

A high temperature approach to synthesize new optical and x-ray luminescent nanomaterials for biomedical applications

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Abstract: A high temperature reactor was developed to synthesize new scintillating nanoparticles that traditionally would sinter. Yttrium pyrosilicate nanoparticles were synthesized with optical properties suitable for x-ray biomedical applications. © 2021 The Author(s)

1.Introduction

The high energy, low tissue attenuation, and deep penetrating properties of x-rays are attractive properties in the biomedical field and ubiquitously seen in radiograph, positron emission tomography, and computed tomography.^[1] When these x-rays are coupled with scintillating nanoparticles new theranostic tools have been developed such as x-ray induced photodynamic therapy and x-ray optogenetics.^[2] The material's research focuses on synthesizing these nanoparticles with high light yield with controllable size, composition, and functionalities.^[3] Common particulates used for x-ray mediated theranostic are fluoride nanoparticles doped with rare earths and coated with silica.^[4] The limited sub-100 nm scintillators used in the biomedical field has ample room for improvements and creates new opportunity in material's research on scintillators.

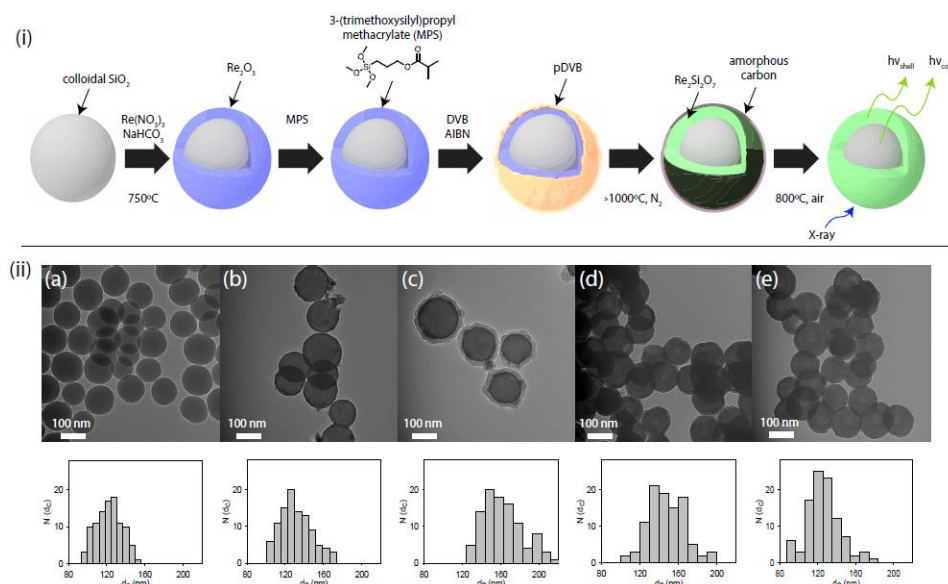


Figure 1i: Schematic of the high temperature multi-composite reactor. ii) Transmission electron images of a) silica b) silica core and Y₂O₃ shell, c) core-shell nanoparticles with a poly(divinyl)benzene overcoat, d) carbonized polymeric overcoat, and e) Y₂Si₂O₇ nanoparticles and their respective particle size distribution below.

Scintillators are a class of materials that can absorb high-energy radiation (e.g. x-rays and gamma rays) and emit a photon in the visible spectrum.^[5] The ideal scintillator has a high density, fast operating speed, and high light yield.^[6] When applied in the biomedical field, scintillators must also be non-hygroscopic and non-toxic.^[7] High density is one of the dominant trait that researchers in this material look at first due to its high stopping power and photo-fraction relationship ($\sim Z^4$).^[8] As such most scintillators are inorganic materials embedded with rare earth dopants such as Lu₂SiO₅:Ce (LSO:Ce).^[9] Rare earth silicate materials are a promising avenue in the x-ray theranostic

for their high density, light yield, and non-toxic properties; however LSO:Ce and its counterparts (i.e. $\text{Lu}_2\text{Si}_2\text{O}_7\text{:Ce}$ and $\text{Y}_2\text{Si}_2\text{O}_7\text{:Ce}$) are difficult to synthesize at the nanoscale due to its high recrystallization temperature ($>1000^\circ\text{C}$).^[9]

A high temperature multi-composite reactor (HTMcR) was developed to expand the available nanoscentillators for biomedical application.^[10] This technique uses a core-shell architecture to synthesize refractory materials at the nanoscale (**Figure 1i**). The core and inner shell are two inorganic oxide species while the outer shell is a highly dense polymer. When sufficient thermal energy is supplied, the inorganic species can recrystallize into a crystal lattice suitable for scintillation. Furthermore, the annealing process takes place in an inert environment that can carbonize the polymer outer shell into amorphous carbon. At this time the composite is composed of an amorphous carbon matrix embedded with inorganic core-shell particulates, where the amorphous carbon acts as a barrier for particle-particle contact while the core-shell nanoparticles reacts with itself. Afterwards the annealing temperature is reduce and air is introduced to remove the amorphous carbon while the nanoparticles have insufficient thermal energy to initiate the first stage of sintering. **Figure ii (a-e)** are transmission electron microscopy images of the different stages of the HTMcR using a silica core and a cerium doped yttrium oxide shell with a poly(divinyl)benzene overcoat. When annealed at 1100°C for 24 hours the particulates retain their spherical shape, monodispersity, and average size (125 nm). When doped with different rare earth ions (i.e. Tb^{3+} or Eu^{3+}) the optical and x-ray emission of these nanoparticles can span different regions of the visible spectrum (**Figure 2**).

2. Experimental

2.1 Materials.

Monodisperse silica-yttrium pyrosilicate particulates were synthesized using a high temperature multi-composite reactor described elsewhere using standard sol-gel, co-precipitation, and polymerization techniques.^[10] The particulates were annealed at 1100°C for 24 hours with nitrogen followed by combustion at 800°C for 1 hour with a constant flow of air. A Hitachi 7600 transmission electron microscopy was used to obtain the particle size, morphology, and its distribution.

2.2. X-ray luminescence characterization

X-ray luminescence was obtained using a oriel optical fiber bundle coupled to a Jobin Yvon MicroHR spectrometer with a Synapse CCD detector. X-rays were generated using a Amptek Mini-X at 40 kV and 99 μA equipped with tungsten target. Photoluminescence excitation and photoluminescence obtained by Jobin Yvon Fluorolog spectrometer.

3. Acknowledgments

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4. References:

- [1] Chen, X., Song, J., Chen, X., & Yang, H. *Chemical Society Reviews.*, 48(11), 3073-3101, 2019.
- [2] Wenpei, F., Tang, W., Lau, J., Shen, Z., Xie, J., Shi, J., and Chen. X., *Advanced Materials* 31(12), 1806381, 2019.
- [3] Hao, R., Xing, R., Xu, Z., Hou, Y., Gao, S. and Sun, S., *Advanced materials*, 22(25), 2729-2742, 2010.
- [4] Sun, W., Zhou, Z., Pratz, G., Chen, X. and Chen, H., *Theranostics*, 10(3), 1296, 2020.
- [5] Weber, M.J., *Journal of Luminescence*, 100(1-4), 35-45, 2002.
- [6] Derenzo, S.E., Weber, M.J., Bourret-Courchesne, E. and Klintenberg, M.K., *Nuclear Instruments and Methods in Physics Research Section A*, 505(1-2), 111-117, 2003.
- [7] Burdette, M.K., Bandera, Y.P., Zhang, E., Trofimov, A., Dickey, A., Foulger, I., Kolis, J.W., Cannon, K.E., Bartley, A.F., Dobrunz, L.E. and Bolding, M.S., *Langmuir*, 35(1), 171-182, 2018.
- [8] Gektin, A., and Korzhik, M., 2017. *Inorganic scintillators for detector systems*. Springer: Berlin, Germany.
- [9] Feng, H., Ding, D., Li, H., Lu, S., Pan, S., Chen, X. and Ren, G., *Journal of alloys and compounds*, 489(2), pp.645-649., 2010.
- [10] Zhang, E., Bandera, Y., Dickey, A., Foulger, I., Kolis, J.W. and Foulger, S.H., *Journal of Colloid and Interface Science*, 582, 1128-1135, 2021.

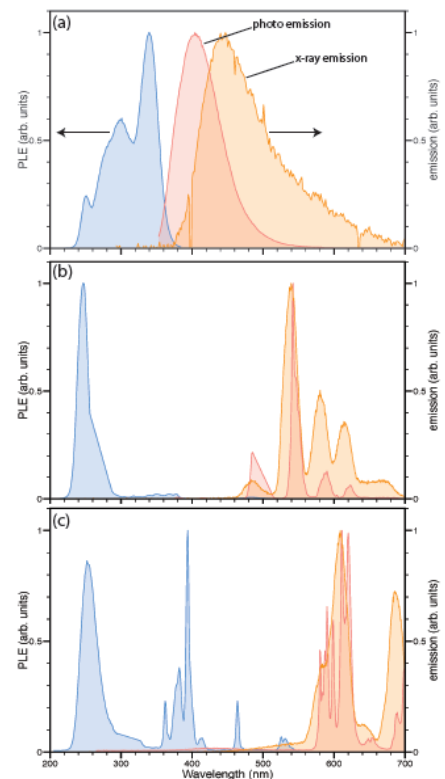


Figure 2: Photoluminescence excitation, photoluminescence, and x-ray luminescence of $\text{Y}_2\text{Si}_2\text{O}_7$ doped with a) cerium, b) terbium, and c) europium.