanning electron microscopy, and X-ray diffractometry. The obtained nanoparticles of solid solutions had an elliptical shape with a size of 10–15 nm along the long axis and good crystallinity with the structure of a  $CeF_3$  crystal. The spectral-kinetic properties of the obtained nanoparticles, and the effect of the concentration of  $Tb^{3+}$  activator ions on the energy transfer from  $Ce^{3+}$  to  $Tb^{3+}$  ions were investigated. Energy transfer from  $Ce^{3+}$  to  $Tb^{3+}$  ions in nanocrystals of the  $Y_{0.5-x}Ce_{0.5}Tb_xF_3$  solid solutions occurs mainly through the dipole–dipole interaction. The results of evaluating the efficiency of energy transfer from  $Ce^{3+}$  to  $Tb^{3+}$  ions show its increase with increasing concentration of  $Tb^{3+}$  ions.*

**Keywords:** nanoparticle, rare-earth element, terbium, cerium.

**Introduction.** Photodynamic therapy (PDT) is a developing method for the treatment of cancer, which includes the selective activation of photosensitizer (PS) molecules that can generate reactive oxygen species (ROS) upon absorption of light. PDT has several advantages over conventional oncology treatments, such as radiation therapy or chemotherapy; for example, it does less harm to healthy organs. However, PDT can only be applied to surface cancers, since the visible dye spectrum is required to excite the dyes used in PDT. To overcome this limitation, in recent years, "hybrid" PDT methods have been actively investigated, which use the property of some compounds, for example, in the form of nanoparticles (NPs), to luminesce in response to excitation by ionizing radiation [1]. In [2], it was proposed to conjugate a NP-scintillator to a dye used in PDT. The idea is that the absorption spectrum of the photosensitizer should overlap with the emission spectrum of the NP-scintillator, effectively converting the energy of ionizing radiation into ROS generation. In this case, it is possible to make the dye generate ROS, as in PDT, using the NPs as a sensitizer to ionizing radiation [3, 4]. The generation of singlet oxygen by complexes of  $CeF_3$  NPs and benzoporphyrin (a VP preparation) upon excitation by gamma rays was demonstrated in [5]. The quantum yield of  $^1O_2$  generation is estimated at  $0.79 \pm 0.05$ , which indicates a high efficiency and promising approach.

In order to be suitable for use in PDT, materials must meet several requirements: NPs must be relatively small (tens of nanometers), have low toxicity, stable chemical composition, and high efficiency of energy conversion into the visible range when excited by ionizing radiation and luminescence spectrum localized in the wavelength range suitable for excitation of the PS. Fluoride materials are characterized by a relatively narrow phonon spectrum, which reduces the probability of nonradiative losses and meets most of the above requirements. In the case of activation by rare-earth metal ions, these materials can provide a large set of radiation wavelengths in the UV and visible spectral ranges [6–9]. Also, rare-earth elements are characterized by a large atomic number, which is necessary for a high quantum yield of scintillation. In addition, there is a significant list of formulations suitable for testing the hybrid PDT approach [2, 10]. The compound  $YF_3$  is an example of a metal fluoride that has already been used as a crystalline matrix for phosphors activated by rare-earth metal ions. Its low toxicity was previously proven [11].

\*To whom correspondence should be addressed.