Electronic Supplementary Information

An efficient strategy to achieve hydrophilic polymeric silver(I) materials with exceptional antibacterial activity

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Contents

1. Materials and General Methods

All reagents and solvents for synthesis and analysis were commercially available and used as received.

Fourier transform (FT) IR data (KBr pellets) were recorded on a Nicolet ESP 460 FT-IR spectrometer.

Elemental analyses of carbon, hydrogen and nitrogen were performed on a PE-2400II (Perkin-Elmer) analyzer.

Melting points were obtained in sealed glass capillaries under N_2 on a WRS-2 melting point apparatus (Shen-Guang, Shang Hai) and are uncorrected.

Thermogravimetric analysis (TGA) experiments were carried out on a Dupont thermal analyzer from room temperature to 800 °C at a heating rate of 10 °C min^{-1} under nitrogen stream.

Light scattering: Dynamic light scattering (DLS) experiments were conducted using a Malvern Zetasizer, NANO ZS apparatus (Malvern Instruments Limited, U.K.) equipped with a 4 mW He-Ne laser operating at 633 nm, an avalanche photodiode detector with high quantum efficiency, and an ALV/LSE-5003 multiple tau digital correlator electronics system. Aqueous electrophoresis measurements were carried out on a water solution (0.2 wt%) of the complex at room temperature and at a scattering angle of 173°, known as backscatter detection.

ESI-MS analysis: Mass spectrometry measurements were performed on a Thermo-Scientific LCQ-Fleet ion trap instrument by electrospray ionization (ESI). The sample was dissolved in water (containing 0.1% methanol) with concentration of ca. 1 mg·mL^{-1}, and was introduced to the ion source by an infusion of 10 μL·min^{-1} and a capillary temperature of 289.94 °C. The voltages of the capillary and cone were –45.04 V and 4.03 kV in the negative mode. Each mass spectrum, acquired in the *m*/*z* range of 200–2000, was obtained as an average result of 50 scans, with each one requiring 0.1 s. The Mass Frontier software (HighChem, Slovakia) was used to confirm the suggested identity and structure of compound based on observed fragmentation patterns.

Titration analysis: To determine the amount of released Ag(I) ion in water, the Mohr's titration method was used at room temperature, and a typical titration procedure was shown as follows. Complex **1** (713.3 mg, 0.37 mmol) was dissolved in deionized water (300 mL) in a prerinsed beaker. Then, the solution was transferred to a volumetric flask (500 mL) and deionized water was added to the mark. The total Ag content was also determined by ICP (Varian Vista AX) analysis, which was in agreement with the calculated value based on single-crystal structure. Then, different volumes (6.7, 13.3, 16.7, 20.0, 26.7, 33.3, 50.0, 66.7, and 83.3 mL) of solutions were transferred to volumetric flasks (100 mL) and diluted to 100 mL with deionized water. Those solutions were titrated by a standardized NaCl solution (1×10^{-3} mol·L^{-1}) with potassium chromate (0.1 mol·L^{-1}) as an indicator. The amount of free Ag^+ ion is based on the corresponding consumption amount of chloride anion. Reproducibility was confirmed by repeating each measurement three times. For **2a** and **2b**, the same procedure was used. The linear least-squares fits of the experimental data were performed by using Microcal Origin software (Origin 7.5).

Antimicrobial tests: Cultures of *Staphylococcus aureus* CGMCC 1.1361, *Escherichia coli* CGMCC 1.1100, and *Bacillus subtilis* CGMCC 1.1628 were grown in LB broth. Fresh overnight culture (5 h for *S. aureus* and *E. coli* at 37 °C, and 12 h for *B. subtilis* at 37 °C, respectively) was inoculated into LB broth containing 500 μg·mL^{-1} of a sample and incubated at 37 °C for 12 h. On the compounds showing no turbidity after incubation, a more extensive test was performed. The MIC (the lowest concentration of silver complex leading to turbidity) was measured by using a series of glass test-tubes containing the compound in concentration of 500.00, 250.00, 125.00, 62.50, 31.25, 15.63, 7.81, 3.91, 1.95, 0.98, 0.49 and 0.24 μg·mL^{-1}. Each tube was inoculated with exponential-growth-phase organisms (*S. aureus*, *E. coli* or *B. subtilis*) to a 1% concentration and incubated at 37 °C for 12 h. The optical density at 660 nm was measured before and after incubation. Broth containing bacteria alone was used as a positive control and, for comparison, bacteria were also tested in broth supplemented with 15 μg·mL^{-1} of chloramphenicol. Each test was performed in duplicate.

2. Experimental Section

Synthesis of 1

A methanol solution (2 mL) of H_2L (24 mg, 0.1 mmol) was added to a DMF/methanol solution (2 mL/2 mL) of silver nitrate (34 mg, 0.2 mmol) in a beaker, which was then covered with aluminum foil and allowed to stir for ca. 15 min. The resulting solution was filtered and left to stand at room temperature. Needle colorless single crystals suitable for X-ray analysis were obtained after several days in ca. 75% yield (53 mg, based on H_2L). Elemental analysis (%) calcd for $C_{38}H_{14}Ag_8F_{16}N_2O_{18}$: C, 47.42; H, 3.41; N, 7.90. Found: C, 47.35; H, 3.42; N, 7.93. m. p. > 102.8 ^oC (dec, see also Fig. S7). IR (KBr, cm^{-1}): 3364bs, 1641s, 1600vs, 1573s, 1487m, 1444s, 1413s, 1335vs, 1218m, 1151m, 1117w, 1069m, 1037m, 1095m, 947w, 853m, 753m, 697s, 616s.

Syntheses of 2a and 2b

Synthesis of **2a**: The similar synthetic procedure as that for **1** was used except that imidazole (7 mg, 0.1 mmol) was added, affording colorless block crystals in ca. 71% yield (50 mg, based on H_2**L**). Elemental analysis (%) calcd for $C_{19}H_7Ag_4F_8NO_9$: C, 47.42; H, 3.41; N, 7.90. Found: C, 47.49; H, 3.41; N, 7.85. m. p. > 112.5 ^oC (dec, see also Fig. S7). IR (cm^{-1}): 3428bs, 2932w, 1681s, 1602vs, 1507m, 1465m, 1379vs, 1261w, 1105w, 1059m, 942w, 859w, 753m, 726m, 661w, 613w.

Synthesis of **2b**: The similar synthetic procedure as that for **2a** was used except that imidazole was replaced by 2,2'-bipyridine (16 mg, 0.1 mmol), forming colorless sheet crystals in ca. 77% yield (55 mg, based on H_2**L**). Elemental analysis (%) calcd for $C_{19}H_7Ag_4F_8NO_9$: C, 47.42; H, 3.41; N, 7.90. Found: C, 47.45; H, 3.42; N, 7.82. m. p. > 139.2 ^oC (dec, see also Fig. S7). IR (cm^{-1}): 3338bs, 2930w, 1681s, 1624vs, 1507m, 1462m, 1380vs, 1262w, 1105w, 1060m, 942w, 840w, 753m, 726m, 660w, 614w.

X-ray Crystallographic Studies

Single-crystal X-ray diffraction data collection was carried out on a Bruker SMART Apex II CCD-based X-ray diffractometer by using graphite-monochromated Mo K α radiation (λ = 0.71073 Å). Crystal data for **1**: monoclinic, space group $P2_1/c$, a = 17.9401(17), b = 12.8038(11), c = 23.0195(16) Å, β = 120.181(5)° , V = 4570.8(7) Å^3, Z = 4, ρ_{calcd} = 2.839 g cm^{-3}, μ = 3.498 mm^{-1}, 25557 reflections collected, 8358 independent reflections, R (all data) = 0.0412, wR (all data) = 0.0895, GOF = 1.003. Crystal data for **2a**: triclinic, space group $P\bar{1}$, a = 7.659(7), b = 11.510(10), c = 13.686(12) Å, α = 74.096(9), β = 82.415(9), γ = 76.996(9)° , V = 1127.4(16) Å^3, Z = 2, ρ_{calcd} = 2.877 g cm^{-3}, μ = 3.546 mm^{-1}, 7708 reflections collected, 3886 independent reflections, R (all data) = 0.0441, wR (all data) = 0.1393, GOF = 1.076. Crystal data for **2b**: monoclinic, space group $P2_1/c$, a = 15.6663(14), b = 11.4910(11), c = 13.2146(12) Å, β = 108.8200(10)° , V = 2251.7(4) Å^3, Z = 4, ρ_{calcd} = 2.881 g cm^{-3}, μ = 3.551 mm^{-1}, 19131 reflections collected, 5200 independent reflections, R (all data) = 0.0295, wR (all data) = 0.0781, GOF = 1.087. CCDC 805806 – 805808 contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

3. Stability testing of samples

The stability of samples in water solutions was tested in air at room temperature. Water solutions of $AgNO_3$ (0.4 wt%), the reference sample ($AgNO_3$-H_2L), and complexes **1**, **2a** and **2b** were stored under ambient conditions in the laboratory (florescent lighting). Black precipitations were formed after one week in the bottom of the tubes containing the former two solutions. However, the solutions of the three complexes **1**, **2a** and **2b** were clear for more than one month.

4. Molecular structures of complexes 2a and 2b

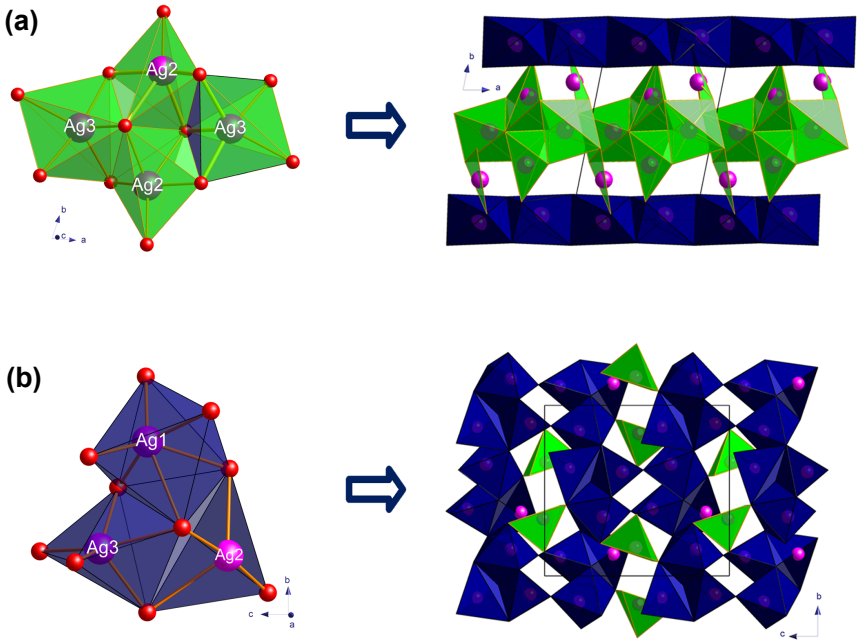

Fig. S1 Edge-sharing polynuclear subunits: tetranuclear $[Ag_4O_{12}]$ for **2a** (a), and trinuclear $[Ag_3O_{10}]$ for **2b** (b) and their 2D inorganic connectivity with 1D arrays highlighted as blue polyhedra.

5. ESI-MS spectra in water solution

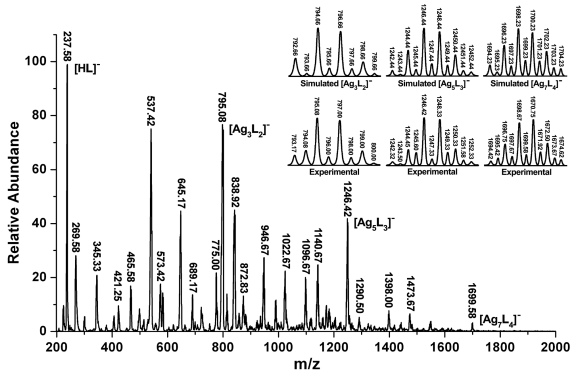

Fig. S2 ESI-MS (negative ion mode) of **1** in water (containing 0.1% methanol) using a cone voltage of 4.03 kV. Simulated (top) and experimental (bottom) isotopic distributions for the anionic species $[Ag_3L_2]^-$, $[Ag_5L_3]^-$ and $[Ag_7L_4]^-$ are shown.

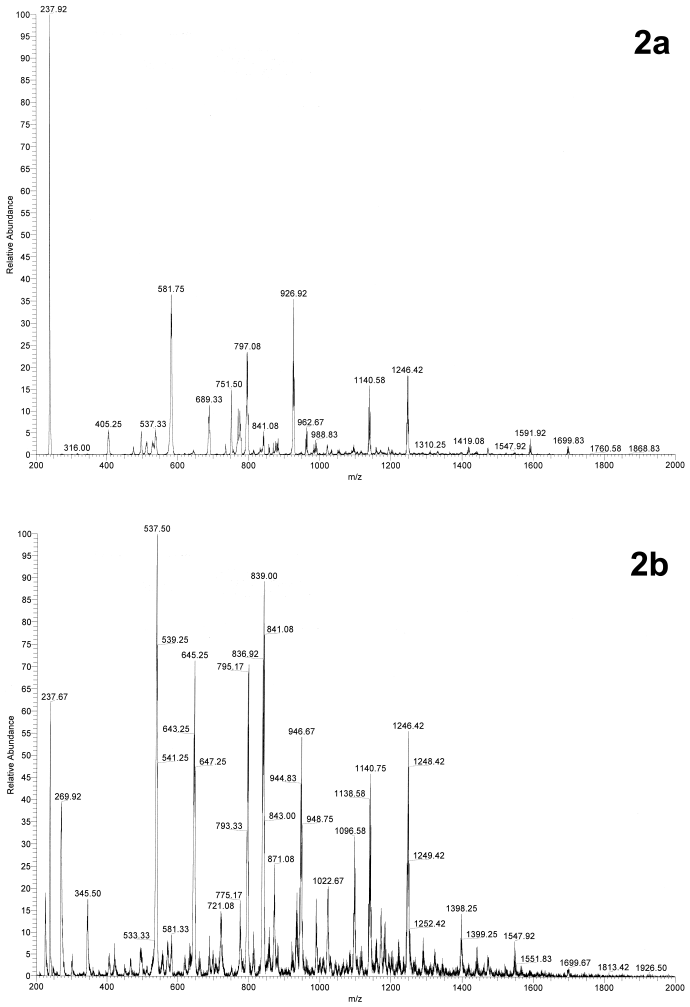

Figure S3 ESI-MS (negative ion mode) spectra of **2a** and **2b** in water solution (containing 0.1% methanol) using a cone voltage of 4.03 kV.

6. Photos of antibacterial testing results

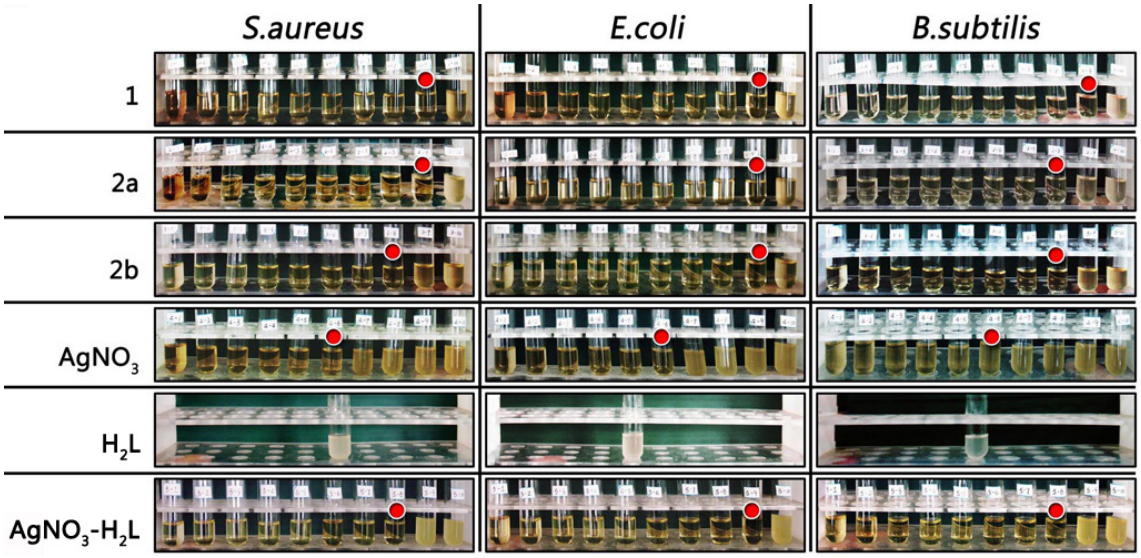

Figure S4 Photos of antibacterial testing results for **1**, **2a**, **2b**, $AgNO_3$, H_2**L** and $AgNO_3$-H_2**L** against *S. aureus, E. coli, and B. subtilis.* The concentrations are reduced from left to right, and these in the test tubes with red dots are MICs of samples.

7. Single-crystal photographs

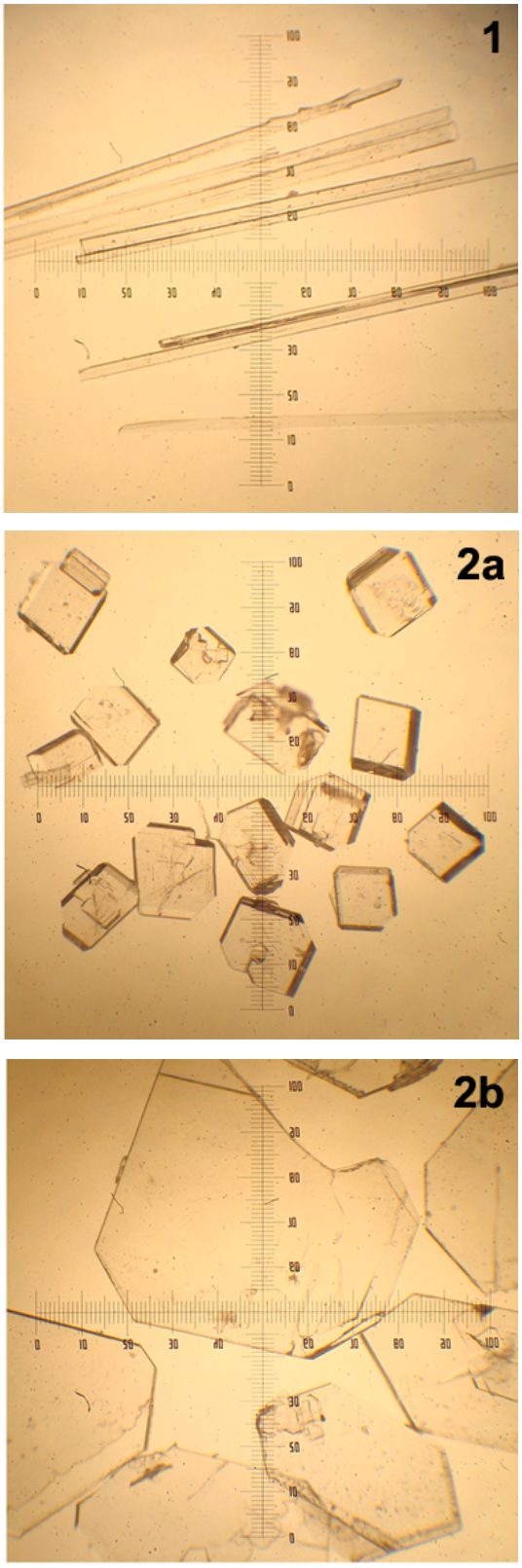

Figure S5 Single-crystal photographs of **1**, **2a** and **2b** (ruler scale: 0.025 mm).

8. Infrared spectra

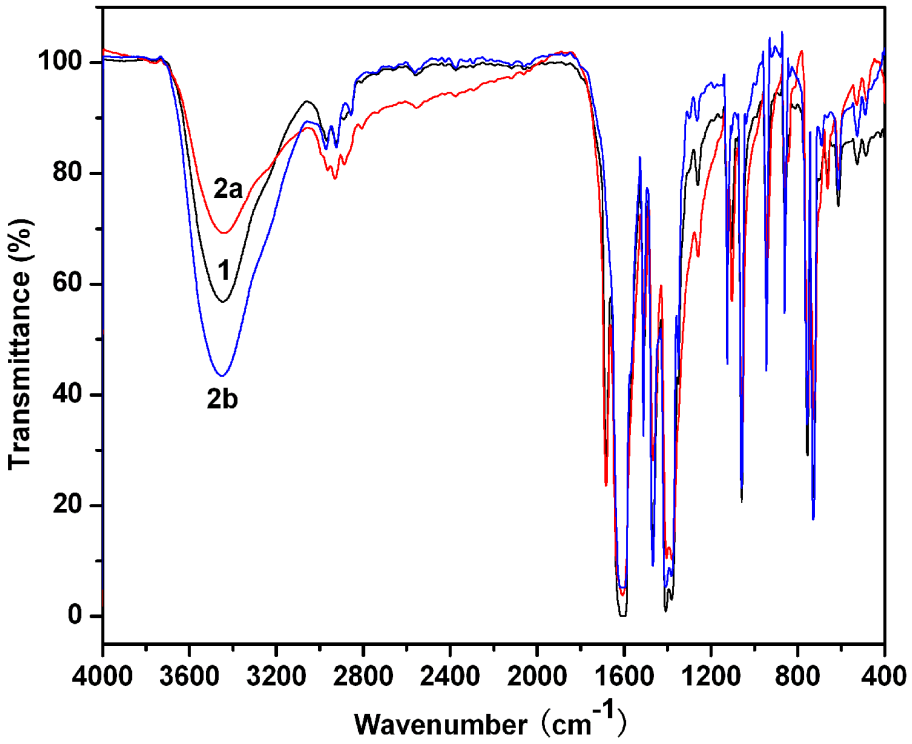

Figure S6 Infrared spectra of complexes **1**, **2a** and **2b**.

9. TGA curves

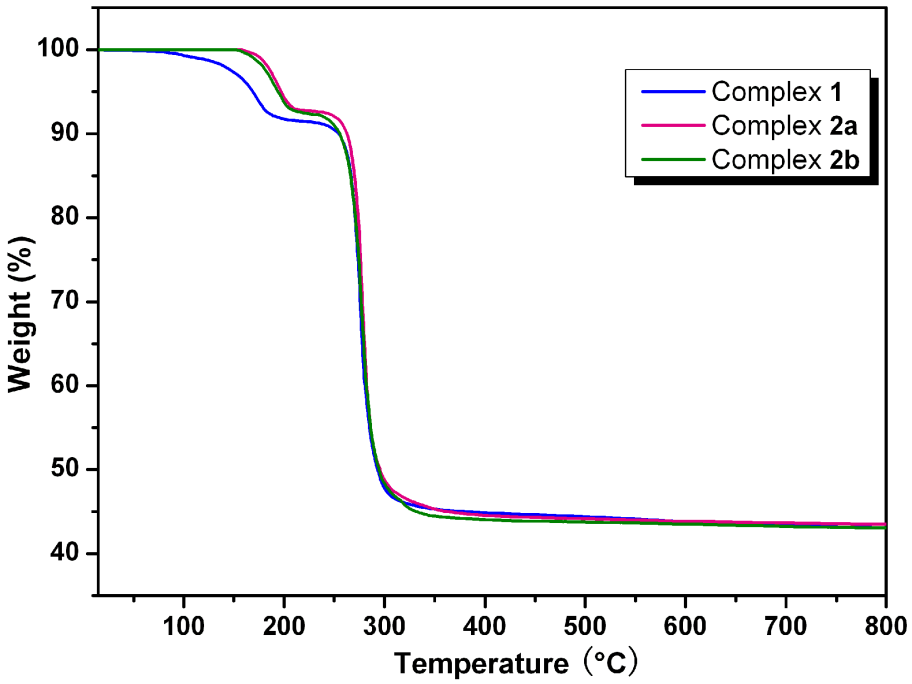

Figure S7 TGA curves of **1**, **2a** and **2b**.