

Supporting Information for:

Plasmonic Vesicles of Amphiphilic Gold Nanocrystals: Self-Assembly and External Stimuli-Triggered Destruction

Jibin Song,^{†,§} Lin Cheng,^{†,§} Aiping Liu,[†] Jun Yin,[†] Min Kuang,[‡] Hongwei Duan^{*,†}

[†]School of Chemical and Biomedical Engineering, Nanyang Technological University, 70 Nanyang Drive, Singapore 637457. [‡]Ocean Nanotech, 2143 Worth Lane, Springdale, Arkansas 72764. Email: hduan@ntu.edu.sg

[§]These authors contribute equally to this work.

Materials and Characterization.

Methoxy-poly(ethylene glycol)-thiol (PEG-SH) with a molecular weight of 5 kDa was purchased from Laysan Bio, Inc. Hydrogen tetrachloroaurate (III) trihydrate (HAuCl₄·3H₂O) was obtained from Alfa Aesar. N,N,N',N',N''-pentamethyl diethylenetriamine (PMDETA), methyl methacrylate (MMA), 4-vinyl pyridine (4VP), copper (I) bromide, cetyltrimethylammonium bromide (CTAB, 98%), ascorbic acid (99%), sodium borohydride (96%), sodium citrate(99%), silver nitrate (99%) were purchased from Sigma-Aldrich. The monomers (MMA and 4VP) were passed through a basic alumina column, respectively, to remove the inhibitor and dried over CaH₂, then distilled in vacuum. 2, 2'-dithiobis [1-(2-bromo-2-methyl- propionyloxy)]s ethane (DTBE) and the amphiphilic nanocrystals were synthesized according to our previous report.^{1,2} All the other chemical reagents were obtained from commercial suppliers and used without further purification.

Transmission Electron Microscopy (TEM) observations were conducted on a Jeol JEM 2010 electron microscope at an acceleration voltage of 300 kV. Scanning electron microscopy images were obtained on a FESEM (JSM-6700F, Japan). UV-vis absorption spectra were recorded by using a SHIMADZU UV-2501 spectrophotometer. Single-particle measurements were carried out in an Olympus71 inverted microscope with an oil-immersion dark field condenser, and colored images were collected using Photometrics CoolSNAP-cf cooled CCD camera. ¹H NMR spectra were obtained at Bruker AV300, using CDCl₃ as the solvent. Gel permeation chromatography (GPC) was measured on a Shimadzu HPLC system using THF as the eluent, and the molecular weight is calibrated with polystyrene standards. Polymer grafts were cleaved from the nanoparticles by treating the nanoparticles with 5mM iodine

solution in dichloromethane and PMMA was separated from PEG by precipitating the solution in methanol. Thermogravimetric analysis (TGA) was performed on a Perkin-Elmer Diamond TG/DTA. Samples were placed in platinum sample pans and heated under a nitrogen atmosphere at a rate of 10 °C/min to 100 °C and held for 30 min to completely remove residual solvent. Samples were then heated to 700 °C at a rate of 10 °C/min. Dynamic light scattering experiments were carried out on Malvern Zetasizer Nano-ZS at 25 °C.

Synthesis of 2, 2'-dithiobis [1-(2-bromo-2-methyl-propionyloxy)] ethane (DTBE).¹ DTBE was prepared by acrylation of bis(2-hydroethyl) disulfide. In a typical experiment, 2-bromo-2-methylpropionyl bromide (14.8 mmol) was added dropwise to a mixture of the disulfide (6.17 mmol) and triethylamine (31.5 mmol) in dichloromethane (150 mL) at 0°C under an argon atmosphere. The solution was stirred at 0°C for 1h and then for another 2 h at room temperature. After the precipitates were filtered off, the organic phase was extracted with 2N Na₂CO₃ solution saturated with NH₄Cl to remove the excess bromides. Subsequent removal of dichloromethane yielded DTBE. ¹H NMR (300 MHz, CDCl₃) δ: 1.95 (s, 12 H, -CH₃), 3.12 (t, 4 H, -SCH₂), 4.58 (t, 4 H, -OCH₂). ¹³C NMR (300 MHz, CDCl₃) δ: 30.7 (-CH₃), 36.7 (-SCH₂), 63.5 (-OCH₂), 76.3(-C(CH₃)₂), 77.5 (-C=O).

Synthesis of Gold Nanoparticles.² Uniform 14-nm gold nanoparticles were prepared by citrate reduction of HAuCl₄ in aqueous phase. Typically, a sodium citrate (102 mg) DI-water solution (2 mL) was rapidly injected into a boiling aqueous HAuCl₄ (30 mg in 200 mL of water) solution under vigorous stirring. After boiling for 15 min, the solution was cooled to room temperature. TEM analysis of more than 200 particles gave a standard deviation in diameters of the obtained gold nanoparticles of <10%.

Gold Nanorods Synthesis.² Original CTAB-stabilized gold nanorods (AuNR@CTAB) were synthesized by a seed-mediated growth method at 30 °C through reduction of HAuCl₄ with ascorbic acid in the presence of CTAB and AgNO₃ according to the method reported previously.³ After purified by centrifugation (9000g, 30 min) three times, AuNR@CTAB was stored in water for further use. The obtained nanorods have an average aspect ratio of 3.9 and a diameter of 13 nm.

“Grafting to” Reactions on Gold Nanoparticles.² Au@PEG/DTBE was prepared by

coadsorption of PEG and DTBE ligand through the Au-S bond. In brief, a solution of PEG (25 mg) and DTBE (12 mg) in DMF (2 mL) was slowly added into 50 mL of the original 14 nm Au nanoparticles (3.5 nM) in water. After the solution was stirred for 24h, nanocrystals were recovered by centrifugation (10000g, 20 min). Any free polymers and DTBE present were removed by ultrafiltration (cutoff =100 kDa) of an ethanol solution of the nanocrystals. Au@PEG/DTBE can be stored in chloroform or DMF for further use.

“Grafting to” Reaction on Gold Nanorods.² Typically, a solution (solution A) of PEG (45 mg) and DTBE (15 mg) in DMF (3 mL) was added slowly into 3 mL (25 nM) of the original AuNR@CTAB in water. Notably, there are two steps for this ligand-exchange reaction. In the first step, nanorods aggregated 2 h after addition of 1 mL of solution A. The nanorods were collected by centrifugation and redispersed in DMF. In the second step, the remaining solution A (2 mL) was mixed with the DMF solution of the nanorods. After stirred for 24 h, the reaction mixture was still a clear solution, and the coated nanorods were purified by repeated centrifugation (9000g, 30 min) and redispersing for more than 3 times.

“Grafting from” Reactions on Gold Nanoparticles and Gold NanoRods.² Surface-initiated ATRP was used for the synthesis of amphiphilic nanocrystals of Au@PEG/PMMA, Au@PEG/P(MMAVP). Typically, 0.2 mL of monomer (MMA or the mixture of MMA and 4VP with molar ratio of 7:3) and the initiator-coated gold nanocrystals (0.15 nmol) were mixed in DMF (2.0 mL). After the mixture was deaerated for 30 min by nitrogen, CuBr (4 mg) and PMDETA (15 mg) were introduced to initiate the polymerization. The reaction was carried out at 40 °C for 10 h. Catalysts and unreacted monomer were removed by repeated centrifugation, and the amphiphilic nanocrystals were stored as chloroform solutions.

Preparation of Plasmonic vesicles. The vesicles were prepared using the film rehydration method. Briefly, 0.2 mL solution (80nM for gold nanoparticles and 20nM for gold nanorods) of amphiphilic nanocrystals in chloroform was first thoroughly dried on the wall of a glass vial under a steady flow of N₂ gas. Afterwards, 1mL DI-water was added to rehydrate the film under sonication at 30 °C. In 2-5 min, the solution became clear, indicating the formation of the vesicle. The as-prepared vesicles were stored at 4 °C for further uses. To trigger the dissociation of Au@PEG/PMMAVP vesicles, pH 2 HCl solution was added dropwise to tune the solution pH to predetermined values. A 785nm diode laser was utilized for photothermal experiments using 5mm diameter and 2W/cm² intensity beam for 2min.

Calculation of the ratio of PEG and PMMA grafts on the nanocrystal surface.² ¹H-NMR measurement (Figure S3) shows that the resonance of -CH₂CH₂O- (3.65 ppm) of PEG and that of -OCH₃ group (3.60 ppm) of PMMA has a ratio of 1:3, which leads to a molar ratio of 1:4 for ethylene glycol (EG) and MMA monomer. With the molecular weights of PMMA (M_n= 22 kDa, PDI=1.26) and PEG (5 Ka), the ratio of PEG and PMMA grafts can be calculated using Equation S1, where MW_{MMA} is the molecular weight of MMA monomer and MW_{EG} is the molecular weight of EG monomer. The result is 1:2 (PEG:PMMA).

$$Ratio(PEG:PMMA) = Ratio(EG:MMA) \left(\frac{MW_{PMMA}/MW_{MMA}}{MW_{PEG}/MW_{EG}} \right) \quad (Equation S1)$$

Calculation of graft density of polymer brushes on Au nanoparticles.² Given the size of a gold atom (0.017nm³), the number of gold atom (N_{Au atom}) in 14nm Au nanoparticles can be calculated using Equation S2, where R is the radius of the gold nanoparticles. The result is 84472 gold atoms per nanoparticle and therefore the molar mass (M_{Au nanoparticle}) of the gold nanoparticle is 197N_{Au atom}. Combining the molar mass of the gold nanoparticle, the ratio of PEG and PMMA and the weight fraction obtained in TGA analysis, the average number of polymer grafts can be calculated by Equation S3, where W_{polymer} is the weight fraction (20%) of the organic part, W_{Au nanoparticle} is the weight fraction of gold nanoparticle and M_{PEG+2PMMA} is the sum of the molar mass of one PEG and two PMMA grafts. The result is 264 grafts per nanoparticle, which include 88 PEG chains and 176 PMMA chain and the graft density is ~0.4 chain/nm².

$$N_{Au atom} = \frac{V_{Au nanoparticle}}{V_{Au atom}} = \frac{4\pi}{3} \left(\frac{R^3}{V_{Au atom}} \right) \quad (Equation S2)$$

$$N_{grafts per nanoparticle} = \left(\frac{3W_{polymer}/M_{PEG+2PMMA}}{W_{Au nanoparticle}/M_{Au nanoparticle}} \right) \quad (Equation S3)$$

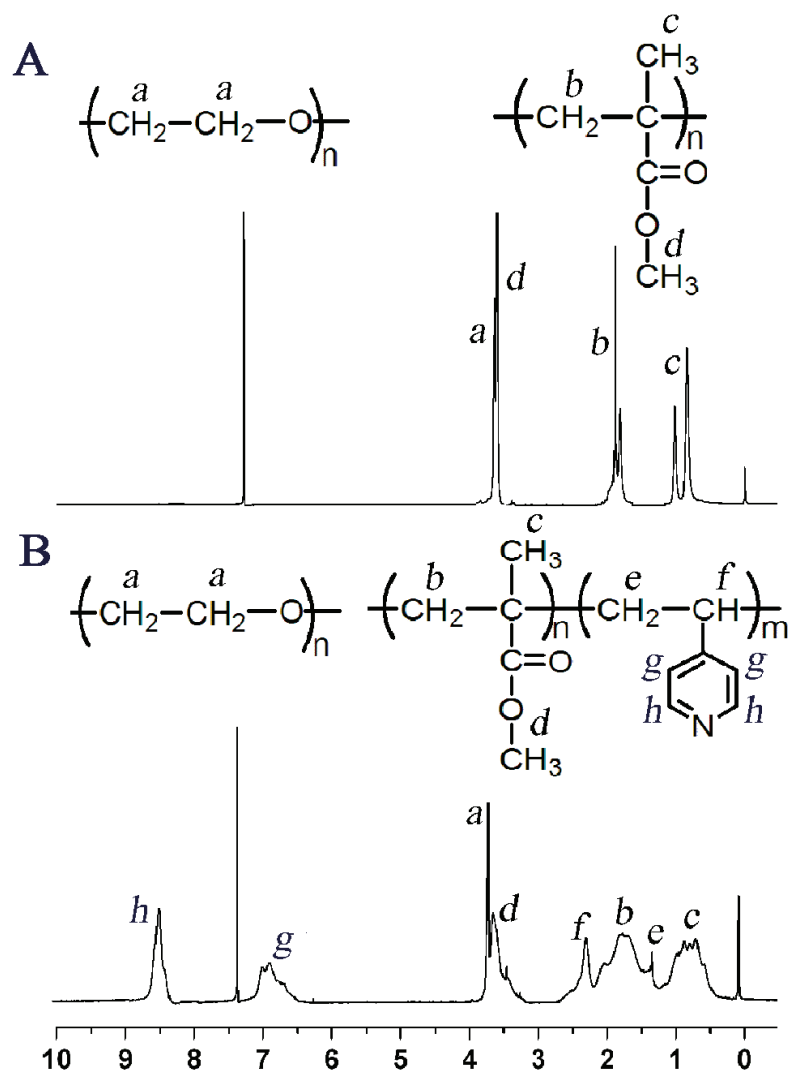


Figure S1. (A) ^1H NMR (300 MHz, δ , ppm, CDCl_3) of Au@PEG/PMMA: 3.65 ($-\text{OCH}_2\text{CH}_2-$), 3.60 ($-\text{OCH}_3$), 1.71-2.08 ($-\text{CH}_2-$), 0.75-1.05 ($-\text{CH}_3$). (B) ^1H NMR (300 MHz, δ , ppm, CDCl_3) of Au@PEG/PMMAVP: 8.44 and 6.85 (*pyridine*), 3.65 ($-\text{OCH}_2\text{CH}_2-$), 3.60 ($-\text{OCH}_3$), 2.23 ($-\text{CH}$), 1.26-2.15 ($-\text{CH}_2$), 1.25 ($-\text{CH}_2$), 0.35-1.25 ($-\text{CH}_3$). The ratio of MMA and 4VP in the copolymer was calculated based on the resonance of pyridine (8.44 ppm) and that of $-\text{CH}_3$ group (0.35-1.25 ppm) of PMMA, leading to 25% of 4VP in the copolymer.

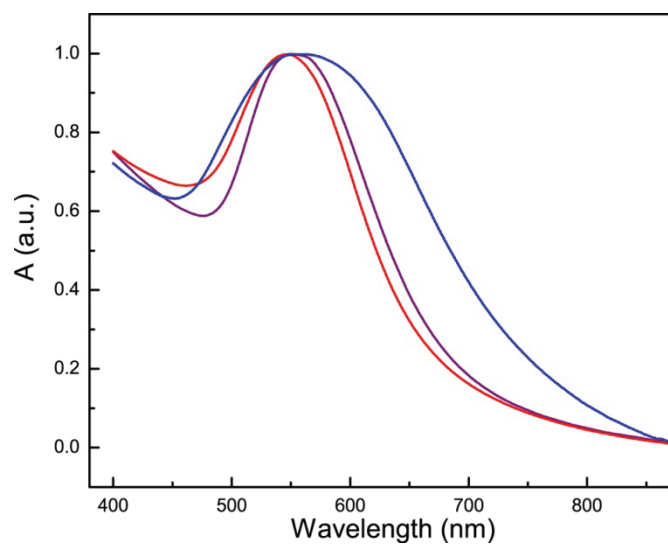


Figure S2. UV-vis spectra of vesicles formed by Au@PEG/PMMA (blue line), Au@PEG/PMMAVP containing 10% 4VP (purple line), and Au@PEG/PMMAVP containing 25% 4VP (red line) at pH 7.0.

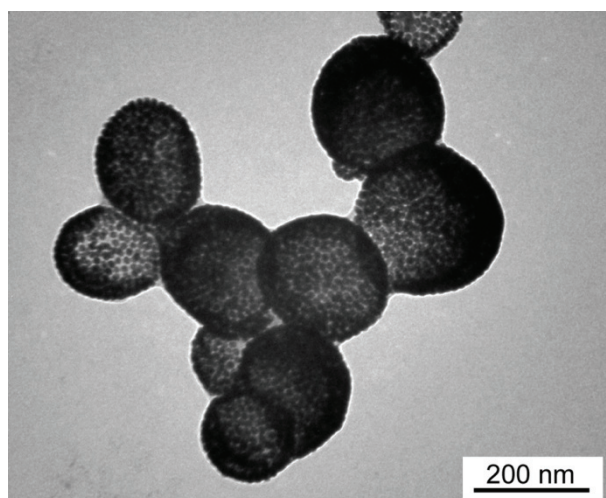


Figure S3. TEM image of vesicles of Au@PEG/PMMAVP containing 25% 4VP.

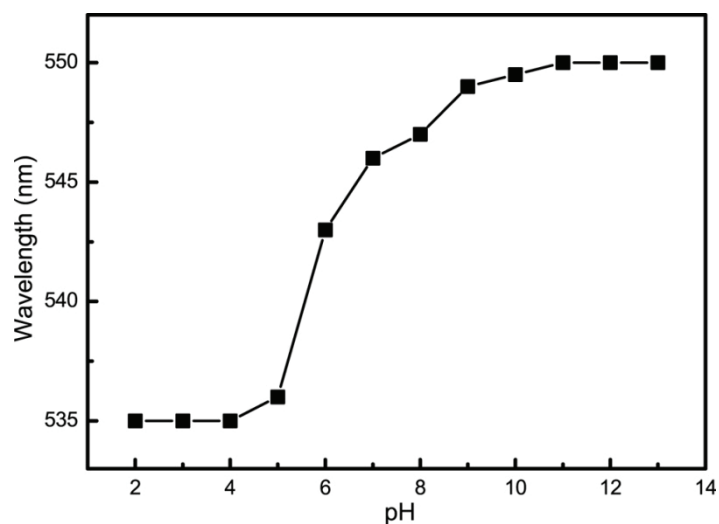


Figure S4. The peak position of surface plasmon resonance of vesicles of Au@PEG/PMMAVP containing 25% 4VP as a function of solution pH.

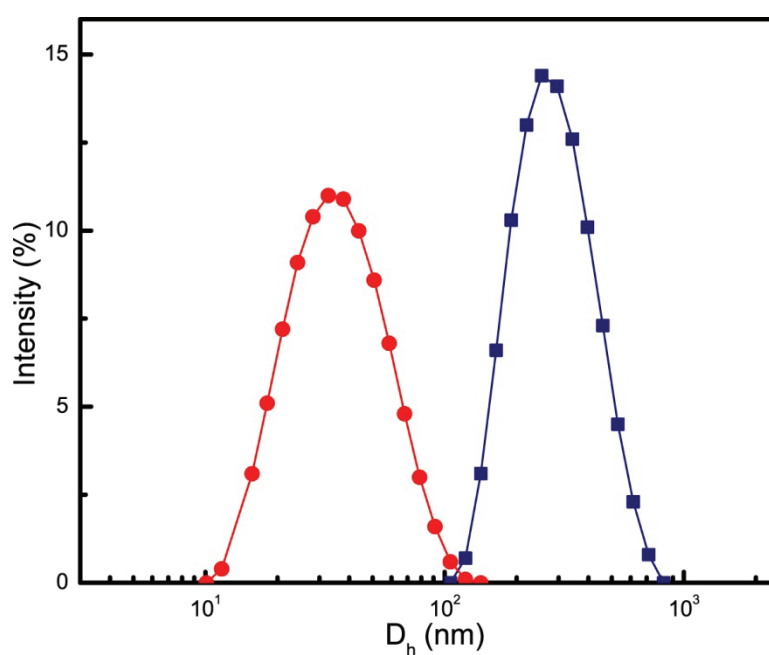


Figure S5. Hydrodynamic diameter distribution of the vesicles of Au@PEG/PMMAVP at pH 7.0 (blue) and pH 5.0 (red).

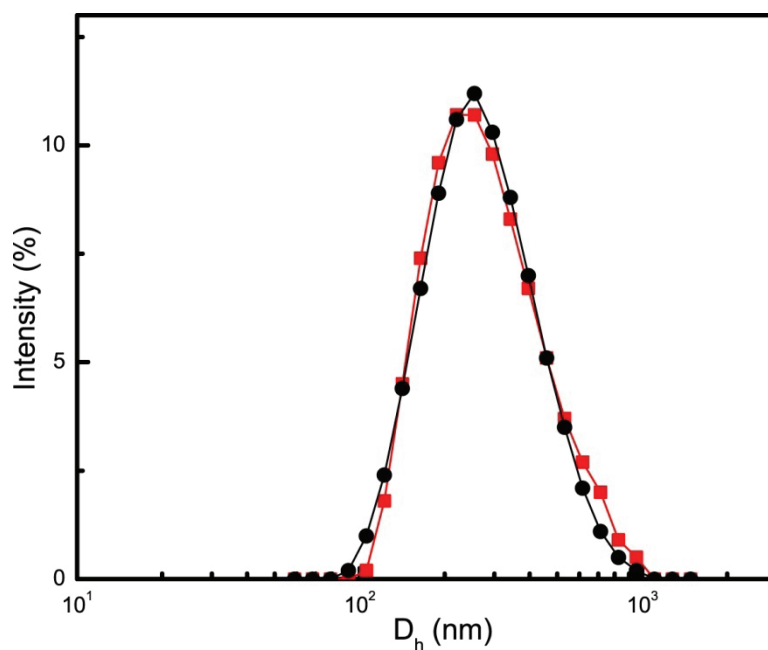


Figure S6. Hydrodynamic diameter distribution of the gold nanorod vesicles before (black) and after (red) heated at 60 °C.

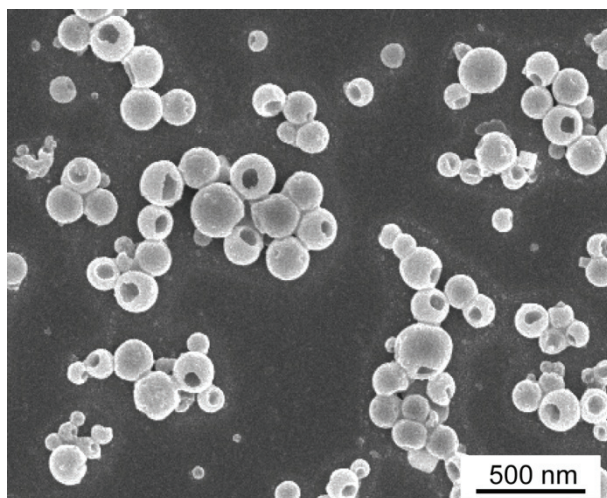


Figure S7. SEM image of vesicles of AuNR@PEG/PMMA.

References

- (1) Duan, H.; Wang, D.; Kurth, D. G.; Möhwald, H. *Angew. Chem., Int. Ed.* **2004**, *116*, 5757.
- (2) Cheng, L.; Liu, A. P.; Peng, S.; Duan, H. W. *ACS Nano* **2010**, *4*, 6098.
- (3) Nikoobakht, B.; El-Sayed, M. A. *Chem. Mater.* **2003**, *15*, 1957.

Complete reference 3(a)

Percec, V.; Wilson, D. A.; Leowanawat, P.; Wilson, C. J.; Hughes, A. D.; Kaucher, M. S.; Hammer, D. A.; Levine, D. H.; Kim, A. J.; Bates, F. S.; Davis, K. P.; Lodge, T. P.; Klein, M. L.; DeVane, R. H.; Aqad, E.; Rosen, B. M.; Argintaru, A. O.; Sienkowska, M. J.; Rissanen, K.; Nummelin, S.; Ropponen, J. *Science* **2010**, 328, 1009-1014.