Electronic Supplementary Information (ESI)

One-pot Synthesis of Multifunctional Bi_2S_3 Nanoparticles and Construction of Core-shell Bi_2S_3@-Ce6-CeO_2 Nanocomposites for NIR-Triggered Phototherapy

Lingwan Zeng, Huan Zhao, Yuda Zhu, Suping Chen, Yusheng Zhang, Dan Wei, Jing Sun and Hongsong Fan*

National Engineering Research Center for Biomaterials, Sichuan University, Chengdu, 610064, China.

*Address correspondence to hsfan@scu.edu.cn.

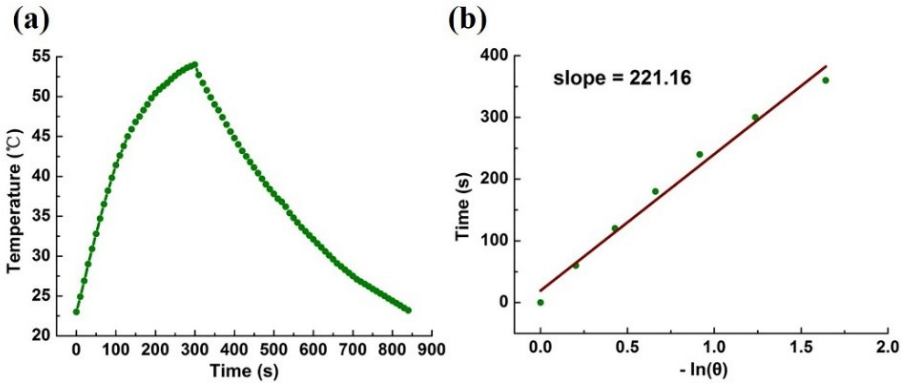

Figure S1. (a) Photothermal property of 1 mg mL^{-1} Bi_2S_3 NPs aqueous dispersion when irradiated with 808 nm laser (1.5 W cm^{-2}). The laser was turned off after irradiation for 5 min. (b) Plot of cooling time versus negative natural logarithm of the temperature driving force obtained from the cooling stage as shown in (a). The time constant for heat transfer of the system is determined to be τ_s = 221.16.

To evaluate the photothermal conversion efficiency of spheral Bi_2S_3 synthesized, the temperature change of 0.5 mL aqueous dispersion (1.0 mg mL^{-1}) was recorded for 5 min under continuous irradiation by the 808 nm laser with a power density of 1.5 W cm^{-2}, then the laser was shut off. The photothermal conversion efficiency, η, was calculated using Eq. (S1-4)

$$\eta = \frac{hS(T_{max,\ NPs} - T_{max,\ solvent})}{I(1 - 10^{-A808})} \qquad \text{(Eq.S1)}$$

where h is the heat transfer coefficient, S is the surface area of the container, $T_{max, NPs}$ and $T_{max, solvent}$ are maximum steady-state temperature for Bi_2S_3 NPs solution and water, which are 31 °C and 2.2 °C, respectively. I is the laser power ~ 1.5 W, and A_{808} is the absorbance of Bi_2S_3 NPs at 808 nm ~ 0.335. The value of hS is calculated by Eq S2:

$$\tau_s = \frac{m_D C_D}{hS} \quad \text{(Eq. S2)}$$

Where the mass of the nanoparticles solution (m_D) was 0.5 g, and its heat capacity (C_D) was approximated to be 4.2 J g^{-1} k^{-1} (the heat capacity of water). τ_s is the characteristic thermal time constant, which can be determined by applying the linear time data from the cooling period vs –lnθ (τ_s = 221.16, Figure S3).

$$t = -\tau_s \ln(\theta) \quad \text{(Eq. S3)}$$

$$\theta = \frac{T - T_{surr}}{T_{max, NPs} - T_{surr}} \quad \text{(Eq. S4)}$$

The photothermal conversion efficiency of Bi_2S_3 NPs was calculated according to Eq. S1:

$$\eta = \frac{\frac{0.5 \times 4.2}{221.16} \times (31 - 2.2)}{1.5 \times \left(1 - 10^{-0.335}\right)} \times 100\% = 33.91\%$$

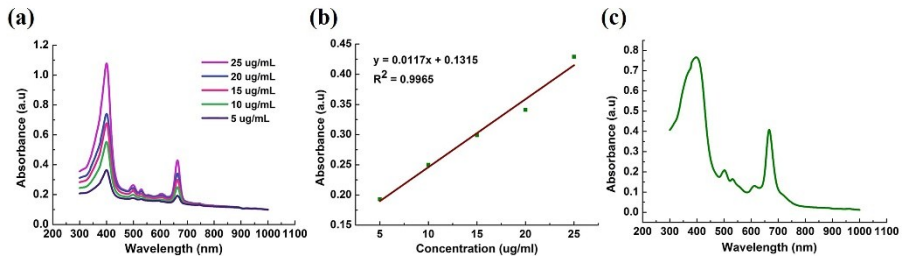

Figure S2. (a) The UV-visible absorption curve of Ce6 ethanol solution at different concentrations. (b) The UV-visible absorption standard curve of Ce6 obtained from the absorption peak at 664 nm as shown in (a). (c) The UV-visible absorption curve of 0.5 mL

supernatant.

Encapsulation rate of photosensitizer Ce6

The UV-visible absorption spectrum standard curve of Ce6 at 664 nm was obtained throughmeasuring the UV-visible absorption curve of Ce6 ethanol solution with different concentration:

$$y=0.0177x + 0.1315 \text{ (Figure S4b)}$$

There were 3.5 mg Ce6 totally added to the Bi_2S_3 NPs solution. The UV-visible absorption peak of 0.5 mL supernatant at 664 nm was measured ~0.408 (Figure S4c), thus the concentration of Ce6 in supernatant is calculated:

$$\frac{0.408 - 0.1315}{0.0177} = 15.6 .$$

There were 34 mL supernatant collected, thus the amount of Ce6 unencapsulated into Bi_2S_3 NPs was obtained: 15.6 μg × 34 = 1.06 mg.the encapsulation rate φ of Ce6 was calculated according to:

$$\varphi = \frac{Ce6_{total\ amount} - Ce6_{supernatant}}{Ce6_{total\ amount}} \times 100\% = \frac{3.5 - 1.06}{3.5} \times 100\% = 69.7\%$$

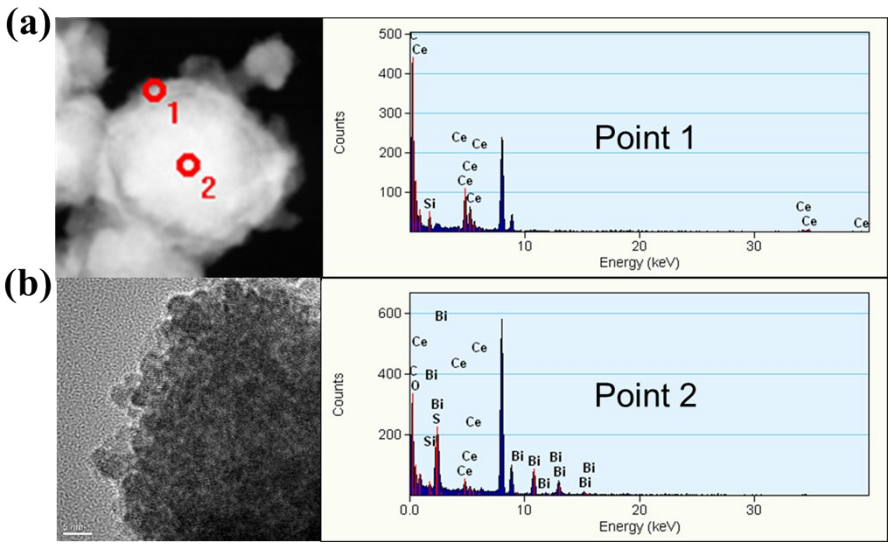

Figure S3. (a) the energy spectrum analysis of two points in Bi_2S_3@Ce6-CeO_2 NCs (b) the HRTEM image of Bi_2S_3@Ce6-CeO_2 NCs.

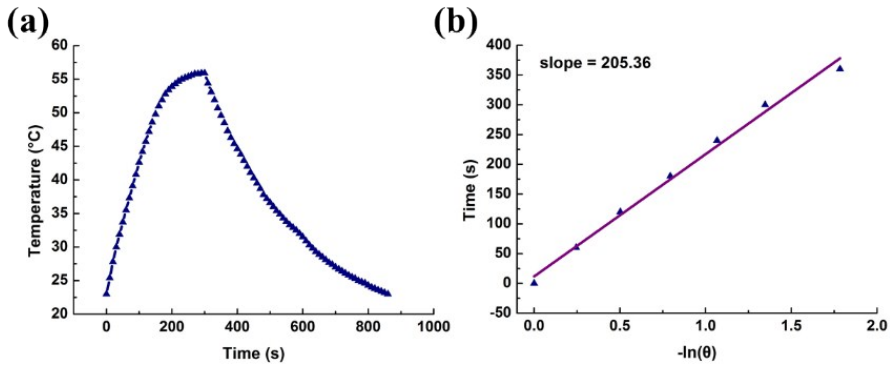

Figure S4. (a) Photothermal property of 1 mg mL^{-1} Bi_2S_3@-Ce6-CeO_2 NCs aqueous dispersion when irradiated with 808 nm laser (1.5 W cm^{-2}). The laser was turned off after irradiation for 5 min. (b) Plot of cooling time versus negative natural logarithm of the temperature driving force obtained from the cooling stage as shown in (a). The time constant for heat transfer of the system is determined to be τ_s = 205.36.

To evaluate the photothermal conversion efficiency of Bi_2S_3@-Ce6-CeO_2 NCs, the temperature change of 0.5 mL aqueous dispersion was recorded for 5 min under continuous irradiation by the 808 nm laser with a power density of 1.5 W cm^{-2}, then the laser was shut off. The photothermal conversion efficiency, η, was calculated using Eq. (S1-4)

$$\eta = \frac{hS(T_{max,\ NPs} - T_{max,\ solvent})}{I(1 - 10^{-A808})} \quad \text{(Eq. S1)}$$

where h is the heat transfer coefficient, S is the surface area of the container, $T_{max,\ NPs}$ and $T_{max,\ solvent}$ are maximum steady-state temperature for Bi_2S_3@-Ce6-CeO_2 NCs solution and water, which are 32.9 °C and 2.2 °C, respectively. I is the laser power ~ 1.5 W, and A_{808} is the absorbance of Bi_2S_3@-Ce6-CeO_2 NCs at 808 nm ~ 0.597. The value of hS is calculated by Eq2:

$$\tau_s = \frac{m_D C_D}{hS} \quad \text{(Eq. S2)}$$

Where the mass of the nanoparticles solution (mD) was 0.5 g, and its heat capacity(C_D) was approximated to be 4.2 J g^{-1} k^{-1} (the heat capacity of water). τ_s is the characteristic thermal time constant, which can be determined by applying the linear time data from the cooling period vs –lnθ (τ_s = 205.36).

$$t = -\tau_s \ln(\theta) \quad \text{(Eq. S3)}$$

$$\theta = \frac{T - T_{surr}}{T_{max,NPs} - T_{surr}} \quad \text{(Eq. S4)}$$

The photothermal conversion efficiency of Bi_2S_3@-Ce6-CeO_2 NCs was calculated according to Eq. 1:

$$\eta = \frac{\frac{0.5 \times 4.2}{205.36} \times (33.9 - 2.2)}{1.5 \times \left(1 - 10^{-0.597}\right)} \times 100\% = 28.01\%$$

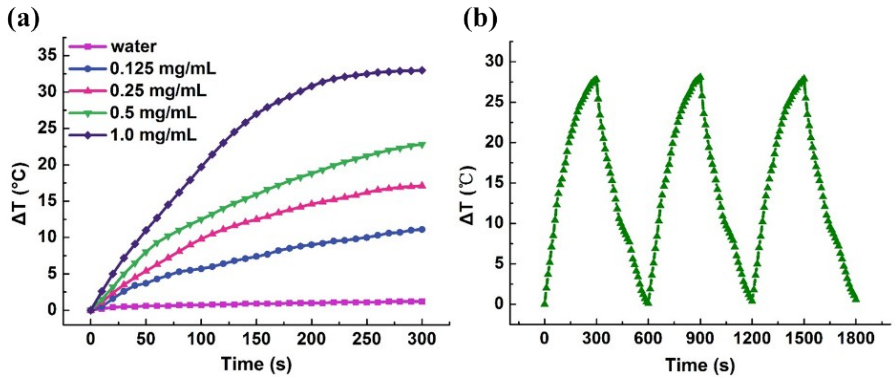

Figure S5. ΔT curves of (a) Bi_2S_3@Ce6-CeO_2 NCs aqueous solution of various concentrations after 5 min irradiation of 808 nm NIR laser (1.5 W cm^{-2}). (b) Bi_2S_3@Ce6-CeO_2 NCs aqueous solution with 808 nm NIR laser irradiating and then self-cooling for 3 cycles.

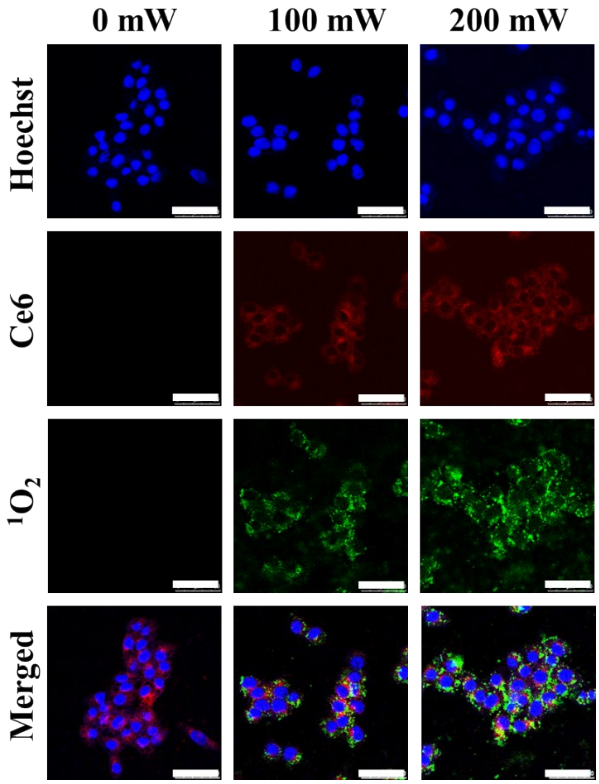

Figure S6. the production of $^1O_2$ in 4T1 cells after incubation with Bi_2S_3@Ce6-CeO_2 NCs at 200 μg mL^{-1} and then get a 660 nm laser's illumination of different light power (0, 110, 200

mW) for two minutes. Scale bar: 100 μm

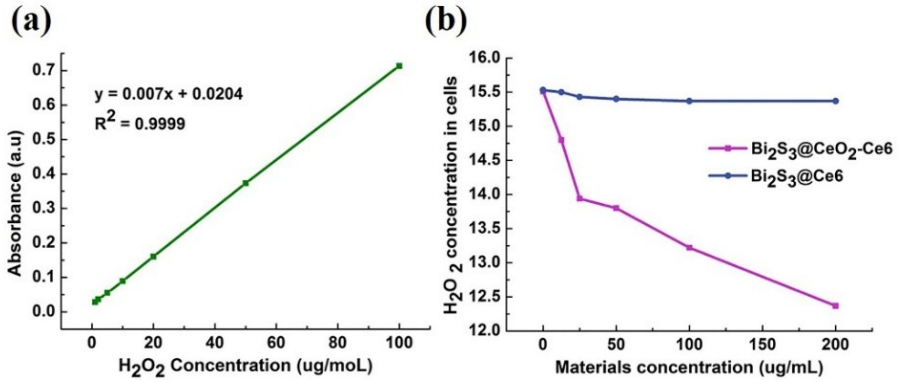

Figure S7. (a) Standard curve of H_2O_2 concentration measured by H_2O_2 standard kit H_2O_2 consumption. (b) Curve of H_2O_2 concentration in 4T1 cells after incubating with a series of different concentrations of Bi_2S_3@Ce6-CeO_2 and Bi_2S_3@-Ce6 (0, 12.5, 25, 50, 100 and 200 μg mL^{-1}) by H_2O_2 detection kit.

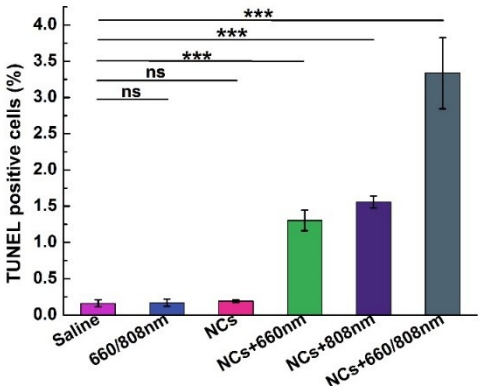

Figure S8. The percentage of TUNEL positive cancer cells after getting saline, 660/808 nm, NCs, NCs + 660 nm, NCs + 808 nm and NCs + 660/808 nm treatment, respectively (ns means no statistical difference compared with the control group. *$p<0.05$, **$p<0.01$ and ***$p<0.001$ compared with the control group).

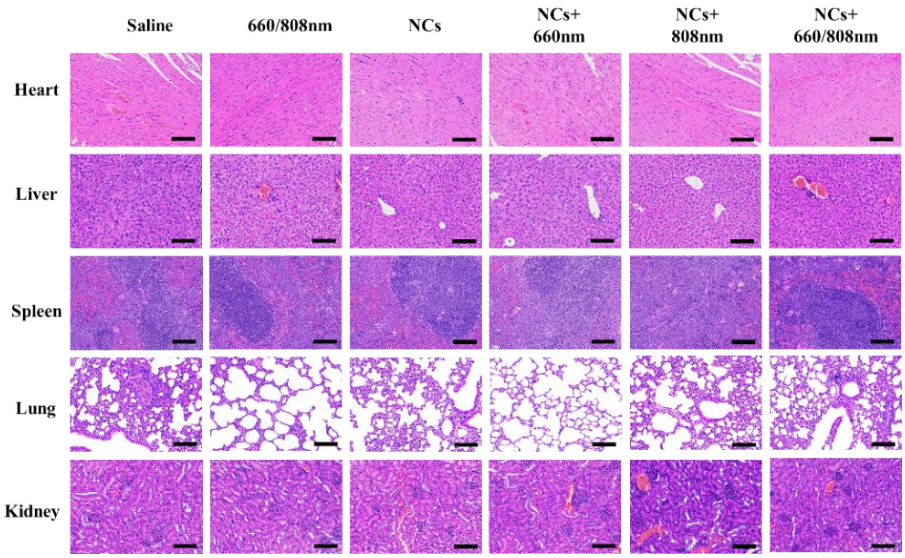

Figure S9. Representative H&E staining of heart, liver, spleen, lung, and kidney from saline, 660/808 nm, NCs, NCs + 660 nm, NCs + 808 nm and NCs + 660/808 nm treated rats. The percentage of TUNEL positive cancer cells after various treatments. Scale bar: 100 μm.