Self-assemblies of Cyclodextrin Derivatives Modified by Ferrocene with Multiple Stimulus Responsiveness

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Supporting Information

1. Materials

N-Methyl pyrrolidone (NMP), 1, 4-butanediamine, 1,6-Diaminohexane, triethylamine, isopropanol, aqueous ammonia, formylferrocene, sodium borohydride, acetone and other chemical reagents were all commercially available from Sinopharm Chemical Reagent Co. Ltd., China. β-cyclodextrin and OTs-β-cyclodextrin were purchased from Binzhou Zhiyuan Biotechnology Co. Ltd., China.

2. Synthesis

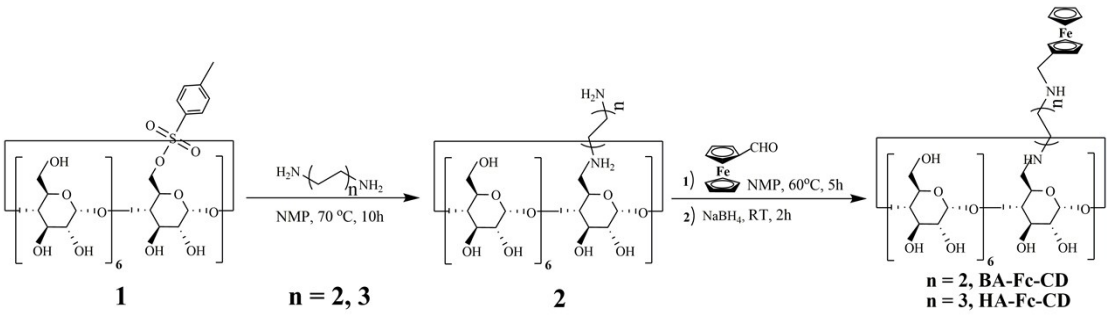

Fig. S1 Synthesis route of BA-Fc-CD and HA-Fc-CD.

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Mono [6-(2-amino-butylamino)-6-deoxy]-β-cyclodextrin (2) was prepared according to the literature[1]. 1, 4-butanediamine (0.088 g, 1 mmol) was added into a solution of dry NMP (10 mL) containing 0.6445 g (0.5 mmol) of OTs-β-cyclodextrin (1). Then 0.25 ml triethylamine was added into the mixture as catalyst. The reaction solution was heated to 70 °C and stirred for 10 h and monitored by TLC with a mixed eluent of isopropanol, water, and 30% aqueous ammonia (5:3:2, by volume). Then the reaction solution was cooled to room temperature and was poured into 30 mL acetone. The mixture was sonicated 10 minutes and then was filtered. The obtained cake was washed with acetone for three times. The crude product was used to synthesis mono[6-deoxy-N-butylamino-(N'-1-ferrocenylmethylene)]-β-cyclodextrin (BA-Fc-CD) without further purification.

BA-Fc-CD was prepared via the direct reaction of 2 and formylferrocene in NMP without any catalyst. Formylferrocene (0.107g, 0.5 mmol) was allowed to react with 2 (0.6025 g, 0.5 mmol) in dry NMP (5 mL) at 60 °C under N_2 and protection from light for 6 h. The reaction was monitored by TLC with a mixed eluent of isopropanol, water, and 30% aqueous ammonia (5:3:2, by volume). Then, sodium borohydride (0.03783 g, 1 mmol) was added in several portions to the reaction mixture and the solution was allowed to stand for 2 h at room temperature under N_2. The crude reduction product was purified by silica gel column chromatography with a mixed eluent of isopropanol, water, and 30% aqueous ammonia (5:3:2, by volume) to give the product BA-Fc-CD. ^{1}H NMR (300 MHz, DMSO-D6, 300 K, TMS, δ ppm): 5.97-5.61 (m, 9H, C_5H_5), 4.92-4.81 (m, 4H, H_1), 4.27-4.17 (m, 3H, H_1), 3.94-3.37 (m, 28H, H_3, H_5, H_6), 3.36-3.20 (m, 14H, H_2, H_4), 2.70-2.68 (s, 2H, CH_2), 2.31-2.15 (m, 2H, CH_2), 2.10-2.06 (s, 2H, CH_2), 2.02-1.74 (m, 2H, CH_2), 1.27-1.17 (m, 2H, CH2). ^{13}C NMR (75 MHz, DMSO-D_6, 300 K, δ ppm): 17.06, 20.80, 28.97, 30.04, 30.62, 48.39, 60.19, 68.52, 72.42, 73.00, 101.94, 125.25, 127.93. FT-IR (KBr pellet, υ cm^{-1}): 3236.44 (υ_{O-H}), 2928.42 (υ_{C-H}), 1657.16 ($\upsilon_{C=C}$), 618.49 ($\delta_{C=C}$). ESI-MS: Calcd. for $C_{57}H_{92}N_2O_{34}Fe^{2+}$, m/z = 702.1850, found m/z = 702.2503.

For mono[6-deoxy-N-hexylamino-(N'-1-ferrocenylmethylene)]-β-cyclodextrin (HA-Fc-CD) synthesis, it's almost the same as BA-Fc-CD synthesis. 1,6-Diaminohexane (0.116 g, 1 mmol) was added into a solution of dry NMP (10 mL) containing 0.6445 g (0.5 mmol) of OTs-β-cyclodextrin

(1). Then 0.25 ml triethylamine was added into the mixture as catalyst. The reaction solution was heated to 70 °C and stirred for 10 h and monitored by TLC with a mixed eluent of isopropanol, water, and 30% aqueous ammonia (5:3:2, by volume). Then the reaction solution was cooled to room temperature and was poured into 30 mL acetone. The mixture was sonicated 10 minutes and then was filtered. The obtained cake was washed with acetone for three times. The crude product was used to synthesis mono[6-deoxy-N- hexylamino-(N'-1-ferrocenylmethylene)]-β-cyclodextrin (HA-Fc-CD) without further purification.

HA-Fc-CD was prepared via the direct reaction of 2 and formylferrocene in NMP without any catalyst. Formylferrocene (0.107g, 0.5 mmol) was allowed to react with 2 (0.6165 g, 0.5 mmol) in dry NMP (5 mL) at 60 °C under N_2 and protection from light for 6 h. The reaction was monitored by TLC with a mixed eluent of isopropanol, water, and 30% aqueous ammonia (5:3:2, by volume). Then, sodium borohydride (0.03783 g, 1 mmol) was added in several portions to the reaction mixture and the solution was allowed to stand for 2 h at room temperature under N_2. The crude reduction product was purified by silica gel column chromatography with a mixed eluent of isopropanol, water, and 30% aqueous ammonia (5:3:2, by volume) to give the product HA-Fc-CD. ^{1}H NMR (300 MHz, DMSO-D_6, 300 K, TMS, δ ppm): 6.08-5.58 (m, 9H, C_5H_5), 4.89-4.79 (m, 4H, H_1), 4.29-4.18 (m, 3H, H_1), 4.12-3.36 (m, 28H, H_3, H_5, H_6), 3.35-3.09 (m, 14H, H_2, H_4), 3.02-2.56 (m, 4H, CH_2), 2.40-1.76 (m, 2H, CH_2), 1.73-0.84 (m, 8H, CH_2). ^{13}C NMR (75 MHz, DMSO-D_6, 300 K, δ ppm): 17.58, 20.78, 21.22, 25.94, 29.41, 30.49, 31.09, 49.01, 60.41, 62.36, 69.04, 73.68, 73.60, 82.08, 102.43, 125.93, 128.38. FT-IR (KBr pellet, υ cm^{-1}): 3248.80 (v_{O-H}), 2938.66 (v_{C-H}), 1662.28 ($v_{C=C}$), 618.50 ($\delta_{C=C}$). ESI-MS: Calcd. for $C_{59}H_{96}N_2O_{34}Fe^{2+}$, m/z = 716.1100, found m/z = 716.2684.

3. Analytical instruments and methods

^{1}H NMR and ^{13}C NMR spectra were gotten on an API Bruker Avance 300 M NMR at room temperature. ESI-MS spectrum was performed on API 4000 MS equipment. 2D NMR ROESY experiments were recorded using an API Bruker Avance 300M NMR at ambient temperature referenced to the solvent peak at δ = 4.70 ppm in D_2O, with a mixing time of 0.200 s, a relaxation

delay time of 1.000 s, and an acquisition time of 0.228 s. TEM images were obtained on a JEM-1011 electron microscope. For FF-TEM, a freeze-fracture apparatus (Balzer BAF 400, Germany) was used at -140 ^{o}C for fracturing and replication, the replicas were examined with a JEM-1011 electron microscope. SEM pictures were gotten with a Hitachi S-4800 scanning electron microscope. The samples for TEM detection were dropped in a copper wire mesh. Then the samples were air-dried. The samples of SEM measurement were obtained by dropping the vesicle solution to the copper wire mesh and then dried and sprayed with the gold. AFM test was conducted with a Veeco Nanoscope Multimode III SPM and operated in tapping contact mode at ambient temperature. The AFM sample was dropped on the smooth silicon wafer and dried by freeze drying for 4 days. The average diameter of vesicles was recorded by DLS measurement with a Wyatt QELS Technology DAWN HELEOS instrument, which used a 12-angle replaced detector in a scintillation vial and a 50 mW solid-state laser. The water for preparation samples of DLS was filtered by a 0.45 μm filter and samples of DLS were also filtered by a 0.45 μm filter before testing. The FT-IR spectrum was obtained on an Avatar 370 FT-IR Spectrometer with the KBr pellet method at room temperature. UV-vis curves were obtained at room temperature with a TU-1800pc UV-vis spectrophotometer which was purchased from Purkinje General Co. Ltd., Beijing, China. A certain concentration of solution was poured into a quartz cuvette to detect the absorption peaks. The sonication was performed with a KQ3187 ultrasonic cleaner for jewelry, Kunshan ultrasonic apparatus Co. Ltd., China. Rheological properties were measured by a Thermo Haake RS6000 rheometer with cone and plate geometry (35 mm diameter, 0.105 mm cone gap). Cyclic voltammetry (CV) was performed in a three-electrode cell using a model CHI650 electrochemical workstation at room temperature. SAXS measurement was carried out using an in-house set-up with rotating anode X-ray generator (Rigaku RU 300, 12 kW) equipped with two laterally graded multilayer optics in a side-by-side arrangement, giving a highly focused parallel beam of mono-chromatic Cu Ka radiation. The size of BA-Fc-CD molecule was obtained from the software Materials Studio 5.5 by Accelrys.

4. Detection of the stoichiometries of BA-Fc-CD/β-CD

The 10^{-2} mol/L mother solutions of BA-Fc-CD and β-CD were prepared by dissolving certain

molar quantities powder samples in water respectively. Then a series of aqueous solutions with the host and guest molecules molar ratio 10:0, 9:1, 8:2, 7:3, 6:4, 5:5, 4:6, 3:7, 2:8, 1:9 and 0:10 were prepared respectively.

5. Stimulus responsiveness of BA-Fc-CD supramolecular polymer, BA-Fc-CD/β-CD vesicles and BA-Fc-CD gel.

The effect of stimulus was detected by adding one equivalent H_2O_2 and copper ions into BA-Fc-CD supramolecular polymer system, BA-Fc-CD/β-CD vesicles system and BA-Fc-CD gel system.

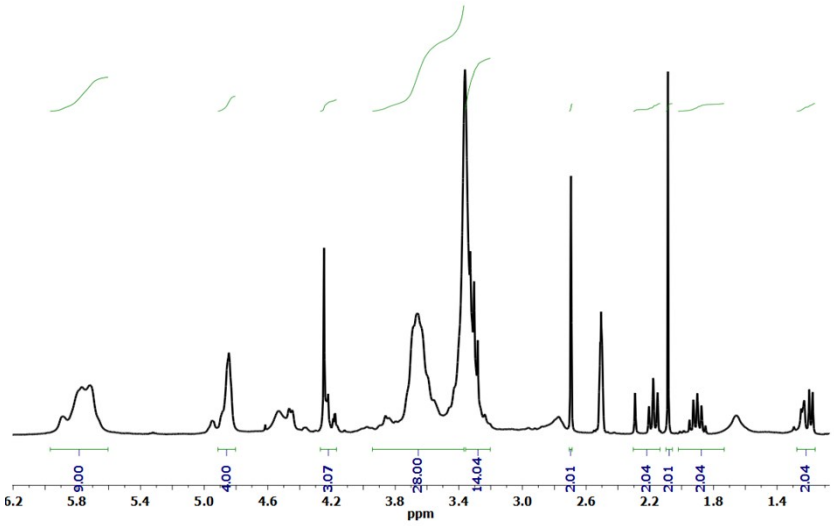

Fig. S2 ^{1}H NMR spectrum (300 MHz) of BA-Fc-CD in Deuterated DMSO.

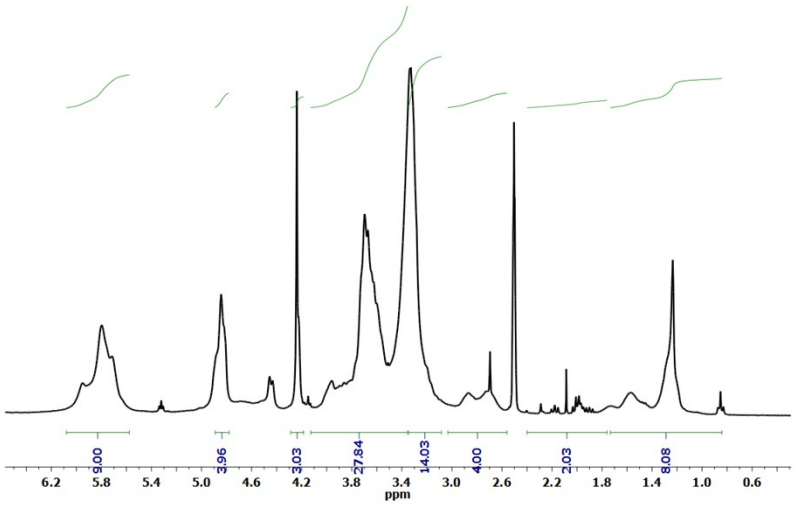

Fig. S3 ^{1}H NMR spectrum (300 MHz) of HA-Fc-CD in Deuterated DMSO.

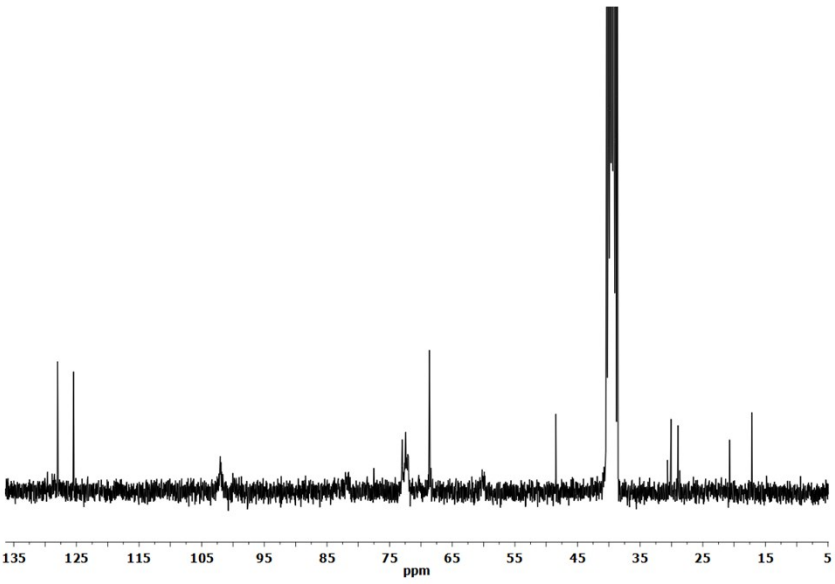

Fig. S4 ^{13}C NMR spectrum (300 MHz) of BA-Fc-CD in Deuterated DMSO.

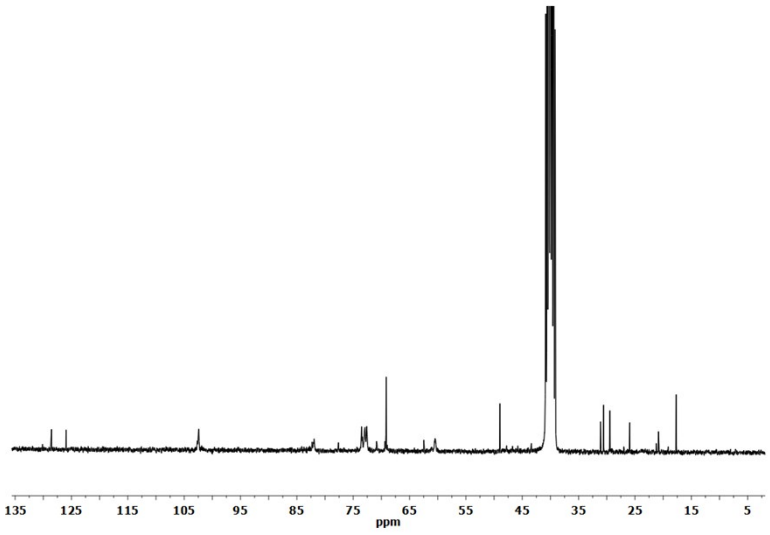

Fig. S5 ^{13}C NMR spectrum (300 MHz) of HA-Fc-CD in Deuterated DMSO.

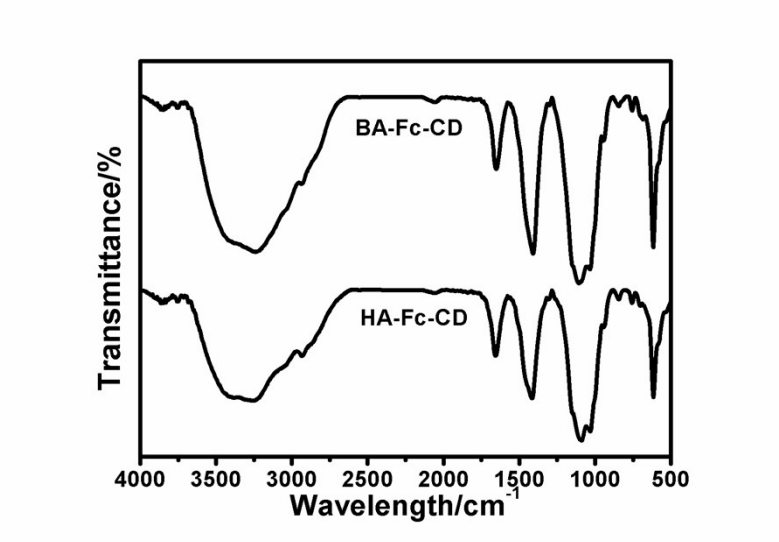

Fig. S6 FT-IR spectra of BA-Fc-CD and HA-Fc-CD.

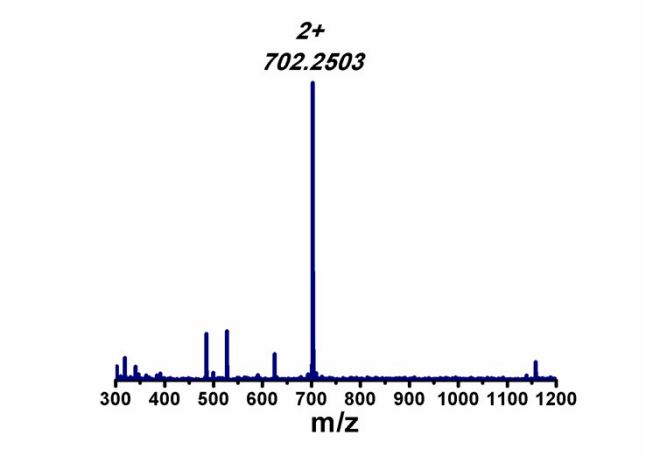

Fig. S7 ESI-MS spectrum of BA-Fc-CD in H_2O.

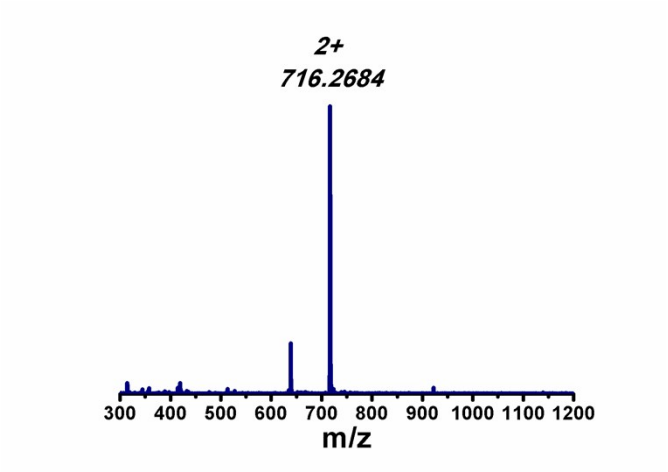

Fig. S8 ESI-MS spectrum of HA-Fc-CD in H_2O.

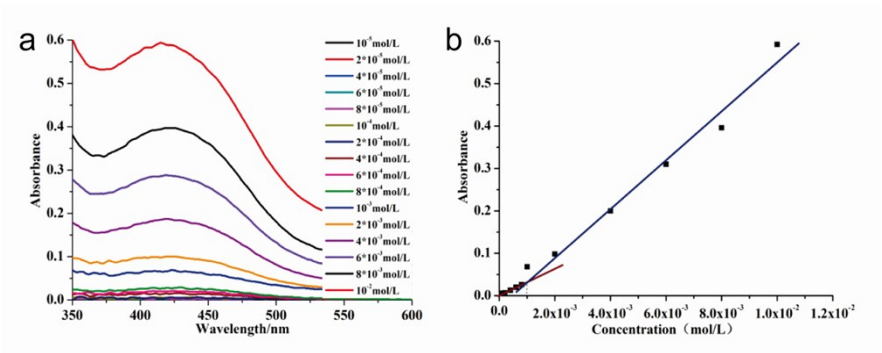

Fig. S9 a) UV-vis absorption spectra comparison of BA-Fc-CD in different concentration, b) the maximum absorption intensity change along with concentration of BA-Fc-CD increases, peaks at 418 nm were selected.

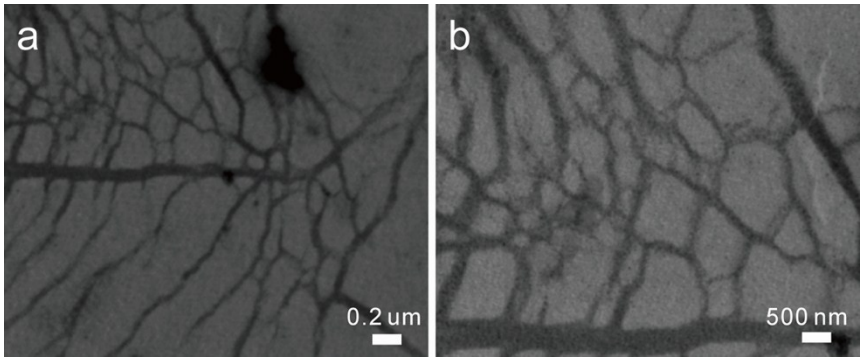

Fig. S10 TEM images of HA-Fc-CD (7 mM) in H_2O with at room temperature, a) scale bar = 0.2 μm, b) scale bar = 500 nm.

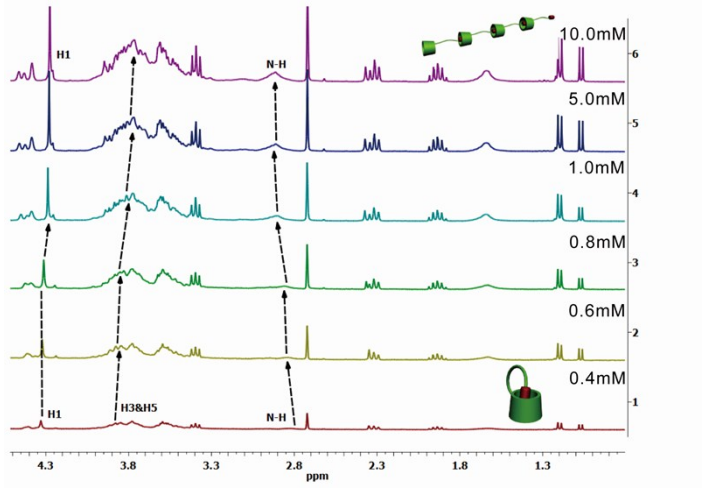

Fig. S11 ^1H NMR spectra comparison of BA-Fc-CD in different concentration.

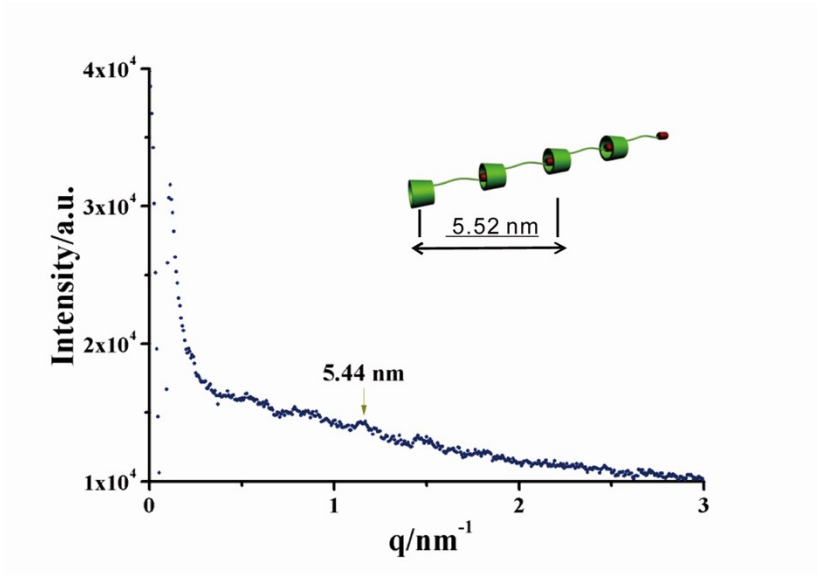

Fig. S12 SAXS pattern of BA-Fc-CD (7 mM) in H_2O at room temperature.

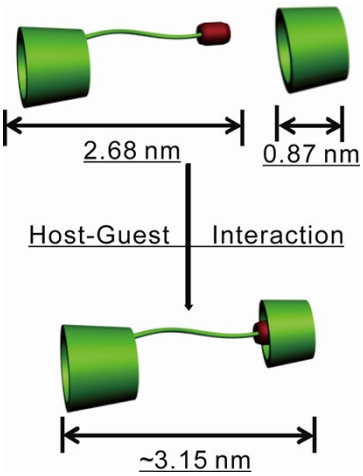

Fig. S13 Size of BA-Fc-CD and β-CD calculated by Material Studio 5.5.

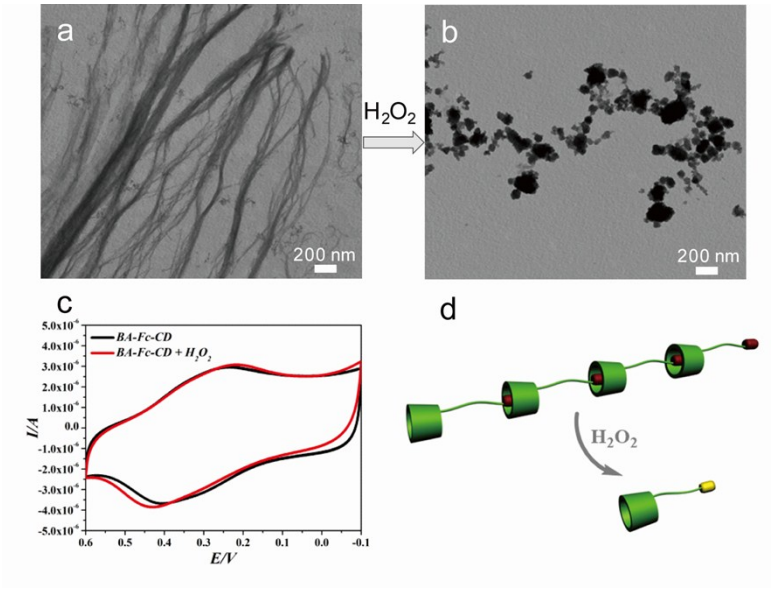

Fig. S14 TEM images of BA-Fc-CD (7 mM) in H_2O at room temperature, a) scale bar = 200 nm, b) TEM image of BA-Fc-CD (7 mM) treated with 1 equvi. H_2O_2, scale bar = 200 nm, c) Cyclic voltammograms comparison of the BA-Fc-CD sample and BA-Fc-CD sample treated with 1 equvi. H_2O_2 at room temperature, d) cartoon representation of H_2O_2 responsiveness for BA-Fc-CD sample.

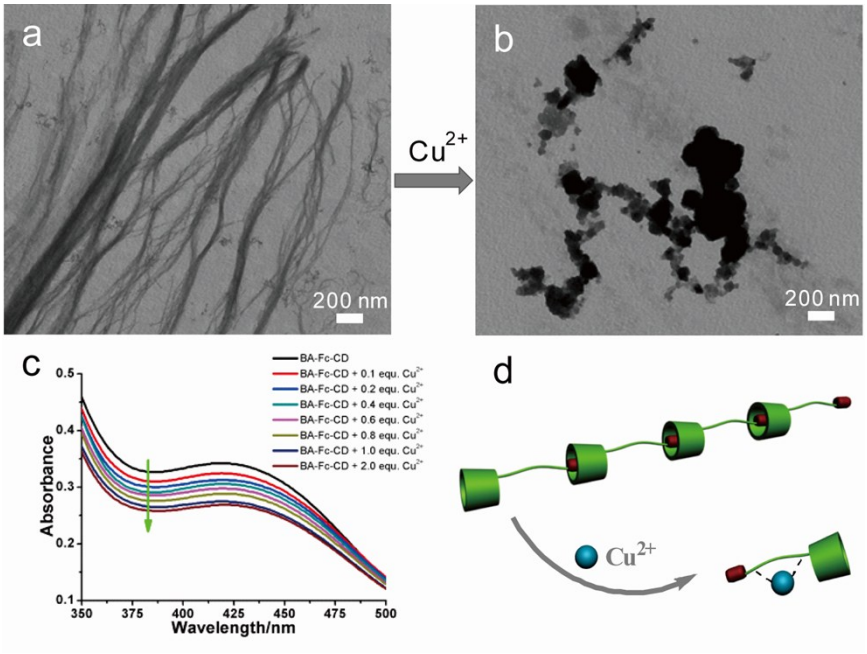

Fig. S15 TEM images of BA-Fc-CD (7 mM) in with at room temperature, a) scale bar = 200 nm, b) TEM image of BA-Fc-CD (7 mM) treated with one equvi. Cu^{2+}, scale bar = 200 nm, c) UV-vis spectra comparison of the BA-Fc-CD sample and BA-Fc-CD sample treated with one equvi. Cu^{2+} at room temperature, d) cartoon representation of Cu^{2+} responsiveness for BA-Fc-CD sample.

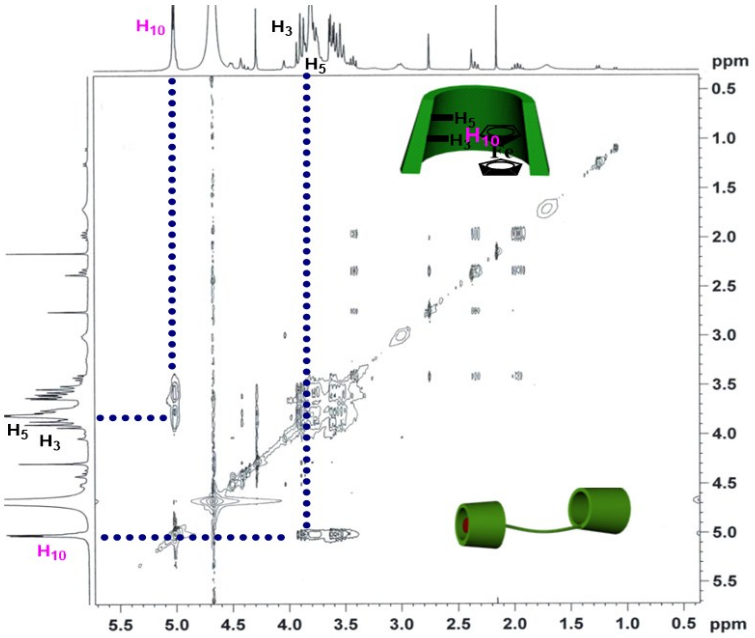

Fig. S16 2D NMR ROSEY (300 MHz) spectrum of BA-Fc-CD/β-CD (7 mM) sample with D_2O as the reference at room temperature.

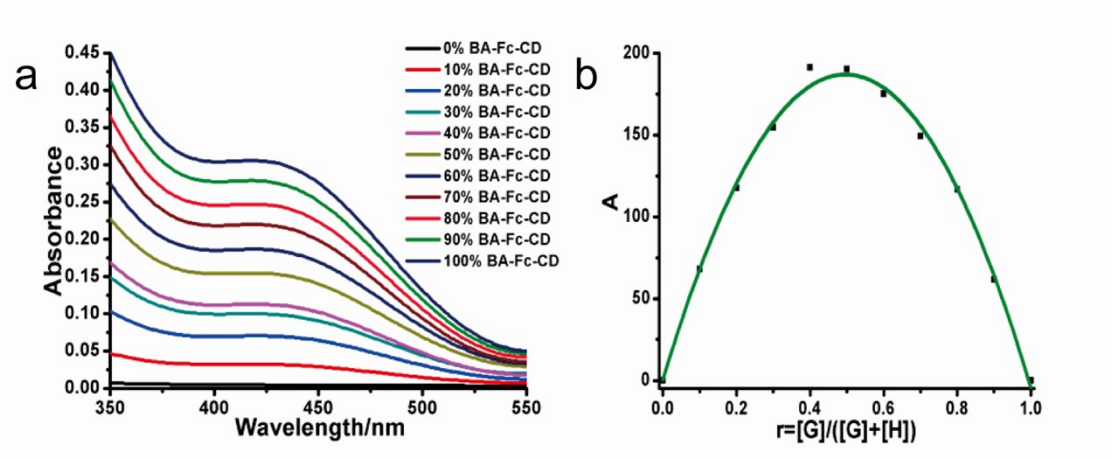

Fig. S17 a) UV-vis spectra comparison of different ratio between BA-Fc-CD and β-CD, b) the Job's plot for the inclusion rate of BA-Fc-CD/β-CD in water by UV-vis detection.

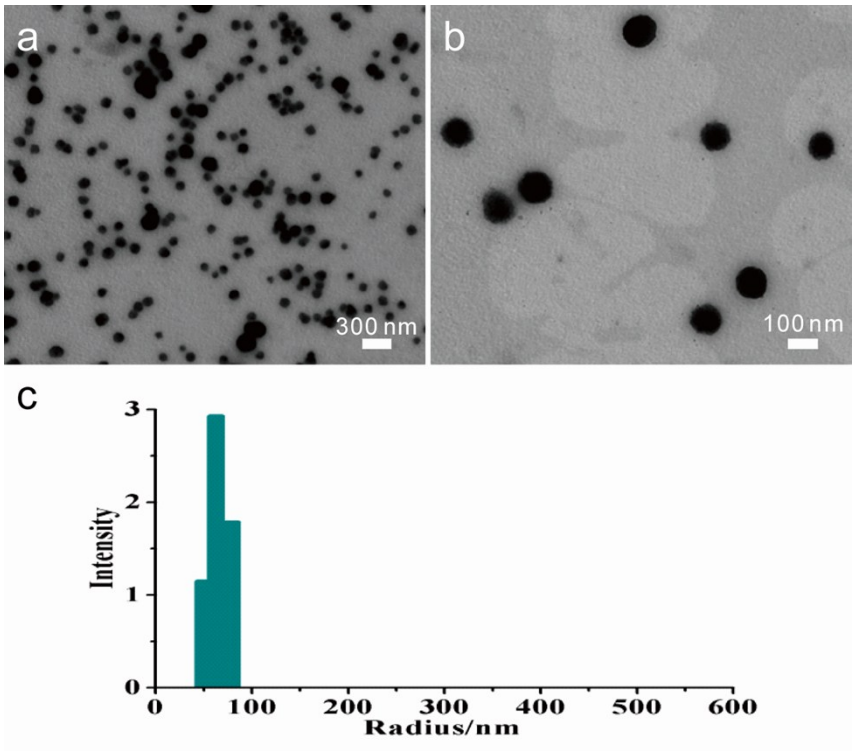

Fig. S18 TEM images of HA-Fc-CD/β-CD vesicles (7 mM) in water at room temperature, a) scale bar = 300 nm, b) scale bar = 100 nm, c) DLS radius distribution of HA-Fc-CD/β-CD vesicles (7 mM) in water at room temperature.

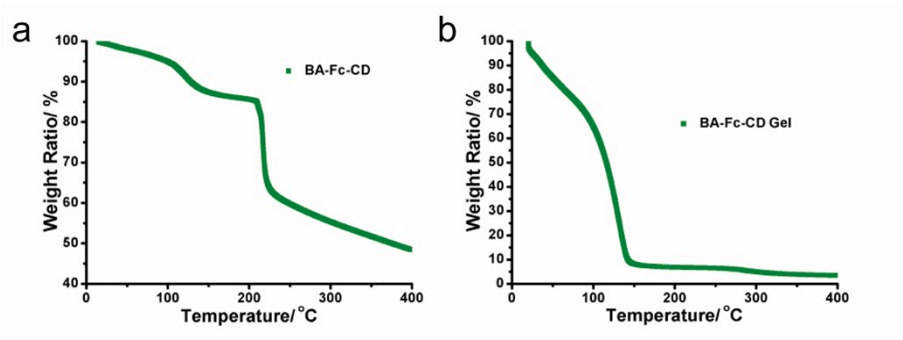

Fig. S19 TGA thermogram comparison of BA-Fc-CD and BA-Fc-CD gel.

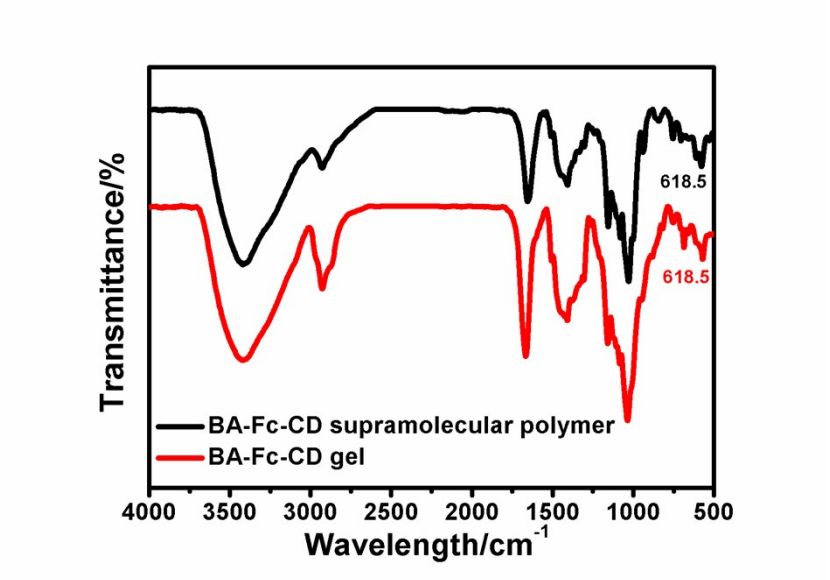

Fig. S20 FT-IR spectra of dried BA-Fc-CD supramolecular polymer fibers and dried BA-Fc-CD gel.

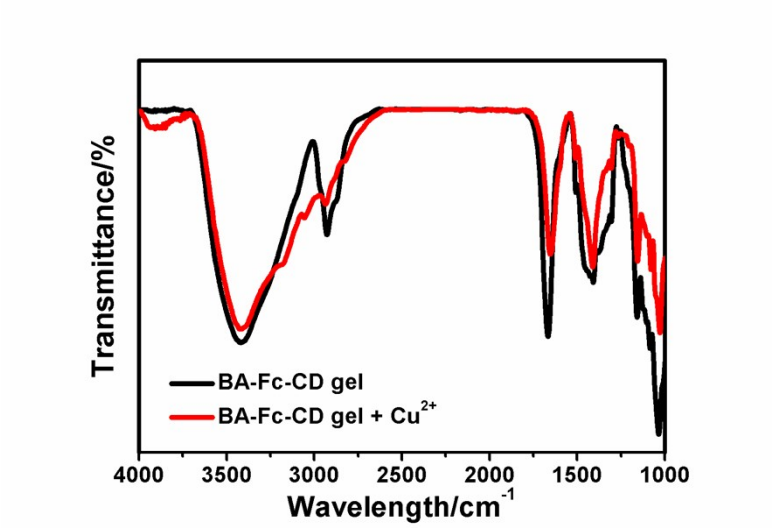

Fig. S21 FT-IR spectra comparison of dried BA-Fc-CD gel and BA-Fc-CD gel treated with one equivalent copper ions.

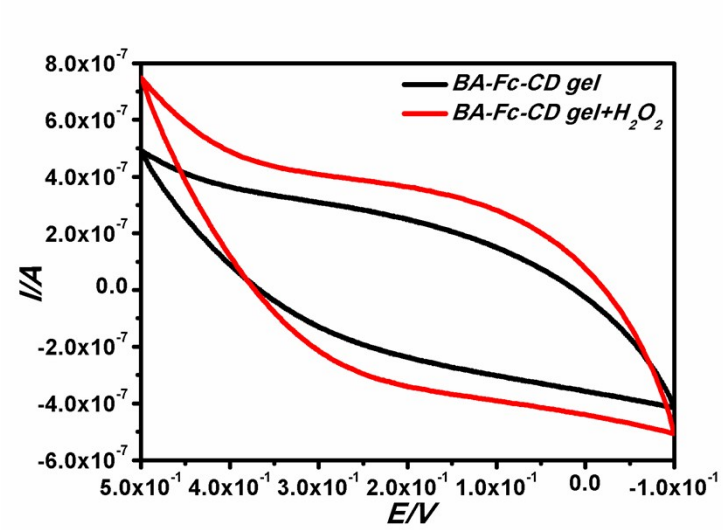

Fig. S22 Cyclic voltammograms comparison of the BA-Fc-CD gel and BA-Fc-CD gel treated with one equivalent H_2O_2 at room temperature.

References

1. T. Sun, Q. Guo, C. Zhang, J. Hao, P. Xing, J. Su, S. Li, A. Hao and G. Liu, Langmuir, 2012, 28, 8625-8636.