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Ultra small gold nanoclusters supported on two-dimensional bismuth selenium nanosheets for synergistic photothermal and photodynamic tumor therapy†

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Two-dimensional (2D) bismuth selenium (Bi₂Se₃) nanosheets have exceptional surface area and superior surface modification capabilities, facilitating the effective loading of nanoprobcs, metal particles, and other substances. Additionally, thiolated ultrasmall gold nanoclusters (Au NCs), distinguished by their high photoluminescent activity and modulatable surface charges, enable efficient loading onto the 2D Bi₂Se₃ surfaces. In this study, we successfully prepared Bi₂Se₃ nanosheets by sonication-assisted liquid phase exfoliation and loaded Au clusters on their surface through an amide bond reaction. The loading of Au NCs significantly augments the photothermal and photocatalytic capabilities of Bi₂Se₃ nanosheets and exhibits obvious anti-cancer therapeutic effects through *in vitro* and *in vivo* experiments. In summary, the as-prepared AuNC@Bi₂Se₃ nanocomposites showed combined near-infrared light-initiated photothermal/photodynamic therapy (PTT/PDT) against tumors, demonstrating their potential as novel theranostic agents for biomedical applications.

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1. Introduction

Cancer poses a significant threat to human health, due to its high incidence and mortality rates. Traditional therapeutic modalities, such as radiation and chemotherapy, frequently result in adverse body damage and undesirable side effects.^{1,2} In recent years, a growing body of research has focused on light-triggered therapeutic strategies against cancer based on nanomaterials.^{3–5} Near-infrared (NIR) light-triggered therapeutic strategies, including photothermal therapy (PTT) and photodynamic therapy (PDT), can destroy tumor cells through local high temperature or *in situ* generation of reactive oxygen species (ROS).^{6–8} These methods are particularly appealing due to their minimal systemic toxicity, non-invasive nature, and high selectivity towards cancer cells. PTT refers to the process where photothermal agents (PTAs) concentrated at the tumor site generate local high temperatures under the irradiation of

an NIR laser, effectively targeting and eliminating tumor cells.^{9–11} Hence, the efficacy of PTT hinges on the photothermal conversion efficiency (PTCE) of the PTAs.¹² PDT entails the generation of cytotoxic reactive oxygen species (ROS), including hydroxyl radicals ([•]OH), singlet oxygen (¹O₂), and superoxide radicals ([•]O₂[−]), by irradiating photosensitizers (PSs) located in tumor tissues with an NIR laser.^{13,14} A substantial accumulation of cytotoxic ROS in tumor regions can initiate intracellular mitochondrial apoptosis or stimulate immune responses, ultimately destroying tumor cells.^{15–17} The synergistic treatment of PTT and PDT can improve the therapeutic effect and maximize the anti-tumor effect of nanomaterials without increasing drug toxicity to surrounding normal tissues, which is conducive to the healthy recovery of patients.

Recently, noble metal nanoparticles (NMNPs) have garnered significant attention in the field of biomedicine. Under the influence of laser irradiation, NMNPs can facilitate temperature increase predominantly *via* the localized surface plasmon resonance (LSPR) mechanism. LSPR refers to the phenomenon of collective oscillations of free electrons on the surface of metallic particles or nanostructures upon light excitation. This phenomenon can lead to thermal dissipation through radiative processes, resulting in localized heating and electromagnetic field amplification proximate to the particles. Alternatively, it may generate hot carriers, such as electrons and holes, through non-radiative mechanisms. These characteristics offer the potential for augmenting the photothermal responsiveness and

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photocatalytic efficiency of nanomaterials. For instance, Yuan *et al.* used the sodium hydroxide-mediated reduction of sodium borohydride to successfully synthesize glutathione-protected Au nanoclusters (NCs) with excellent catalytic effects.¹⁸ These Au NCs are suitable for heterogeneous catalysis due to their relatively large surface area and abundant active centers. However, the stability of NMNPs is a critical issue, as they are unstable under laser irradiation due to their high surface energy, which can lead to a decrease or disappearance of the photocatalytic effect.^{19–22} Two-dimensional (2D) nanomaterials with superior physicochemical characteristics have emerged as the optimal choice for maintaining the stability of these cluster vectors.²³ And when certain NMNPs are loaded onto the surface of 2D nanomaterials, they can achieve enhanced photothermal and photocatalytic abilities.^{24–26} As an illustration, the extensive surface area of the 2D bismuth selenium (Bi_2Se_3) nanosheets can offer ample space for NMNPs loading. It has been demonstrated that selenium is an essential trace element in the human body and Bi_2Se_3 nanosheets can release a certain amount of selenium in the physiological environment, which can effectively prevent the incidence of cancer, inflammation, and cardiovascular diseases.^{27,28} What's more, Bi_2Se_3 nanosheets have shown promise as superior photothermal conversion agents according to their light absorption coefficient and they can generate plenty of ROS under light irradiation due to their narrow band gap.^{29,30} In 2017, Song *et al.* used ultra-thin Bi_2Se_3 nanosheets for targeted cancer therapy, achieving promising therapeutic effects.³¹

In this study, we construct rationally designed 2D $\text{AuNC@Bi}_2\text{Se}_3$ nanocomposites for effective photothermal-photodynamic synthetic tumor therapy (Fig. 1). Bi_2Se_3 nanosheets were modified with chitosan (CS) to improve stability. Then, Au NCs were covalently bound to CS-stabilized Bi_2Se_3 nanosheets through amido bond, enhancing their photothermal and photodynamic efficiency. Under 808 nm NIR laser irradiation, $\text{AuNC@Bi}_2\text{Se}_3$ nanocomposites can exhibit good photothermal efficacy and catalyze the excess hydrogen peroxide (H_2O_2) in the tumor microenvironment (TME) for the production of $\cdot\text{O}_2^-$ to trigger PDT. *In vitro* and *in vivo* antitumor experiments performed under laser irradiation showed superior tumor-suppressing effects. This study develops a new nano-platform tailored for PDT/PTT synergistic cancer therapy.

2. Materials and methods

2.1 Materials

Powder of Bi_2Se_3 was purchased from Beijing Yan Nuo Xin Cheng Technology Company. CS, NaOH, and MPA were obtained from Maclin Company. All other solvents and chemicals were acquired from Sinopharm Chemical Reagent Co., Ltd. All the items used for cell culture were purchased from Thermo Fisher Scientific Corporation.

2.2 Synthesis of 2D Bi_2Se_3

Firstly, chitosan powder (0.8 mg ml^{-1}) was dissolved in a 5% acetic acid liquor to prepare a chitosan solution. Bi_2Se_3 powder

(10 mg ml^{-1}) was then dissolved in the chitosan solution and exfoliated using sonication in $4 \text{ }^\circ\text{C}$ ice water for two hours. Following this, the supernatant was collected by centrifugation at 1500 rpm for 30 minutes. This process was repeated approximately six times to obtain more Bi_2Se_3 nanosheets supernatant. Finally, the ultrathin CS-modified Bi_2Se_3 nanosheets ($\text{Bi}_2\text{Se}_3@\text{CS}$) were obtained from the precipitate by centrifugation at 12 000 rpm for 20 minutes.

2.3 Synthesis of $\text{AuNC@Bi}_2\text{Se}_3$ nanocomposite

Au NCs were synthesized as reported.²¹ These clusters were then added to the Bi_2Se_3 nanosheets solution and stirred with NHS and EDC for 12 h. Following this, the pure $\text{AuNC@Bi}_2\text{Se}_3$ nanocomposites were acquired by dialysis for 24 h.

2.4 Characterizations of $\text{AuNC@Bi}_2\text{Se}_3$

The TEM (Thermo Fisher) was utilized to verify the morphology and structure of $\text{AuNC@Bi}_2\text{Se}_3$. Particle size analysis and zeta potential of the nanocomplex were characterized using a Linessizer 500 (Anton Paar GmbH). Additionally, (X-ray photoelectron spectroscopy) XPS was employed to verify the structure and chemical characteristics.

2.5 Photothermal effects

For the measurement of photothermal performance, UV-vis spectroscopy (Thermo Fisher) was used to verify the absorption ability of $\text{AuNC@Bi}_2\text{Se}_3$ nanocomposites with varying concentrations (0 ppm, 3.125 ppm, 6.25 ppm, 12.5 ppm, 25 ppm, 50 ppm). $\text{AuNC@Bi}_2\text{Se}_3$ nanocomposites (25 ppm) were irradiated under NIR laser with different power densities (0.5, 0.75, 1.0, 1.25, and 1.5 W cm^{-2} , 6 min). Additionally, $\text{AuNC@Bi}_2\text{Se}_3$ nanocomposites with various concentrations (0 ppm, 3.125 ppm, 6.25 ppm, 12.5 ppm, 25 ppm, 50 ppm) were irradiated by NIR laser (808 nm, 1 W cm^{-2}). What's more, the $\text{AuNC@Bi}_2\text{Se}_3$ aqueous solution (25 ppm) was irradiated by NIR laser (808 nm, 1 W cm^{-2}) until reaching its maximum temperature, then naturally decreased to room temperature to measure its photothermal stability. This cycle was repeated three times, and an infrared thermal camera (FLIR) was used to record these temperature changes. The PTCE (η) of the $\text{AuNC@Bi}_2\text{Se}_3$ nanocomposites was calculated based on these temperature changes.

2.6 Detection of superoxide radicals ($\cdot\text{O}_2^-$)

Electron spin resonance (ESR) was employed to confirm the production of $\cdot\text{O}_2^-$. The dihydrorhodamine 123 (DHR123) assay can detect the production of $\cdot\text{O}_2^-$ through a colorimetric reaction and the fluorescence generated in this reaction can be excited at 530 nm.^{14,32} The DHR123 simulating solution comprised 100 ppm DHR, 100 ppm H_2O_2 , and 10 ppm $\text{AuNC@Bi}_2\text{Se}_3$. These mixed solutions were irradiated under 808 nm laser, with a power density of 1 W cm^{-2} , for 5 minutes. The optical density was observed using a multimode microplate reader.



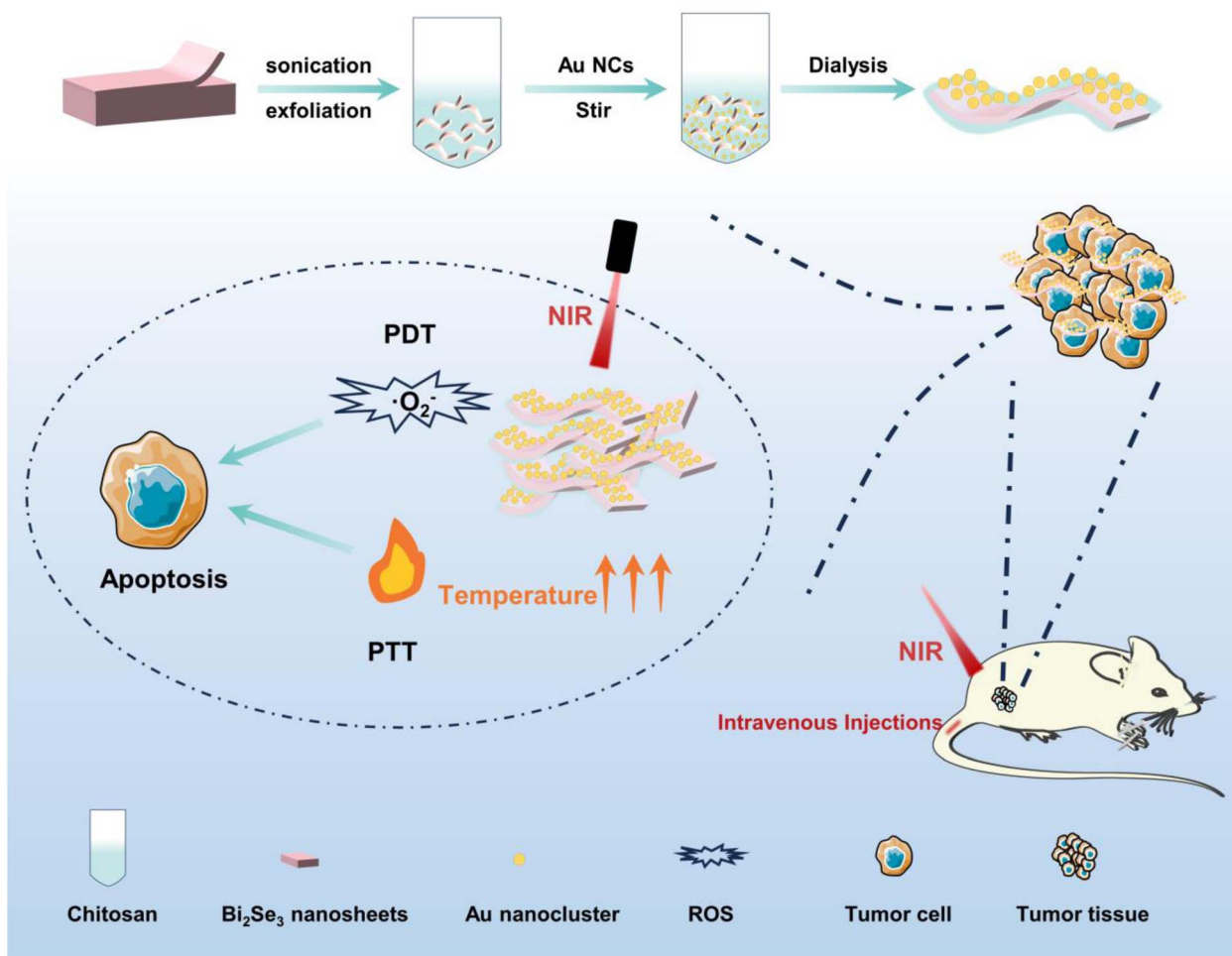


Fig. 1 Illustration of the synthesis of AuNC@Bi₂Se₃ nanocomposites and its synthetic photothermal/photodynamic therapy (PTT/PDT) in tumor microenvironment (TME).

2.7 Cytotoxicity experiment

4T1 cells were seeded in a 96-well plate for 12 h with 1×10^4 cells per well and then incubated with varying concentrations of Bi₂Se₃ and AuNC@Bi₂Se₃ (0 ppm, 5 ppm, 10 ppm, 15 ppm, 20 ppm, 25 ppm), respectively. After a 4 h incubation, NIR laser irradiation (808 nm, 1 W cm^{-2}) was conducted for 5 minutes, followed by treatment with CCK8 solution for 2 h the next day.³³ The results at 450 nm were then observed using a multifunctional microplate reader.

2.8 In vitro ROS detection

To detect the generation of ROS *in vitro*, 4T1 cells treated with four different groups (PBS, PBS + laser, AuNC@Bi₂Se₃, AuNC@Bi₂Se₃ + laser) were stained with 2',7'-dichlorodihydrofluorescein diacetate (DCFH-DA) and DHE (AuNC@Bi₂Se₃ concentration: 12.5 ppm; laser: 808 nm, 1 W cm^{-2} , 5 min), respectively. After 30 minutes of incubation, DCFH-DA formed a green fluorescent substance (DCF), and DHE exhibited red fluorescence. The intracellular fluorescence was captured by an Echo Hybrid Microscope.

2.9 AM/PI

4T1 cells were seeded in a 12-well plate at 1×10^5 cells per well and incubated for 12 h. After 4 h incubation with various groups (PBS, PBS + laser, Bi₂Se₃, Bi₂Se₃ + laser, AuNC@Bi₂Se₃, AuNC@Bi₂Se₃ + laser), the cells were irradiated with an 808 nm laser (1 W cm^{-2}) for 5 min. Subsequently, calcein AM and propidium iodide (AM/PI) were added to form different fluorescent substances in living and dead cells after 30 minutes of incubation. The intracellular fluorescence of the stained cells was observed using an Echo Hybrid Microscope.

2.10 Apoptosis analysis

4T1 cells were seeded in a 6-well plate at a density of 1.5×10^5 cells per well, and incubated for 12 h. Following 4 h incubation of different groups, including PBS, PBS + laser, Bi₂Se₃, Bi₂Se₃ + laser, AuNC@Bi₂Se₃, and AuNC@Bi₂Se₃ + laser, 4T1 cells were irradiated by an 808 nm laser (1 W cm^{-2}) for 5 minutes. Subsequently, in 4 h incubation, the cells were stained with annexin V-fluorescein isothiocyanate/propidium iodide (annexin V-FITC/PI). The rate of cell apoptosis was quantified by flow cytometry analysis.



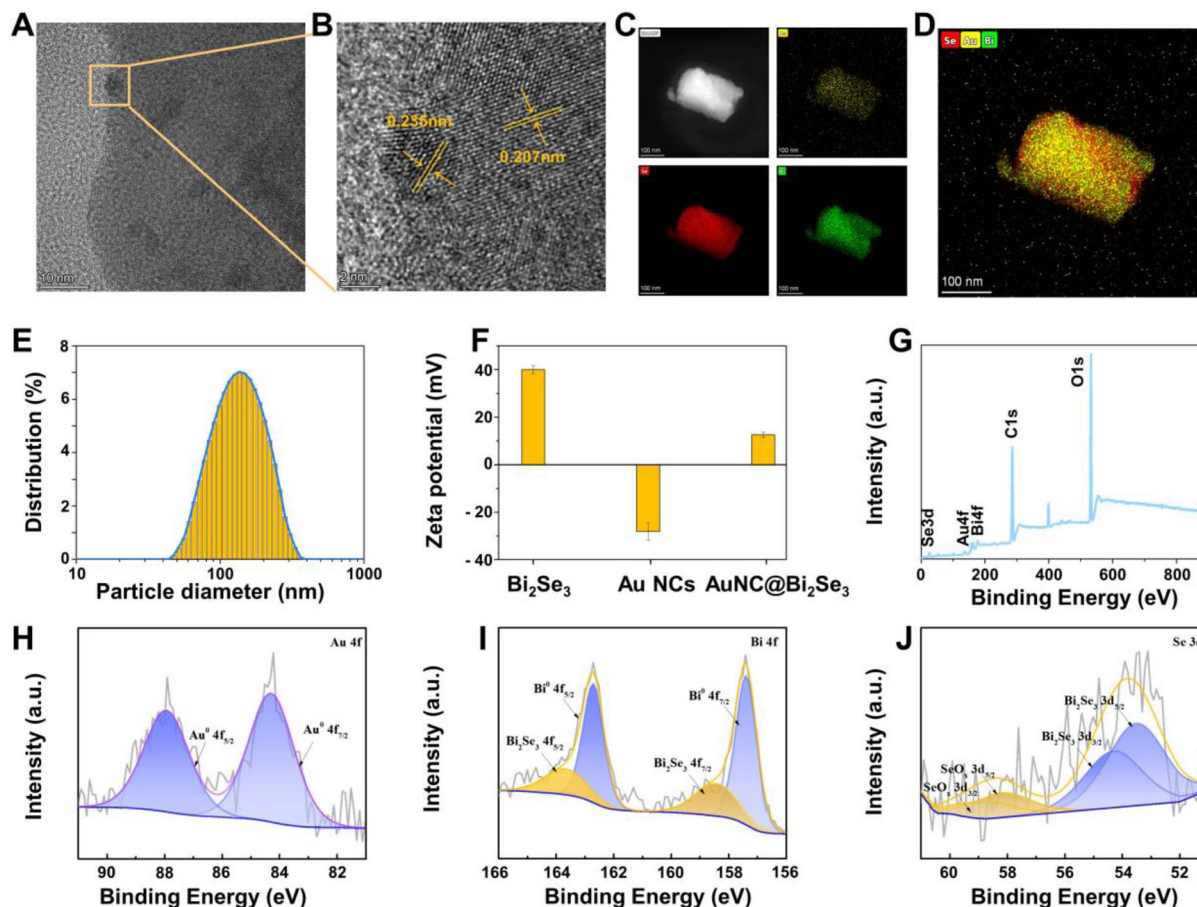


Fig. 2 (A) Representative TEM image of AuNC@Bi₂Se₃. (B) HRTEM image of AuNC@Bi₂Se₃. (C and D) HAADF-STEM image of AuNC@Bi₂Se₃ nanocomposites and its corresponding elemental mapping. (E) DLS measurement of AuNC@Bi₂Se₃. (F) Zeta potential changes of Bi₂Se₃, AuNC and AuNC@Bi₂Se₃. (G) XPS spectrum of AuNC@Bi₂Se₃. (H–J) High-resolution XPS spectrum of Au 4f, Bi 4f and Se 3d electrons.

2.11 *In vivo* therapeutic

1×10^6 4T1 cells (100 μ l) suspension was subcutaneously implanted into the right hind limb of BALB/c mice to establish a 4T1 tumor-bearing model. The 4T1 mice models were randomly divided into four groups: PBS, PBS + laser, AuNC@Bi₂Se₃ and AuNC@Bi₂Se₃ + laser ($n = 5$ per group) after 7 days. These mice were then intravenously injected with corresponding solutions (3 mg kg⁻¹) when the tumors had grown to an average volume of approximately 100 mm³. After 8 h post-injection, PBS + laser and AuNC@Bi₂Se₃ + laser groups received NIR irradiation (808 nm, 1 W cm⁻², 10 min). The body weight and tumor volume of the mice were recorded during the treatment process, with the tumor volume calculated as (length \times width²)/2. The mice were euthanized after 18 days of treatment, and their main organs, blood, and tumor tissues were collected for more analysis. The animal study protocol was approved by the Animal Ethics Committee at The Second People's Hospital of Shenzhen (protocol code 20240099). All experimental procedures were conducted by institutional guidelines for the care and use of laboratory animals and protocols, which were approved by the Animal Care and Use Committee of Shenzhen

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2.12 Biosafety

The main organs, including the heart, liver, spleen, lung, and kidney, were used for the preparation of biosafety detection. Hematoxylin/eosin (H&E) staining was performed for the histological examination of these organs following treatment with AuNC@Bi₂Se₃. The collected whole blood was analyzed for levels of alanine aminotransferase (ALT), aspartate aminotransferase (AST), blood urea nitrogen (BUN), total protein (TP), albumin (ALB), alkaline phosphatase (ALP), creatinine (CREA), and total bilirubin (TBIL) using an Automatic Biochemical Analyzer.

3. Results and discussions

3.1 Synthesis and characterizations

The fabrication of AuNC@Bi₂Se₃ is illustrated in Fig. 1. Briefly, Bi₂Se₃ nanosheets were prepared *via* the sonication-assisted liquid exfoliation process. AuNC@Bi₂Se₃ nanocomposites were synthesized by stirring the Au NCs aqueous solution with



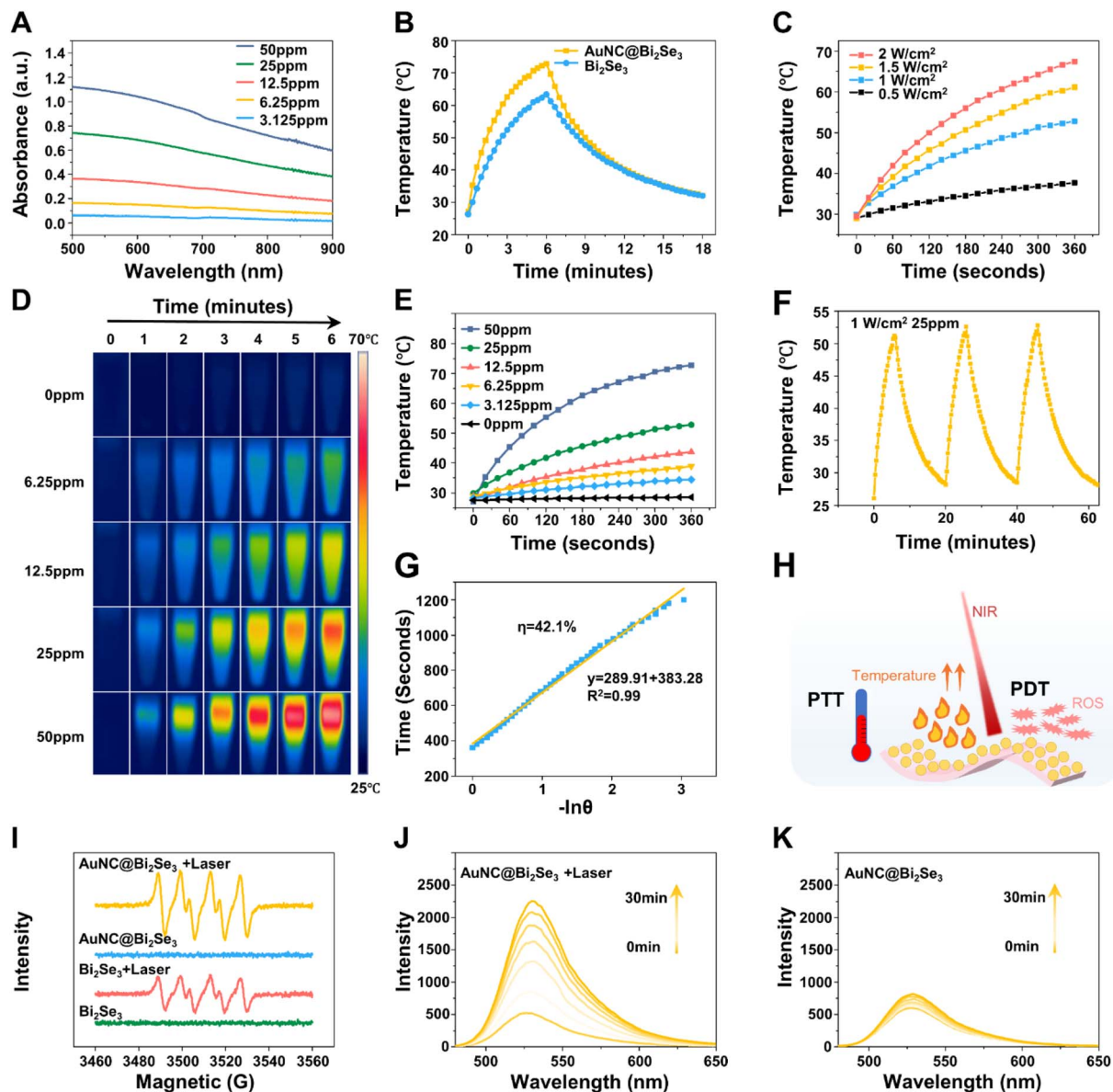


Fig. 3 (A) Absorbance spectra of AuNC@Bi₂Se₃ nanocomposites in different concentrations. (B) The photothermal heating curve of AuNC@Bi₂Se₃ and Bi₂Se₃ dispersions at 50 ppm. (C) The temperature curves of AuNC@Bi₂Se₃ at various power densities. (D) Thermal images of AuNC@Bi₂Se₃ solutions in different concentrations (0 ppm, 6.25 ppm, 12.5 ppm, 25 ppm, 50 ppm) under the irradiation of 808 nm laser (1 W cm⁻²). (E) The temperature curves of AuNC@Bi₂Se₃ at various concentrations. (F) Temperature curve of AuNC@Bi₂Se₃ nanocomposites for three on/off cycles under 808 nm laser irradiation. (G) The calculation of PTCE. (H) Schematic representation of the anti-cancer mechanism involving AuNC@Bi₂Se₃ nanocomposites. (I) Electron spin resonance (ESR) spectra of four different groups to detect the production of [•]O₂⁻ production. (J and K) [•]O₂⁻ production of AuNC@Bi₂Se₃ with and without laser irradiation, respectively.

Bi₂Se₃ nanosheets at room temperature. Transmission electron microscopy (TEM) images indicated the morphology of AuNC@Bi₂Se₃ nanocomposites across different batches and showed their sheet-like structure (Fig. 2A and S1†). We can see in Fig. 2A that numerous AuNCs are uniformly distributed across the Bi₂Se₃ nanosheets' surface. What's more, the atomic force microscopy (AFM) images proved that the thickness of AuNC@Bi₂Se₃ nanocomposites was 6.59 nm which confirmed their 2D structure (Fig. S2†). High-resolution transmission electron microscopy (HRTEM) imaging and XRD patterns revealed that the hexagonal lattice fringes of the nanosheets

have a distance of 0.207 nm, aligning with the (110) plane of the Bi₂Se₃ nanosheets crystal structure (Fig. 2B and S3†).³⁴ Additionally, we can see in Fig. 2B that the lattice fringe of the Au clusters was 0.235 nm, corresponding to the (111) plane of its face-centered cubic. The energy dispersive X-ray spectroscopy (EDX) analysis demonstrated that "Se", "Au" and "Bi" signals were detected in the AuNC@Bi₂Se₃ nanocomposites; whereas the copper peaks originated from the TEM grid. The metal ions distributed in single particles are 65.54, 0.34 and 34.13 weight percent of "Se", "Au" and "Bi", respectively, as seen in the inset of Fig. S3.† The elemental ratio in AuNC@Bi₂Se₃



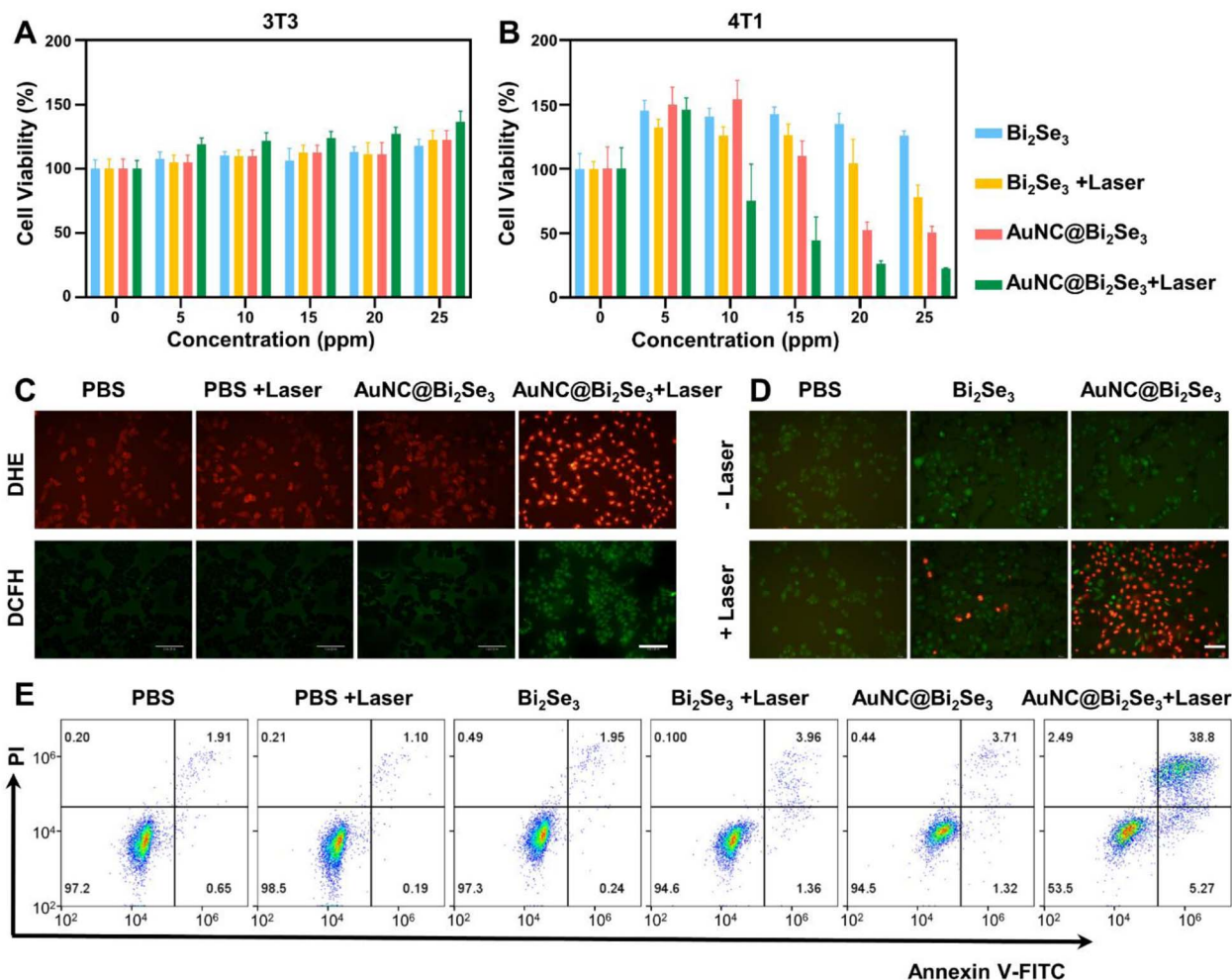


Fig. 4 (A) Cell viability of 3T3 cells and (B) 4T1 cells after incubation with various concentrations of AuNC@Bi₂Se₃ and Bi₂Se₃ nanocomposites. (C) 4T1 cells stained by DCFH and DHE in different groups (12.5 ppm), scale bar = 130 μ m. (D) Calcein AM and propidium iodide (AM/PI) fluorescence images of 4T1 cells with different treatments (12.5 ppm), scale bar = 200 μ m. (E) Flow cytometry of 4T1 cells induced in various treatments with annexin V-FITC/PI staining.

nanocomposites reveals the absence of Au peaks in the XRD spectrum. The high-angle annular dark-field scanning transmission electron microscopy (HAADF-STEM) image of AuNC@Bi₂Se₃ nanocomposites and their corresponding elemental mapping revealed the elemental composition of Au, Bi, and Se (Fig. 2C). The signals of Au elemental were captured in the outer layer, while Bi and Se elements were detected within, suggesting that Au clusters were distributed uniformly across the surface of the Bi₂Se₃ nanosheets (Fig. 2D). The images above suggested the successful synthesis of 2D AuNC@Bi₂Se₃ nanocomposites following the stirring process. The size of AuNC@Bi₂Se₃ nanocomposites and Bi₂Se₃ nanosheets was measured using dynamic light scattering (DLS). The average size of Bi₂Se₃ nanosheets was 171 nm (Fig. S4A†) while the particle diameter of AuNC@Bi₂Se₃ nanocomposites was approximately 146 nm which might be affected by the stirring process (Fig. 2E). The particle diameter of AuNC@Bi₂Se₃ nanocomposites with a well-distributed size range remained stable over 7 days, demonstrating their stability (Fig. S4B†).

However, we still need to sonicate it for five minutes to avoid any potential complications before its utilization. Fig. 2F illustrates that the zeta potentials of Bi₂Se₃, Au NCs, and AuNC@Bi₂Se₃ were +40, -28, and +12 mV, respectively. The observed decrease in the zeta potential of AuNC@Bi₂Se₃ is attributed to the loading of the negatively charged Au NCs. Furthermore, the characterization of the synthesized AuNC@Bi₂Se₃ nanocomposites was detected by XPS. The full-scan XPS spectrum in Fig. 2G indicates that the hybrid nanomaterials are composed of Au, Bi, Se elements.³⁵ Fig. 2H illustrates the valence of Au 4f doublet of the obtained AuNC@Bi₂Se₃ nanocomposites. Two Au 4f peaks were observed at 84.2 and 87.9 eV, respectively, suggesting the presence of the Au⁰ state.³⁶ Fig. 2I shows the peaks for Bi 4f at 157.4 and 162.7 eV, and Fig. 2J displays the broad peak of Se at 53.6 eV and 58.2 eV, which is assigned to the 3d level. These findings coherently indicate that the AuNC@Bi₂Se₃ nanocomposites were successfully fabricated.



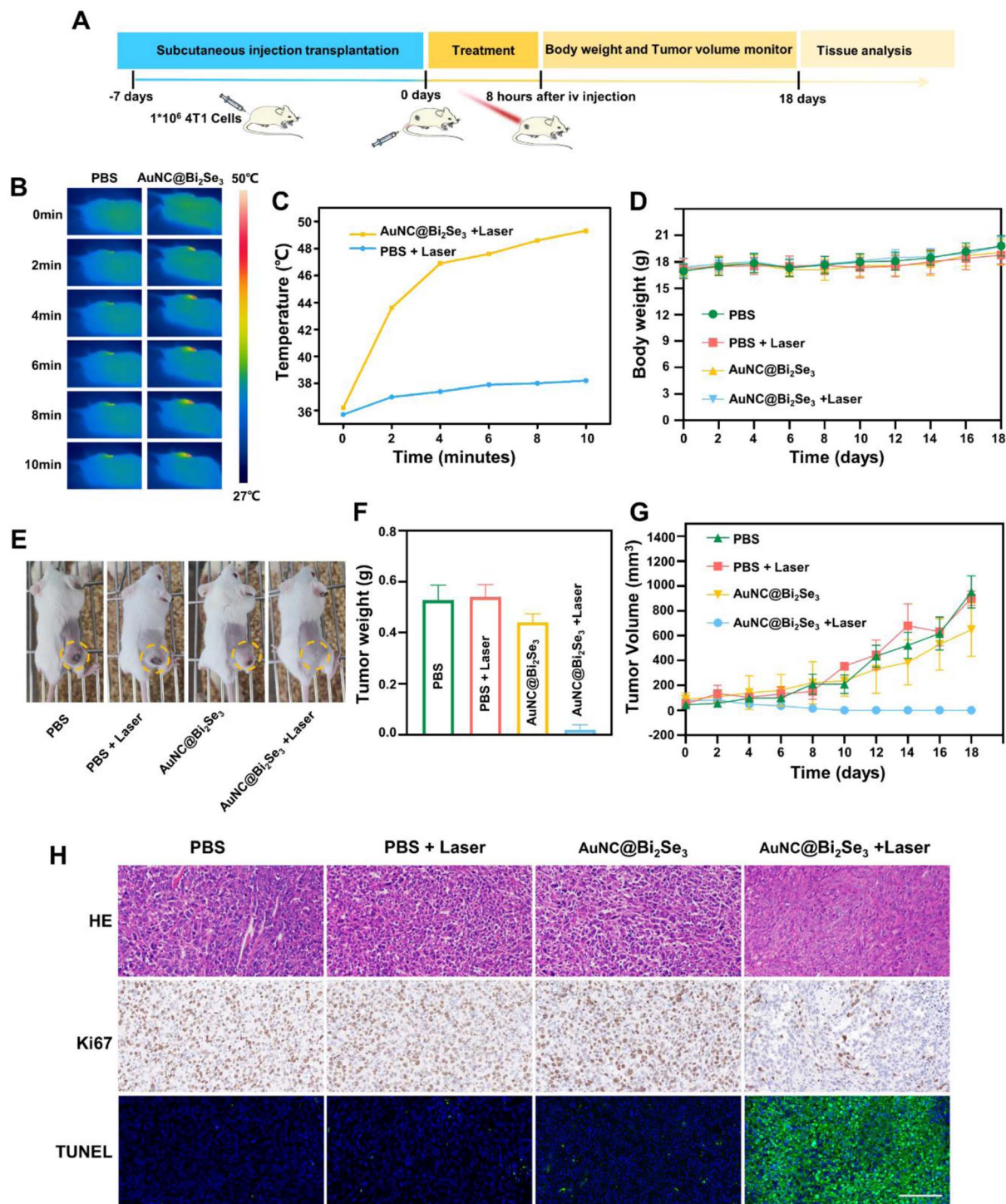


Fig. 5 (A) The treatment process of 4T1 tumor-bearing mice. (B) Thermal images after injection of PBS and AuNC@Bi₂Se₃ respectively and (C) their corresponding temperature curves under 808 nm laser irradiation. (D) The weight curves of 4T1 tumor-bearing mice. (E) Tumor photographs and (F) the excised tumor weights on the 18th day. (G) Their relative tumor growth curves in different groups in the treatment period. (H) H&E, Ki67 and TUNEL staining images of excised tumors of varying treatment groups on the 18th day. Scale bar = 100 μ m.

3.2 Photothermal therapy

The ideal NIR absorption and exceptional PTCE of photothermal reagents are pivotal in PTT. Fig. 3A presents the visible-NIR absorbance spectra of AuNC@Bi₂Se₃ nanocomposites. The

curves in the visible-NIR absorption spectrum revealed that AuNC@Bi₂Se₃ nanocomposites with different concentrations exhibit enhanced optical absorption in the 400–900 nm wavelength range. What's more, AuNC, Bi₂Se₃ nanosheets, and AuNC@Bi₂Se₃ nanocomposites collectively exhibit distinct

absorption peaks within the 800–900 nm wavelength range (Fig. S5†). Upon exposure to 808 nm near-infrared laser irradiation, the resonant frequency of the incident light coincides with the intrinsic frequency of the collective oscillation of free electrons during the LSPR effect, leading to maximal resonance intensity. This alignment results in a photothermal conversion efficacy of 808 nm laser irradiation surpassing that of 660 nm laser irradiation (Fig. S6†). Consequently, AuNC@Bi₂Se₃ nanocomposites showcased superior absorbance compared to Bi₂Se₃ nanosheets under the same concentration conditions (50 ppm), suggesting that the Au NCs play an important role in the improvement of the photothermal conversion capability of AuNC@Bi₂Se₃ nanocomposites (Fig. 3B and S5†). Under 808 nm laser irradiation (1.0 W cm⁻²), the temperature of AuNC@Bi₂Se₃ nanocomposites raised depending on power density (Fig. 3C). Similarly, their temperature increases in a dose-dependent manner as the concentration is elevated. At a concentration of 3.125 ppm, the temperature rises from 28 to 34 °C in 6 minutes of irradiation, and further increases to 70 °C when the concentration is 50 ppm (Fig. 3D and E). In contrast, the thermal images of deionized water captured by the infrared camera shows no significant changes under the same conditions, indicating that AuNC@Bi₂Se₃ nanocomposites can convert NIR light into thermal energy efficiently. The photothermal stability of AuNC@Bi₂Se₃ was assessed by three recycling temperature variations of the AuNC@Bi₂Se₃ solution, with no significant reduction observed (Fig. 3F). This finding underscores the superior potential of AuNC@Bi₂Se₃ nanocomposites as PTAs for cancer treatment. According to calculations, the PTCE of AuNC@Bi₂Se₃ could reach up to 42.1% (Fig. 3G), significantly surpassing that of traditional 2D nanomaterials.^{37–39} In summary, these results demonstrate that AuNC@Bi₂Se₃ nanomaterials possess exceptional photothermal conversion ability under 808 nm NIR laser irradiation, laying a solid foundation for future PTT applications.

3.3 Production of ROS

PDT is crucial in tumor therapy, and the generation of ROS is a key indicator of PDT effectiveness. Fig. 3H illustrates that AuNC@Bi₂Se₃ nanocomposites have both PTT and PDT effects. The ESR spectroscopy was used to evaluate the PDT capability of AuNC@Bi₂Se₃. As we can see in Fig. 3I and S7,† there are no obvious changes took place for the AuNC@Bi₂Se₃, Bi₂Se₃ and AuNC in a dark environment. However, all of them can generate ROS under NIR laser irradiation, with AuNC@Bi₂Se₃ generating more ROS than Bi₂Se₃ under the same concentration. To elucidate the enzymatic reaction mechanism of AuNC@Bi₂Se₃, we used DHR123 as a signal sensor for [•]O₂⁻ to evaluate its PDT capability (Fig. 3J and K). After being irradiated for various minutes, the fluorescence value of AuNC@Bi₂Se₃ solution at 530 nm exhibited a significant upward trend, whereas the dark group showed no significant changes. These findings suggested that AuNC@Bi₂Se₃ nanocomposites can produce a substantial amount of ROS under 808 nm laser irradiation, demonstrating its effective PDT capability.

3.4 Intracellular ROS generation and cytotoxicity

The remarkable photothermal and photodynamic effects of AuNC@Bi₂Se₃ inspired us to investigate their cytotoxic effects on cancer cells. The *in vitro* anti-cancer effectiveness of AuNC@Bi₂Se₃ nanocomposites was assessed using the CCK8 assay. Initially, human normal cell lines, embryonic fibroblast cells (NIH 3T3), were utilized to access the biosafety of Bi₂Se₃ and AuNC@Bi₂Se₃ nanocomposites. As depicted in Fig. 4A, cell viability remained above 95% when the concentration was up to 25 ppm, confirming that there is no significant cytotoxicity of Bi₂Se₃ and AuNC@Bi₂Se₃ in human normal organs. However, within the simulated TME solutions enriched with excessive H₂O₂, a reduction in the viability of 4T1 cells is observed (Fig. 4B). In detail, the cell viability slightly decreased when treated with Bi₂Se₃ or AuNC@Bi₂Se₃ without NIR laser irradiation. After being irradiated by 808 nm laser for 5 minutes, nearly half of the cells were still alive when the concentration of Bi₂Se₃ was up to 25 ppm, whereas only 20% of cells were alive when treated with AuNC@Bi₂Se₃ under the same conditions. This finding demonstrates that the concentration and laser are major factors that affect cell toxicity and AuNC@Bi₂Se₃ exhibits higher efficiency in killing tumor cells under 808 nm laser irradiation. Furthermore, we examined the underlying cell death mechanism induced by AuNC@Bi₂Se₃ by assessing the cytotoxic ROS levels. As depicted in Fig. 4C, a significant production of ROS was observed in the group treated with 12.5 ppm AuNC@Bi₂Se₃ + laser, as indicated by DCFH-DA and DHE probes.^{30,40} No green fluorescence was noted when treated with PBS, NIR laser, or AuNC@Bi₂Se₃ nanocomposites alone. However, strong green fluorescence was observed in 4T1 cells when an 808 nm laser was added to the 12.5 ppm AuNC@Bi₂Se₃ solution, indicating that AuNC@Bi₂Se₃ can efficiently generate ROS in the TME under laser irradiation, aligning with the results of cell experiments. Additionally, a DHE probe was used to detect intracellular [•]O₂⁻. Different from the green fluorescence of DCFH-DA, red fluorescence can be detected in cells enriched with ROS by a DHE probe. As we can see, the group treated with 12.5 ppm AuNC@Bi₂Se₃ + laser showed obvious red fluorescence, while the group treated with PBS, PBS + laser, or AuNC@Bi₂Se₃ alone showed minimal fluorescence. The increased green and red fluorescence intensity in cells treated with AuNC@Bi₂Se₃ + laser exhibited positive generation of ROS and confirmed their superior photodynamic performance. The *in vitro* anti-cancer effect of AuNC@Bi₂Se₃ was directly visualized by fluorescence images of cells co-stained with fluorescent probes calcein AM (green fluorescence, representing live cells) and PI (red fluorescence, representing dead cells) (Fig. 4D). The cells treated with 12.5 ppm AuNC@Bi₂Se₃ + laser exhibited the most intense red fluorescence compared to other groups, confirming that AuNC@Bi₂Se₃ can cause significant cancer cell death under 808 nm laser irradiation. Additionally, the flow cytometry with annexin V-FITC/PI staining was employed to assess tumor cell apoptosis. The results in Fig. 4E indicated that the 12.5 ppm AuNC@Bi₂Se₃ nanocomposites can effectively induce 4T1 cell apoptosis *via* the irradiation of 808 nm laser. Collectively, these results fully demonstrated that AuNC@Bi₂Se₃



can efficiently increase the production of ROS and show extraordinary therapeutic efficiency for cancer cells.

3.5 *In vivo* anti-cancer effects of AuNC@Bi₂Se₃

Inspired by the outstanding *in vitro* photothermal effect of AuNC@Bi₂Se₃, we employed 4T1 tumor-bearing BALB/c mice model to evaluate their *in vivo* phototherapeutic effects. When the tumor volume reached approximately 100 mm³, all the 4T1 tumor-bearing mice were divided into four groups ($n = 5$) at random: PBS, PBS + laser, AuNC@Bi₂Se₃, and AuNC@Bi₂Se₃ + laser and corresponding solutions were injected through tail intravenous injection (Fig. 5A). The infrared thermal camera was utilized to track heat signals, evaluating the *in vivo* thermal behaviors of AuNC@Bi₂Se₃ nanocomposites under the irradiation of an 808 nm laser (1 W cm⁻², 10 min). Zhang *et al.* reported that hyperthermia (temperatures higher than 42 °C) can achieve ideal tumor ablation.^{41,42} We can see in the Fig. S8† that the temperature of PBS and AuNC@Bi₂Se₃ groups were decreased because of the inhalation of anesthetic gases, and PBS + laser group was around 37 °C with the help of 808 nm laser irradiation (Fig. 5B and C). However, the temperature on tumor regions in the AuNC@Bi₂Se₃ + laser group reached 49.3 °C, effectively ablating the tumor cells and inhibiting their malignant proliferation (Fig. 5B and C). Throughout the treatment process (18 days), the body weight of each group followed a similar trend (Fig. 5D), indicating that the treatment of AuNC@Bi₂Se₃ under 808 nm laser irradiation did not exhibit obvious systemic toxicity. Furthermore, the photographs and their corresponding tumor volumes of the 4T1 tumor-bearing mice after 18 days of treatment were illustrated in Fig. 5E–G. These results showed that the mice treated with AuNC@Bi₂Se₃ under 808 nm laser irradiation exhibited a sustainable decrease in tumor volume. In contrast, the tumor volumes of the other three groups did not exhibit any reduction during the treatment period. Additionally, the results from hematoxylin/eosin (H&E), TdT-mediated dUTP nick-end labeling (TUNEL), and Ki67 staining of tumor slices indicate that the group treated with AuNC@Bi₂Se₃ under NIR laser exposure displayed the highest rates of cell necrosis (Fig. 5H). Conversely, the groups treated with PBS, PBS + laser, or AuNC@Bi₂Se₃ alone showed no significant apoptosis or necrosis. These findings underscored that the AuNC@Bi₂Se₃ nanocomposites have superior photothermal efficacy and their anticancer activity is notably enhanced under 808 nm NIR laser irradiation.

3.6 *In vivo* biosafety evaluation

The biosafety of AuNC@Bi₂Se₃ nanocomposites is a critical prerequisite for their biomedical applications. Therefore, we assessed the biosafety of AuNC@Bi₂Se₃ nanocomposites in 4T1 tumor-bearing mice. Histological examinations of the heart, liver, lung, spleen and kidney were conducted using Hematoxylin & Eosin (H&E) staining. There were no significant histopathological lesions in mice treated with AuNC@Bi₂Se₃ or AuNC@Bi₂Se₃ + laser, compared to PBS and PBS + laser groups (Fig. S9†). The effects of these groups on blood functions were further examined by investigating ALT, AST (indicative of liver

function), BUN (indicative of renal function), TP, ALB, ALP, TBIL, and CREA and the results indicated no significant differences among them (Fig. S10†). In summary, these findings demonstrate the excellent biosafety profile of AuNC@Bi₂Se₃ during the treatment period.

4. Conclusions

AuNC@Bi₂Se₃ nanocomposites were successfully fabricated using the sonication-assisted liquid exfoliation method and amide bond reaction. The photothermal conversion ability of AuNC@Bi₂Se₃ nanocomposites reached up to 42.1%, and their strong ability to produce ROS significantly enhances their killing efficiency on cancer cells. Furthermore, the AuNC@Bi₂Se₃ nanocomposites exhibited low toxicity but demonstrated efficient anticancer effects in both *in vitro* and *in vivo* therapeutic applications. Collectively, this work demonstrates that AuNC@Bi₂Se₃ nanocomposites are effective PTAs and PSs, suitable for synergistic PTT and PDT of cancer. We are confident that our strategy offers a valuable example for expanding the applications of Bi₂Se₃-based nanomaterials in biomedical fields.

Data availability

We confirm that the data supporting the findings of this study are available within the main article and ESI.†

Author contributions

Chenxi Li: investigation, methodology, data curation, formal analysis, writing—original draft; Xueyang Fang: writing—reviewing and editing, funding acquisition; Qingdong Zeng: investigation; Li Zeng: validation; Guohui Nie: funding acquisition and supervision; Bin Zhang: conceptualization, writing—reviewing and editing, funding acquisition. All authors read and approved the final manuscript.

Conflicts of interest

There are no conflicts to declare.

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