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2D and 3D silver-based coordination polymers with thiomorpholine-4-carbonitrile and piperazine-1,4-dicarbonitrile: structure, intermolecular interactions, photocatalysis, and thermal behavior

Predrag Ristić, Nenad R Filipović, Vladimir Blagojević, Jovana Ćirković, Berta Barta Holló, Veljko R Đokić, Morgan Donnard, Mihaela Gulea, Ivana Marjanović, Olivera R Klisurić, et al.

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1D and 2D silver-based coordination polymers with thiomorpholine-4-carbonitrile and aromatic polyoxoacids as co-ligands: structure, photocatalysis, photoluminescence and TD-DFT study

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4 **carbonitrile and aromatic polyoxoacids as co-ligands: structure,**
5 **photocatalysis, photoluminescence and TD-DFT study**
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Abstract

Four silver-based coordination polymers $\{[\text{Ag}(\text{L})_2](\text{BF}_4)\}_\infty$ (**1**), $\{[\text{Ag}(\text{H}_2\text{BTC})(\text{L})]\times(\text{H}_3\text{BTC})\}_\infty$ (**2**), $\{[\text{Ag}_2(\text{H}_2\text{BTEC})(\text{L})_2] \times 3.33\text{H}_2\text{O}\}_\infty$ (**3**) and $[\text{Ag}(\text{H}_2\text{5SSA})(\text{L})]_\infty$ (**4**) were synthesized using thiomorpholine-4-carbonitrile (L) as the primary ligand and three aromatic polyoxoacids as co-ligands: trimesic (H_3BTC), pyromellitic (H_4BTEC) and 5-sulfosalicylic acid ($\text{H}_3\text{5SSA}$). Compounds **1** and **3** are two-dimensional, while **2** and **4** are one-dimensional. L acts as a *bis*-monodentate ligand, while Ag(I) ion is three-coordinated in **2**, and four-coordinated in all the other compounds. Tetrahedral coordination of Ag(I) in **3** leads to an almost complete absence of intermolecular interactions with the metal center. All compounds show reasonable photocatalytic activity for photocatalytic degradation of mordant blue 9 dye, with reaction rates in 0.036–0.056 min^{-1} range. Changes in the reaction rates can be correlated with the type and coordination of the co-ligand. Complex **3** exhibits photoluminescence at 77 K, while **4** exhibits photoluminescence at both room temperature and 77 K. Luminescence lifetimes indicate electronic transitions of singlet parentage, where transitions are allowed. TD-DFT study determined the contributions of individual singlet-singlet electronic excitations to the fluorescence, indicating that metal- intra ligand transitions is responsible for luminescence in both complexes.

Keywords: Silver complexes; Coordination polymers; Intermolecular interactions; Photoluminescence; Photocatalysis; TD-DFT.

1. INTRODUCTION

The investigation of coordination polymers (CPs) is a rapidly growing field of material science. 1D–3D CPs have been studied because of the wide range of potential applications, predominantly in catalysis, gas storage and separation, optoelectronics and sensors, molecular electronics, nanomaterial synthesis, illumination and photodetection.^{1–15} Silver is among the top ten metals used for the preparation of 2D CPs,^{16,17} while 8 % of all CPs (1D–3D) deposited in CSD MOFs subset¹⁸ are Ag-CPs. The ability to adopt coordination numbers from 2 to 6, thus offering various coordination geometries, makes silver a viable metal of choice for the synthesis of CPs.¹⁹ In addition, coordination numbers higher than six have been observed in some of Ag-CPs.^{20,21} Structural diversity of Ag-CPs is not only influenced by supramolecular Ag \cdots ligand, Ag $\cdots\pi$, C–H $\cdots\pi$, π - π stacking and anion interactions, as well as H-bonds,^{22,23} but also by

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3 argentophilic (Ag \cdots Ag) and Ag \cdots C interactions.^{24,25} Finally, the structures of Ag-CPs are
4 heavily influenced by the nature of the anion of the starting silver salt.^{26–30} In the case of 1D Ag-
5 CPs, linear, zigzag, helical, ladder and 1D coordination tubes have been identified.²² In 2013, the
6 first ribbon topology was observed for one 1D Ag-CP.³¹ More recently, the structure with metal
7 cluster topology was discovered,³² making rotaxane topology the only unrealized topology type
8 of 1D Ag-CPs up to now. On the other hand, representative topologies of 2D Ag-CPs include **sql**
9 and **hcb**.¹⁸

10 Ag-CPs may undergo structural transformation induced by light,³³ heating,^{34,35}
11 solvation,^{36–40} desolvation,³⁵ guest molecule^{40,41} and anion exchange^{26,36,42,43} stimuli. They can be
12 used as precursors for the preparation of Ag nanoparticles by heating^{25,44} or ultrasonic
13 irradiation.⁴⁵ Some of the investigated Ag-CPs form metallogels^{28,46–52} showing interesting
14 properties, such as the ability to sense hazardous gases.⁴⁹ Metallogels can also act as precursors
15 for Ag-based nanoparticles which can be obtained in situ,⁴⁹ spontaneously⁴⁶ or upon exposure to
16 light.⁵⁰ These nanoparticles exhibit luminescence properties,⁵¹ as well as the ability to be
17 reversibly assembled or disassembled by various stimuli.⁵² Finally, Ag-CPs metallogels can
18 display thixotropic behavior,⁴⁷ stimuli-responsive to some anions as well as antibacterial
19 properties.⁴⁷ A wide variety of functional properties makes Ag-CPs useful for different
20 applications. These properties include antibacterial activity,^{47,53} gas sensing,⁴⁹ proton
21 conductivity, high capacitance and good cycling ability,^{54,55} and chemical sensing.^{19,56} Moreover,
22 Ag-CPs might play a significant role in environmental remediation,^{57–59} as they have been
23 tailored to achieve a particular mechanism of oxoanion exchange to maximize their
24 effectiveness.⁶⁰ Most recently, there were several reports on Ag-CPs manifesting excellent
25 catalytic and photocatalytic properties.^{61–64} Environmentally friendly and recyclable Ag-CP with
26 9,10-anthraquinone-1,4-dicarboxylate acid catalyzed the reaction of the visible-light-driven
27 aerobic oxidation of alkynes into 1,2-diketones under ambient conditions.⁶¹ 1D Ag-CPs with
28 N',N'-2,2-tetrakis(diphenylphosphanyl)methylthiocarbohydrazide showed exceptional
29 performance as a photocatalyst for degradation of organic dyes in water, while-generating higher
30 photocurrent response than molecular complexes with the same ligand.⁶² Nano-microstructured
31 Ag-CPs offer performance at a level competitive with known semiconductors in photocatalytic
32 water splitting and degradation of organic pollutants and dyes.⁶³ They exhibit a highly reactive
33 valence band potential and could be readily recycled, maintaining high activity after four uses.

Two Ag-CPs constructed using Co-metalloligands act as recyclable heterogeneous catalysts for the A3-coupling reactions of aldehydes, secondary amines and alkynes,⁶⁴ where the relative position of substituted pyridyl ring affected both the resulting coordination polymer structures and their catalytic activity.

Luminescent CPs are of great interest since they have been employed in sensing (metal ions, solvents and explosives) and (bio)imaging.⁶⁵⁻⁶⁸ Some of the investigated Ag-CPs showed potential for ion^{19,21,56,59} and solvent⁶⁹ sensing. In that sense, the goal of our work is the preparation of novel Ag-CPs, characterization of their luminescent properties at both low and room temperature, and explanation of its origin using TD-DFT. For the preparation of Ag-CPs, we used thiomorpholine-4-carbonitrile (L) and aromatic polyoxoacids as co-ligands (trimesic acid, H₃BTC; pyromellitic acid, H₄BTEC and 5-sulfosalicylic acid, H₃5SSA, Figure 1). L was chosen as a ligand since it belongs to the class of *bis*-monodentate ligands which are able to form Ag-CPs⁷⁰⁻⁷², although it has never been used for this purpose. On the other hand, selected co-ligands showed photoluminescent properties⁷³⁻⁷⁵ and can easily form Ag-CPs^{56,73,84,85,76-83} – photoluminescent in some cases.^{76-83,85,86}

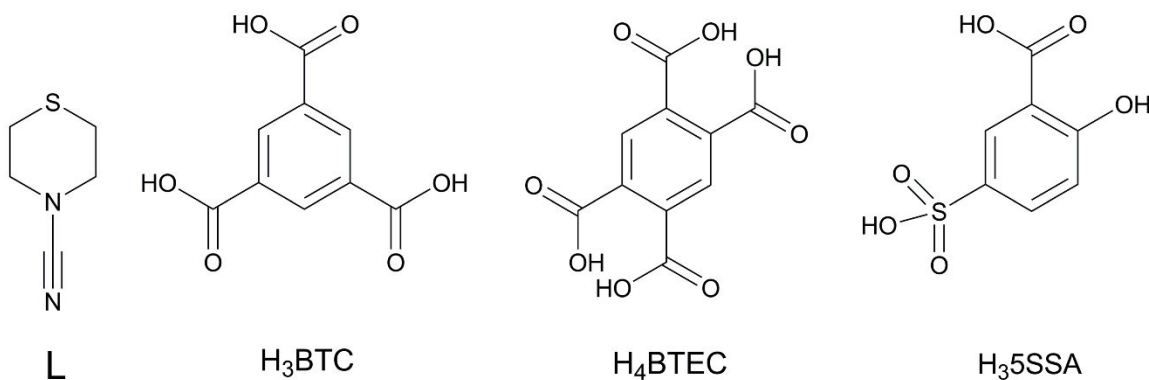


Figure 1. Structures of L and aromatic polyoxoacids co-ligands.

2. EXPERIMENTAL

2.1. Materials and methods

All the employed reagents and solvents were of analytical grade and used without further purification. AgNO_3 ($\geq 99.0\%$), AgBF_4 (98 %), 1,2,4,5-benzenetetracarboxylic acid (96 %) and 5-sulfosalicylic acid dihydrate ($\geq 99.0\%$) were obtained from Aldrich (Sigma-Aldrich Chemie GmbH, Steinheim, Germany). 1,3,5-benzenetricarboxylic acid ($\geq 95.0\%$) was obtained from Merck. Elemental analyses (C, H, N, S) were performed by the standard micro-methods using the ELEMENTARVario ELIII C.H.N.S=O analyzer. Infra-red (IR) spectra were recorded on a Thermo Scientific Nicolet 6700 FT-IR spectrometer by the Attenuated Total Reflection (ATR) technique in the region $4000\text{--}400\text{ cm}^{-1}$. Abbreviations used for IR spectra: vs, very strong; s, strong; m, medium; w, weak. The NMR spectra were performed on a Bruker Avance 500 equipped with a broad-band direct probe.

2.2. Synthesis of the ligand thiomorpholine-4-carbonitrile (L)

The ligand was synthesized according to a modified literature procedure.⁸⁷ In a round bottom flask, thiomorpholine (1 equiv., 1 mmol), acetonitrile (0.5 M, 2 mL) and tetramethylethylenediamine (232 mg, 2 equiv., 2 mmol) were mixed together. Then CuCN (179 mg, 2 equiv., 2 mmol) was added and the mixture was flushed with oxygen. The reaction solution was then let to stir under 1 atmosphere of O_2 for 18 h. After a short filtration over Celite® that was rinsed thrice with AcOEt ($3 \times 3\text{ mL}$), the crude mixture was concentrated under vacuum and purified by flash column chromatography (Pentane/AcOEt, SiO_2) to afford the entitled product. Yield 0.12 g (94%). White solid; m.p.: $41\text{--}43\text{ }^\circ\text{C}$. Anal. Calcd. for $\text{C}_5\text{H}_8\text{N}_2\text{S}$ ($MW = 128.19$): C, 46.85; H, 6.29; N, 21.85; S 25.01 %. Found: C, 46.65; H, 6.73; N, 21.74; S 25.12 %. ^1H NMR (CDCl_3 , 500.26 MHz) δ_{H} : 2.70 (t, 4H), 3.46 (t, 4H); ^{13}C NMR (CDCl_3 , 126 MHz) δ_{C} : 26.1, 50.8, 117.4.

2.3. Synthesis of $\{[\text{Ag}(\text{L})_2](\text{BF}_4)\}_\infty$ (1)

A mixture of AgBF_4 (38.00 mg, 0.195 mmol) and L (50.00 mg, 0.393 mmol) dissolved in H_2O (5 ml) was placed in amber round bottom flask. Reaction mixture was refluxed for 1 h. Colorless single crystals suitable for X-ray diffraction analysis were obtained by slow evaporation and separated by filtration from colorless water solution. Yield: 0.017 g (19 %). Anal. Calcd. for

$C_{10}H_{16}AgBF_4N_4S_2$ ($FW = 451.07$): C, 26.63; H, 3.58; N, 12.42; S 14.22 %. Found: C, 27.04; H, 3.65; N, 12.80; S, 14.38 %. IR (ATR, ν_{max}/cm^{-1}): 3384 (w), 2998 (w), 2978 (w), 2928 (w), 2867 (w), 2225 (vs), 1446 (m), 1393 (m), 1343 (m), 1285 (m), 1161 (m), 1098 (m), 1059 (s), 979 (m), 946 (m), 714 (w), 531 (w), 507 (w).

2.4. Synthesis of $\{[Ag(H_2BTC)(L)] \times (H_3BTC)\}_\infty$ (2), $\{[Ag_2(H_2BTEC)(L)_2] \times 3.33H_2O\}_\infty$ (3) and $[Ag(H_2SSA)(L)]_\infty$ (4)

A mixture of H_3BTC (82.00 mg, 0.390 mmol) in EtOH (5 ml), H_4BTEC (99.00 mg, 0.389 mmol) in MeOH (5 ml) or solid H_3SSA (98.00 mg, 0.400 mmol) was added to the mixture of $AgNO_3$ (66.00 mg, 0.388 mmol) and L (50.00 mg, 0.393 mmol) in H_2O (10 ml) and placed in amber round bottom flask. Reaction mixture was refluxed for 1 h. White single crystals of **2** and pale-yellow single crystals of **3** and **4**, suitable for X-ray diffraction analysis, were obtained by slow evaporation and separated by filtration from colorless water solution.

2: Yield 0.058 g (29.5 %). Anal. Calcd. for $C_{23}H_{19}AgN_2O_{12}S$ ($FW = 655.33$): C, 42.15; H, 2.92; N, 4.27; S, 4.89 %. Found: C, 41.90; H, 2.90; N, 4.25; S, 4.95 %. IR (ATR, ν_{max}/cm^{-1}): 3128 (m), 2927 (m), 2650 (m), 2527 (m), 2227 (vs), 1694 (vs), 1607 (m), 1447 (s), 1393 (s), 1363 (s), 1282 (s), 1213 (s), 1157 (s), 1121 (s), 1031 (m), 982 (m), 943 (s), 739 (m), 698 (m), 675 (m), 656 (m), 532 (m), 509 (m).

3: Yield 0.146 g (68 %). Freshly prepared sample: Anal. Calcd. for $C_{20}H_{20}Ag_2N_4O_8S_2 \times 3.33H_2O$ ($FW = 784.31$): C, 30.63; H, 3.43; N, 7.14; S, 8.18 %. Found: C, 30.70; H, 3.21; N, 7.27; S, 8.10 %. Sample dried in desiccator for seven days: Anal. Calcd. for $C_{20}H_{20}Ag_2N_4O_8S_2$ ($FW = 724.26$): C, 33.17; H, 2.78; N, 7.74; S, 8.85 %. Found: C, 33.05; H, 2.91; N, 7.57; S, 8.76 %. IR (ATR, ν_{max}/cm^{-1} ; dried sample): 2931 (w), 2824 (w), 2511 (w), 2222 (s), 1822 (w), 1676 (vs), 1608 (s), 1490 (s), 1420 (s), 1378 (s), 1285 (s), 1169 (s), 1128 (s), 988 (s), 945 (s), 911 (s), 767 (s), 947 (m), 552 (m), 470 (w).

4: Yield 0.111 g (52 %). Anal. Calcd. for $C_{12}H_{13}AgN_2O_6S_2$ ($FW = 453.23$): C, 31.80; H, 2.89; N, 6.18; S, 14.15 %. Found: C, 31.52; H, 2.78; N, 6.12; S, 14.20 %. IR (ATR, ν_{max}/cm^{-1}): 3000 (w), 2793 (m), 2581 (w), 2500 (w), 2244 (m), 1666 (s), 1610 (m), 1179 (m), 1434 (m), 1370 (m), 1285 (m), 1233 (m), 1200 (m), 1166 (vs), 1118 (s), 1023 (s), 942 (m), 835 (w), 804 (w), 780 (w), 757 (w), 715 (w), 663 (w), 588 (s), 534 (w).

2.5. X-ray crystallography

X-ray diffraction data for **1–3** were collected at room temperature using Graphite-monochromated CuK α radiation ($\lambda = 1.54184 \text{ \AA}$) on an Oxford Diffraction Gemini S diffractometer. CrysAlisPro and CrysAlis RED software packages⁸⁸ were used for data collection and data integration. X-ray diffraction data for **4** were collected at 173 K on the Bruker APEX-II CCD diffractometer. Graphite-monochromated MoK α radiation ($\lambda = 0.71073 \text{ \AA}$) was used to measure diffraction from suitable single crystals of **4**. Bruker APEX2 and Bruker SAINT software packages⁸⁹ were used for data collection and data integration. Space group determinations for **1–4** were based on analysis of the Laue class and systematically absent reflections. Collected data for **1–3** were corrected for absorption effects using analytical numeric absorption correction applying a multifaceted crystal model,⁹⁰ while for **4** we used the multi-scan method, applying an empirical absorption correction using spherical harmonics as implemented in SADABS.⁸⁹ Structure solution and refinement for **1–4** were carried out with the programs SHELXT⁹¹ and SHELXL-2018/3,⁹² respectively. MERCURY⁹³ was employed for molecular graphics and WinGX⁹⁴ software was used to prepare material for publication. Non-hydrogen atoms were refined anisotropically while hydrogen atoms in **1** and **2** were treated by constrained isotropic refinement. On the other hand, hydrogen atoms in **3** and **4** were treated by a mixture of independent and constrained refinement. Even though complex **3** has disordered crystalline water molecules we presented its structure as it is, using SHELXL DFIX instructions to restrain O–H bond lengths. Crystal data and refinement parameters for **1–4** are summarized in Table 1. We also treated complex **3** by the SQUEEZE routine, implemented in Platon⁹⁵, to remove the disordered water molecules and presented crystal data and refinement parameters in Table S1 (Electronic supplementary material, ESI). Topological analysis was performed with the ToposPro program package and the TTD collection of periodic network topologies.⁹⁶

Table 1. Crystallographic data and refinement parameters for **1–4**.

<i>Crystal data</i>				
Compound	1	2	3	4
Chemical formula	2(C ₅ H ₈ Ag _{0.50} N ₂ S)·BF ₄	C ₂₃ H ₁₉ AgN ₂ O ₁₂ S	C ₃₀ H ₃₀ Ag ₃ N ₆ O ₁₂ S ₃ × 5H ₂ O	C ₁₂ H ₁₃ AgN ₂ O ₆ S ₂
<i>FW</i>	451.07	655.33	1176.47	453.23
Crystal system	Tetragonal	Triclinic	Monoclinic	Monoclinic
Space group	<i>P</i> -42 ₁ <i>m</i>	<i>P</i> -1	<i>P</i> 2 ₁ / <i>n</i>	<i>P</i> 2 ₁ / <i>n</i>
<i>a</i> (Å)	13.1613 (6)	9.6126 (5)	9.8212 (10)	12.8066 (4)
<i>b</i> (Å)	13.1613 (6)	11.9927 (8)	26.3006 (4)	8.7191 (3)
<i>c</i> (Å)	4.4326 (6)	12.1218 (6)	16.2293 (3)	13.4239 (6)
α (°)	90	67.755 (6)	90	90
β (°)	90	78.686 (5)	93.666 (10)	97.048 (3)
γ (°)	90	68.517 (6)	90	90
<i>V</i> (Å ³)	767.81 (13)	1200.86 (14)	4183.51 (11)	1487.61 (10)
<i>Z</i>	2	2	4	4
<i>D</i> _x (Mg m ⁻³)	1.951	1.812	1.868	2.024
μ (mm ⁻¹)	13.49	8.20	13.24	1.67
Crystal size (mm)	0.28 × 0.08 × 0.07	0.13 × 0.10 × 0.09	0.37 × 0.16 × 0.07	0.40 × 0.20 × 0.15
<i>Data collection</i>				
Absorption correction	Analytical	Analytical	Analytical	Multi-scan
<i>T</i> _{min} , <i>T</i> _{max}	0.178, 0.466	0.487, 0.606	0.094, 0.482	0.651, 0.746
Reflections collected	3187	7362	16229	29703
Independent reflections	799	4504	7963	5109
Observed reflections [<i>I</i> > 2σ(<i>I</i>)]	744	4022	6801	4548
<i>R</i> _{int}	0.034	0.025	0.026	0.018
Range of <i>h</i> , <i>k</i> , <i>l</i>	<i>h</i> = -16 → 13 <i>k</i> = -15 → 7 <i>l</i> = -5 → 4	<i>h</i> = -11 → 11 <i>k</i> = -14 → 14 <i>l</i> = -14 → 11	<i>h</i> = -12 → 11 <i>k</i> = -32 → 20 <i>l</i> = -19 → 19	<i>h</i> = -19 → 19 <i>k</i> = -12 → 12 <i>l</i> = -19 → 19
θ values (°)	$\theta_{\max} = 72.8$, $\theta_{\min} = 4.8$	$\theta_{\max} = 72.6$, $\theta_{\min} = 4.0$	$\theta_{\max} = 71.7$, $\theta_{\min} = 3.2$	$\theta_{\max} = 32.0$, $\theta_{\min} = 2.1$
<i>Refinement</i>				
<i>R</i> [<i>F</i> ² > 2σ(<i>F</i> ²)], <i>wR</i> (<i>F</i> ²)	0.0373, 0.0955	0.0326, 0.0828	0.0326, 0.0786	0.0222, 0.0525
<i>R</i> [<i>all data</i>], <i>wR</i> 2	0.0410, 0.0998	0.0375, 0.0865	0.0393, 0.0823	0.0276, 0.0567
Goodness-of-fit (<i>S</i>)	1.058	1.025	1.031	1.086
No. of reflections	799	4504	7963	5109
No. of parameters	59	357	574	216
No. of restraints	0	0	136	0
$\Delta\rho_{\max}$, $\Delta\rho_{\min}$ (e Å ⁻³)	0.48, -0.39	0.48, -0.39	0.76, -0.73	0.52, -0.51
CCDC no.	1987944	1987947	1990303	1987949

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3 The X-ray powder diffraction experiment was conducted on Rigaku Smartlab X-ray
4 diffractometer in θ - θ geometry (the sample in horizontal position) in parafocusing Bragg-
5 Brentano geometry using D/teX Ultra 250 strip detector in 1D standard mode with
6 $\text{CuK}_{\alpha 1,2}$ radiation source ($U = 40$ kV and $I = 30$ mA). The XRPD patterns were collected in 5 - 65°
7 2θ range, with a step of 0.01° , and the data collection speed of $5^\circ/\text{min}$ with horizontal sample
8 rotation of 20 rpm. For every compound, a small amount of single-crystal sample was
9 pulverized, and low background single crystal silicon sample holder was used to minimize the
10 background. The crystal phases present in the samples were identified in dedicated Rigaku
11 PDXL 2.0 software, comparing them with user database comprised of CIFs previously obtained
12 by a single crystal X-ray diffraction.
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24 ***2.6. Hirshfeld surface analysis and intermolecular interaction energies***

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26 Hirshfeld surface analysis was carried out using the Crystallographic Information File.
27 Before calculating the surfaces, the lengths of the bonds which include hydrogen atoms were
28 normalized to standard values determined by neutron diffraction. The Hirshfeld surfaces
29 visualization and the presentation of the results as d_{norm} , shape index, and curvedness, as well as
30 the calculation of 2D fingerprint plots with d_e and d_i distances were performed by Crystal
31 Explorer v.17.5.^{97,98} The parameter d_{norm} represents the sum of the distance of the nearest nucleus
32 external to the surface (d_e) and the distance from the surface to the nearest nucleus internal to the
33 surface (d_i), normalized by the van der Waals radius of the atom. The surfaces were mapped over
34 a standard color scale, with the corresponding 2D fingerprint plots calculated using d_e and d_i
35 values in the range 0.4 – 2.8 Å. The intermolecular interaction energies were determined using
36 CrystalExplorer v17.5, with the wavefunction calculated using Gaussian09 software⁹⁹ with
37 B3LYP method and DGDZVP basis set.¹⁰⁰ The model systems were built from supercells of
38 different size by creating a non-polymeric system. This was achieved by removing the metal
39 centers, preserving whole ligand molecules, and capping eliminated covalent bonds with
40 hydrogen atoms to preserve the charge balance.
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52 ***2.7. TGA-DSC analysis***

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3 Thermal data were collected using the TA Instruments SDT Q600 thermal analyzer. The
4 decomposition was followed from room temperature to 400 °C at 10 °C min⁻¹ heating rate in
5 argon carrier gas (flow rate = 30 cm³ min⁻¹). Sample holder/reference is alumina crucible/empty
6 alumina crucible. The sample mass was 3–5 mg.
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10 11 12 **2.8. Photocatalytic and photophysical properties** 13

14 Mordant blue (MB9), a widespread environmental pollutant, is a commonly used dye in
15 the textile industry. A volume of 50 ml of dye solution in water ($c = 0.5$ mol/L), was mixed with
16 50 mg of each of the complexes. The powdered complexes were added to the water solution
17 under constant stirring and left in the dark for 15 min to equilibrate. The samples were
18 illuminated by a spotlight source (Hamamatsu LC5) from a distance of 1 cm (light intensity 5.2
19 mW/cm²). The decomposition rate of MB9 as a function of irradiation time was measured by a
20 Varian Cary 50 Scan UV-Vis spectrophotometer. A lamp with the emission in the UV and
21 visible part of the spectrum was turned on, followed by the extraction of 5 ml of solution at
22 regular intervals later measured in a UV/VIS spectrometer. MB9 has two main absorption
23 regions: around 330 and around 530 nm. The relative concentration of MB9 is tracked using
24 absorption intensities in these regions. The measured absorption intensities were used to
25 calculate relative concentrations of MB9 dye and the corresponding rate constants for the
26 photocatalytic degradation reaction of MB9 dye.¹⁰¹
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37 Diffuse reflectance UV-vis spectra of pressed powder samples diluted with KBr were
38 recorded on a Shimadzu (UV-3600 spectrophotometer with a Harrick Praying Mantis accessory)
39 and recalculated following the Kubelka–Munk function. Excitation and emission spectra in the
40 solid state were recorded with a Jobin-Yvon Horiba Fluorolog 3–22 Tau-3 spectrofluorimeter.
41 Lifetime measurements were recorded with a Datastation HUB-B with a nanoLED controller and
42 DAS6 software. The nanoLED employed for lifetime measurements were of 320 nm with pulse
43 lengths of 0.8–1.4 ns. The lifetime data were fitted with the Jobin-Yvon software package.
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55 56 **2.9. Computational details** 57

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Single point DFT and TD-DFT calculations were carried out for models **3** and **4**. In both the ground-state calculations and the subsequent calculations of the electronic excitation spectra, the B3LYP functional^{102–104} as implemented in TURBOMOLE¹⁰⁵ was used. The excitation energies were obtained at the density functional level by using the time dependent perturbation theory approach (TD-DFT),^{106–109} which is a DFT generalization of the Hartree-Fock linear response (HF-LR) or random-phase approximation (RPA) method.¹¹⁰ In all calculations, the Karlsruhe split-valence quality basis sets augmented with polarization functions^{111,112} were used for the light elements (SVP) whereas the def2-TZVP bases sets were used for Ag.¹¹³ The Stuttgart effective core potential in TURBOMOLE was used for Ag.¹¹⁴

3. RESULTS AND DISCUSSION

3.1 Molecular and crystal structures of 1–4

Complex **1** crystallizes in the tetragonal $P-42_1m$ space group. The asymmetric unit of **1** contains a Ag(I) and a tetrafluoroborate anion, both of a quarter occupancy, as well as a half of the L ligand. Ag(I) atoms are situated on a 2-fold axis along which two mirror planes intersect (Wyckoff position $2c$, site symmetry $2.mm$). Moreover, L lies on the (110) mirror plane (Wyckoff position $4e$, site symmetry $.m$) with half-occupancy, except for the C2 and C3 atoms in general positions. The F1 atom of the tetrafluoroborate anion is in a general position, while the quarter-occupancy B1 atom is located at the Wyckoff $2a$ position (site symmetry $-4..$). The part of infinite structure of **1** depicted in Figure 2A shows that Ls form a distorted tetrahedron around the Ag(I). The geometric index of distortion is $\tau_4 = 0.86$.¹¹⁵ Each of the Ag(I) ions in **1** is coordinated to two nitrogen and two sulfur atoms from four different L ligands. Selected bond lengths are given in Table 2. L acts as a bridging ligand with *bis*-monodentate coordination connecting the Ag(I) ions to form a two-dimensional coordination network (Figure 2B). The crystal packing of **1** comprises of 2D layers stacked along *c*-axis with a thickness of 4.57 Å (Figure 2C).

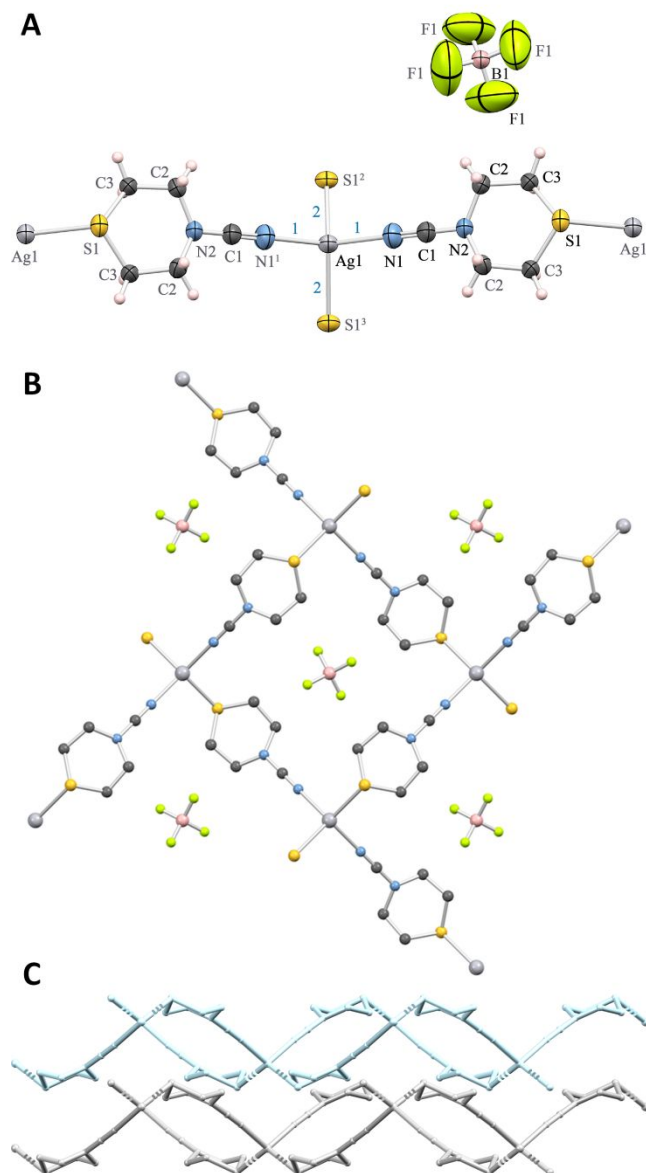


Figure 2. (A) ORTEP drawing (generated by MERCURY⁹³) of the part of infinite structure of **1** with labeled non-H atoms. The atoms of the asymmetric unit are labeled in black. Displacement ellipsoids are shown at the 50% probability level, while the H atoms are drawn as spheres of arbitrary radii. Symmetry codes: (1) $-x+1, -y, z$; (2) $y, -x+1, -z$; (3) $-y+1, x-1, -z$. Lengths of bonds labeled as 1 and 2 (in blue) are given in Table 2. (B) The crystal packing of **1** viewed along *c*-axis. (C) Stacked layers viewed along *b*-axis. All hydrogen atoms (B, C) and tetrafluoroborate anions (C) are omitted for clarity.

Table 2. Selected bond lengths for **1–4**.

Compound	Bond label	Bond type	Bond length (Å)
1	1	Ag1–N1, Ag1–N1 ¹	2.327(9)
	2	Ag1–S1 ² , Ag1–S1 ³	2.555(2)
2	3	Ag1–N1	2.180(3)
	4	Ag1–S1 ⁹	2.4164(7)
	5	Ag1–O1	2.406(2)
3	6	Ag1–N1	2.221(3)
	7	Ag1–O1	2.340(2)
	8	Ag1–S3 ¹¹	2.4309(11)
	9	Ag1–O5 ¹²	2.479(3)
	10	Ag2–N2	2.245(3)
	11	Ag2–O5	2.333(2)
	12	Ag2–S1 ¹³	2.4321(10)
	13	Ag2–O1 ¹⁴	2.467(3)
	14	Ag3–N3	2.216(3)
	15	Ag3–O9	2.343(2)
4	16	Ag3–S2	2.4341(11)
	17	Ag3–O9 ¹⁵	2.494(3)
	18	Ag1–N1	2.1818(15)
	19	Ag1–O1	2.4576(11)
	20	Ag1–S1	2.4903(4)
	21	Ag1–O2	2.6170(1)

Symmetry codes: (1) $-x+1, -y, z$; (2) $y, -x+1, -z$; (3) $-y+1, x-1, -z$; (9) $x-1, y, z$; (11) $-x+2, -y+1, -z+1$; (12) $-x+1, -y+2, -z+1$; (13) $-x+1, -y+1, -z+1$; (14) $x+1, y, z$; (v) $x+1/2, -y+3/2, z+1/2$; (15) $x-1/2, -y+3/2, z-1/2$.

Complex **2** crystallizes in the triclinic $P\bar{1}$ space group. The asymmetric unit consists of a Ag(I) ion, one of each L and H₂BTC⁻ ligands, as well as one neutral non-coordinated H₃BTC molecule. The part of infinite structure of **2**, shown in Figure 3A, reveals that the Ag(I) ion tri-coordinated by a nitrogen and a sulfur atom from two different L ligands and one deprotonated carboxylate oxygen atom from H₂BTC⁻. This gives rise to a distorted trigonal planar geometry with values of N1–Ag1–O1, N1–Ag1–S1⁹, and O1–Ag1–S1⁹ angles of 93.77(12)°, 149.25(11)°,

and $116.24(6)^\circ$, respectively. Selected bond lengths are given in Table 2. The coordination mode of H_2BTC^- is monodentate, while **L** behaves as a *bis*-monodentate ligand creating a centrosymmetric 1D chain parallel to the *a*-axis (Figure 3B). Non-coordinated H_3BTC molecule and H_2BTC^- ligands are connected by the $\text{O}-\text{H}\cdots\text{O}$ hydrogen interactions (Table 3).

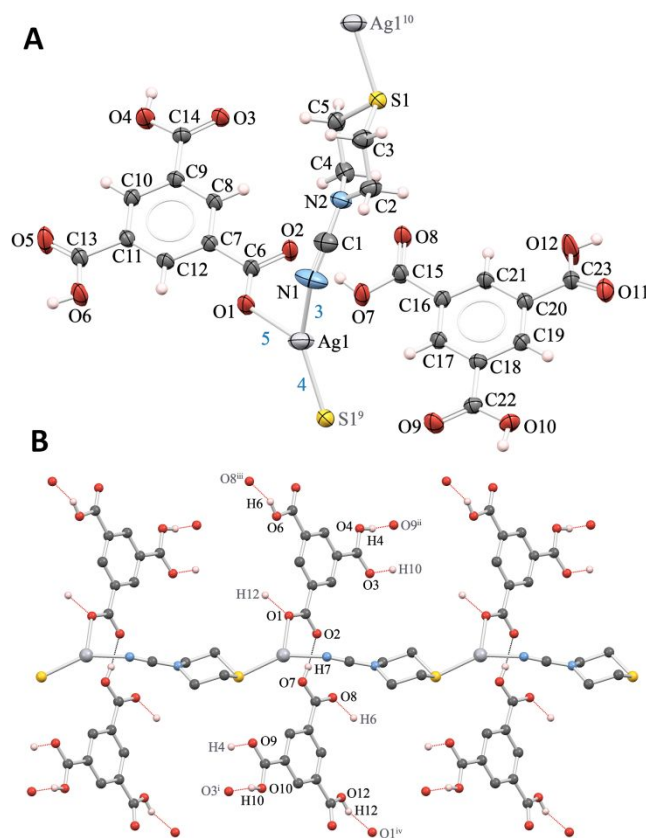


Figure 3. (A) ORTEP drawing (generated by MERCURY⁹³) of the part of infinite structure of **2** with labeled non-H atoms. The atoms of the asymmetric unit are labeled in black. Displacement ellipsoids are shown at the 50% probability level, while the H atoms are drawn as spheres of arbitrary radii. Symmetry codes: (9) $x-1, y, z$; (10) $x+1, y, z$. Lengths of bonds labeled as 3–5 (in blue) are given in Table 2. (B) The crystal packing of **2** viewed along *c*-axis. Selected hydrogen bonds are shown as dashed lines. The hydrogen atoms not involved in the selected hydrogen bonds are omitted for clarity.

Table 3. Selected hydrogen bond parameters in the crystal packing of **2**.

D—H···A	D—H (Å)	H···A (Å)	D···A (Å)	D—H···A (°)
O10—H10···O3 ⁱ	0.82	1.82	2.638 (3)	172.8
O7—H7···O2	0.82	1.70	2.517 (3)	171.0
O4—H4···O9 ⁱⁱ	0.82	1.81	2.613 (3)	166.5
O6—H6···O8 ⁱⁱⁱ	0.82	1.95	2.698 (3)	151.9
O12—H12···O1 ^{iv}	0.82	1.82	2.601 (3)	158.5

Symmetry codes: (i) $x-1, y+1, z-1$; (ii) $x+1, y-1, z+1$; (iii) $x, y-1, z$; (iv) $x, y+1, z$

Complex **3** crystallizes in the monoclinic $P2_1/n$ space group. The asymmetric unit contains three crystallographically different Ag(I) ions, three L ligands, one and a half $\text{H}_2\text{BTEC}^{2-}$ ligand and five disordered water molecules. Each Ag(I) ion is coordinated to one sulfur and one nitrogen atom from different L ligands, as well as two deprotonated carboxylate oxygen atoms from different $\text{H}_2\text{BTEC}^{2-}$ ligands. Selected bond lengths are given in Table 2. The coordination mode of L is *bis*-monodentate, while $\text{H}_2\text{BTEC}^{2-}$ behaves as a *bis*-bidentate bridging ligand. The part of infinite structure is depicted in Figure 4A. The geometry around each of the Ag(I) ions is distorted tetrahedral with the geometric index of distortion of $\tau_4 = 0.70$ (Ag1), $\tau_4 = 0.76$ (Ag2), and $\tau_4 = 0.74$ (Ag3), thus the structure at each Ag(I) in **3** can be described as seesaw.¹¹⁵ The crystal packing comprises of 2D layers of 5.83 Å thickness parallel to the (110) plane (Figure 4 B,C). A CSD¹¹⁶ search performed by Con-Quest 1.18⁹³ showed that **3** is the first compound containing $\text{H}_2\text{BTEC}^{2-}$ ligand coordinated to Ag(I).

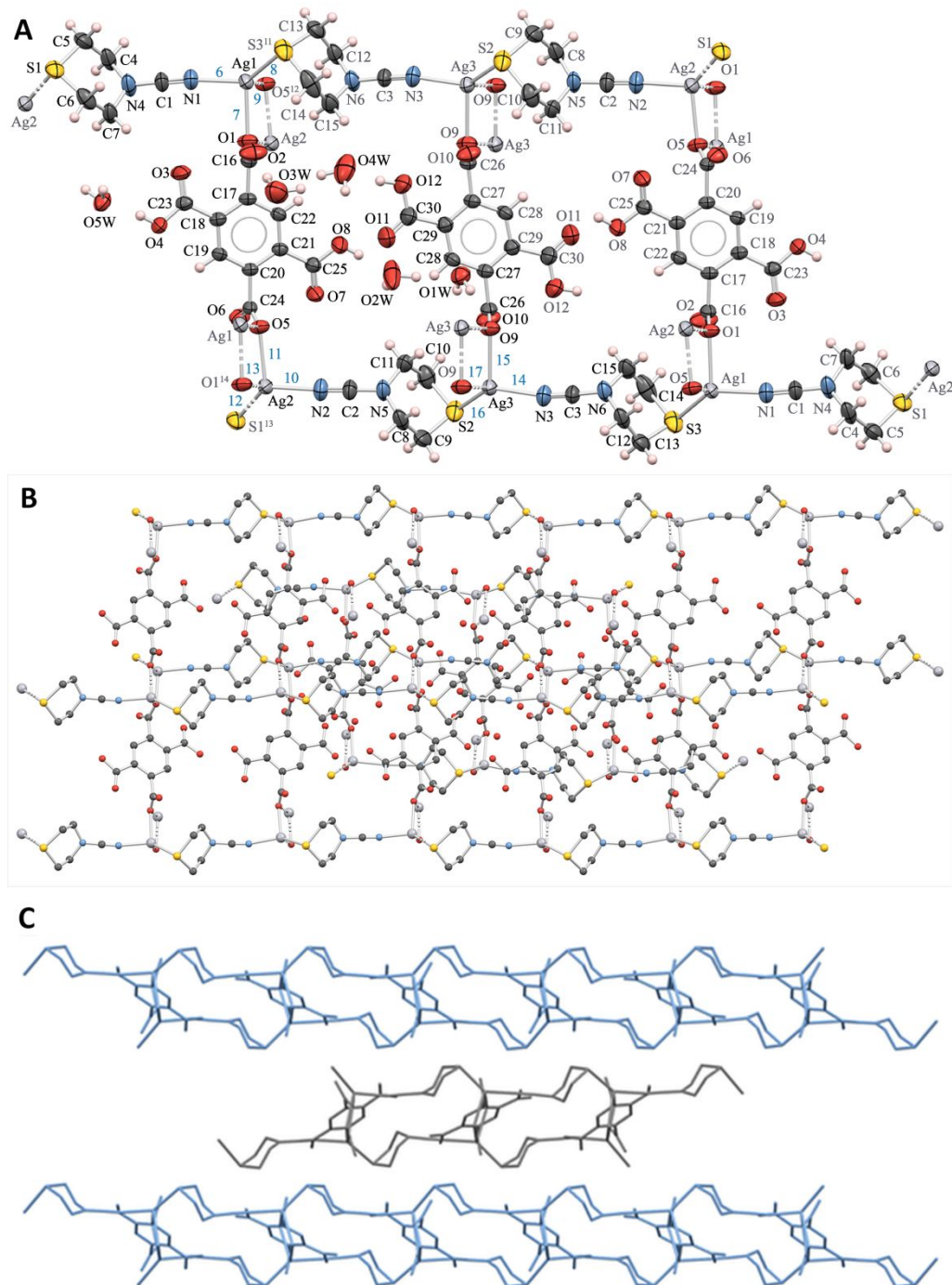


Figure 4. (A) ORTEP drawing (generated by MERCURY⁹³) of the part of infinite structure of **3** with labeled non-H atoms. The atoms of the asymmetric unit cell are labeled in bold. Displacement ellipsoids are shown at the 50% probability level, while the H atoms are drawn as spheres of arbitrary radii. Lengths of bonds labeled as 6–17 (in blue) are given in Table 2. (B)

The extended structure of **3** viewed parallel to *c*-axis. (C) The extended structure of **3** viewed along *a*-axis showing two-dimensional layers. All hydrogen atoms are omitted for clarity (B, C).

Complex **4** crystallizes in the monoclinic $P2_1/n$ space group. The asymmetric unit consists of a single Ag(I) atom and one of each L and H₂5SSA⁻ ligands. Two sulfonate oxygen atoms from two different H₂5SSA⁻ ligands are coordinated to Ag(I), as well as a nitrogen and a sulfur atom from two different L ligands. The part of the infinite structure is illustrated in Figure 5A. As $\tau_4 = 0.75$, the geometry around each of the Ag(I) atoms is seesaw.¹¹⁵ Selected bond lengths are given in Table 2. Both H₂5SSA⁻ and L behave as *bis*-monodentate ligands, with L creating a centrosymmetric double 1D chain parallel to *b*-axis. (Figure 5B). The crystal packing is based on H-interactions (Table 4). A CSD¹¹⁶ search performed by Con-Quest 1.18⁹³ showed that **4** is the first compound containing H₂5SSA⁻ ligand coordinated to Ag(I).

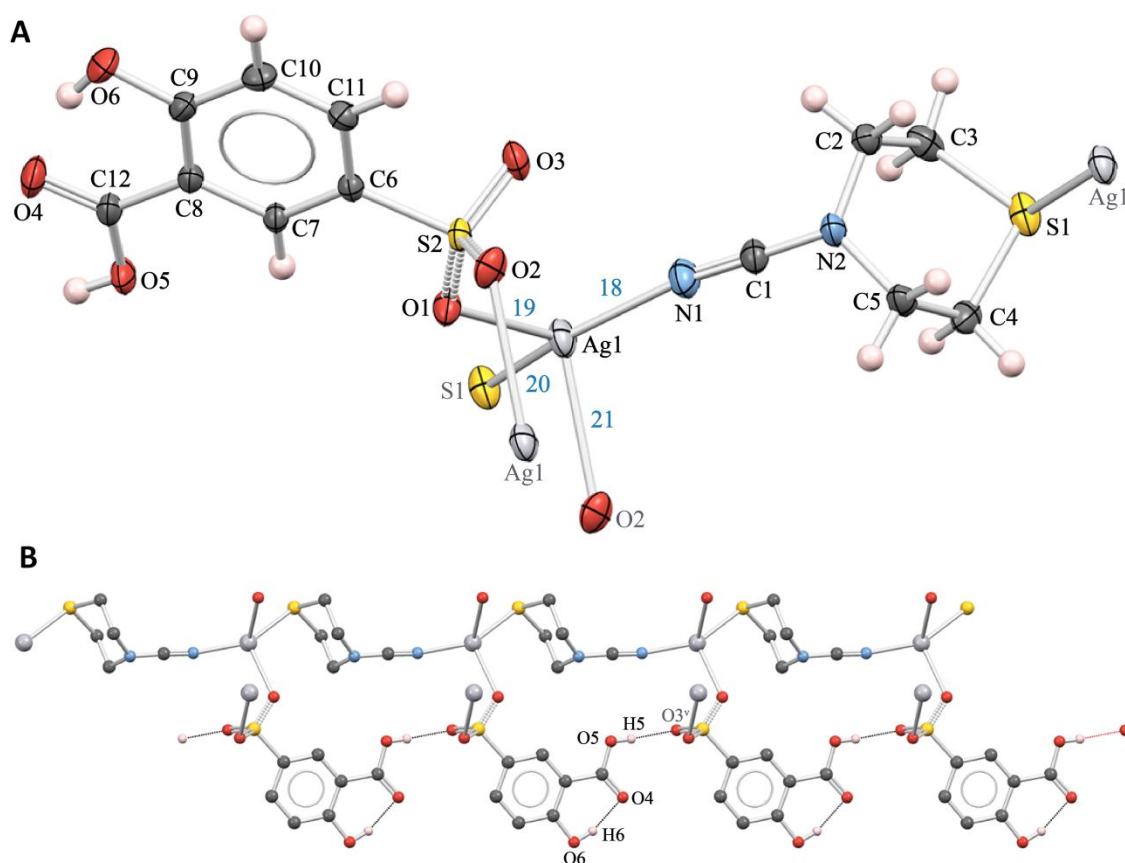


Figure 5. (A) ORTEP drawings (generated by MERCURY⁹³) of the part of infinite structure of **4** with labeled non-H atoms. The atoms of the asymmetric unit cell are labeled in black.

Displacement ellipsoids are shown at the 50% probability level, while the H atoms are drawn as spheres of arbitrary radii. Lengths of bonds labeled as 18–21 (in blue) are given in Table 2. (B) The crystal packing of **4** viewed along *c*-axis. Selected hydrogen bonds are showed as dashed lines. The hydrogen atoms not involved in the selected hydrogen bonds are omitted for clarity.

Table 4. Selected H-bond parameters in the crystal packing of **4**.

D–H···A	D–H (Å)	H···A (Å)	D···A (Å)	D–H···A (°)
O5—H5···O3 ^v	0.80 (3)	1.82 (3)	2.6246 (17)	175 (3)
O6—H6···O4	0.85 (3)	1.76 (3)	2.575 (2)	162 (3)

Symmetry code: (v) $x, y+1, z$

Topological analysis in standard representation suggests that each Ag(I) in **1** and **4** acts as a 4-connected node. The overall structure of **1** has a **sql**, while **4** has (4,4)(0,2) underlying net topology.¹¹⁷ In contrast, each Ag(I) ion in **2** acts as a 2-connected node with 2C1 underlying net topology.¹¹⁷ The structure of **3** can be described as a binodal net. Both Ag(I) ions and H₂BTEC²⁻ ligands act as 4-connected nodes, giving rise to a **4,4L28** underlying net topology.¹¹⁷

All samples correspond to the single-phase X-ray powder patterns (Figure S1, ESI) in accordance with the structural model obtained by the single-crystal X-ray diffraction.

3.2. Hirshfeld and 2D fingerprint plot analysis

Visualization and quick and easy understanding of intra- and intermolecular interactions in the crystal structures can be achieved using Hirshfeld surface and fingerprint plot analysis.^{97,118} The Hirshfeld surfaces and the pseudosymmetric 2D fingerprint plots,¹¹⁹ as well as the existing classical and non-classical interactions in the crystal structures of **1–4** are depicted in Figure 6. In all complexes, interactions can be observed in the shape-index plot as red and blue regions, as well as in the curvature plot as a flat zone in the same position of the surface as

in the shape-index plot. White circles mark the regions of the surfaces through which the complexes interact.

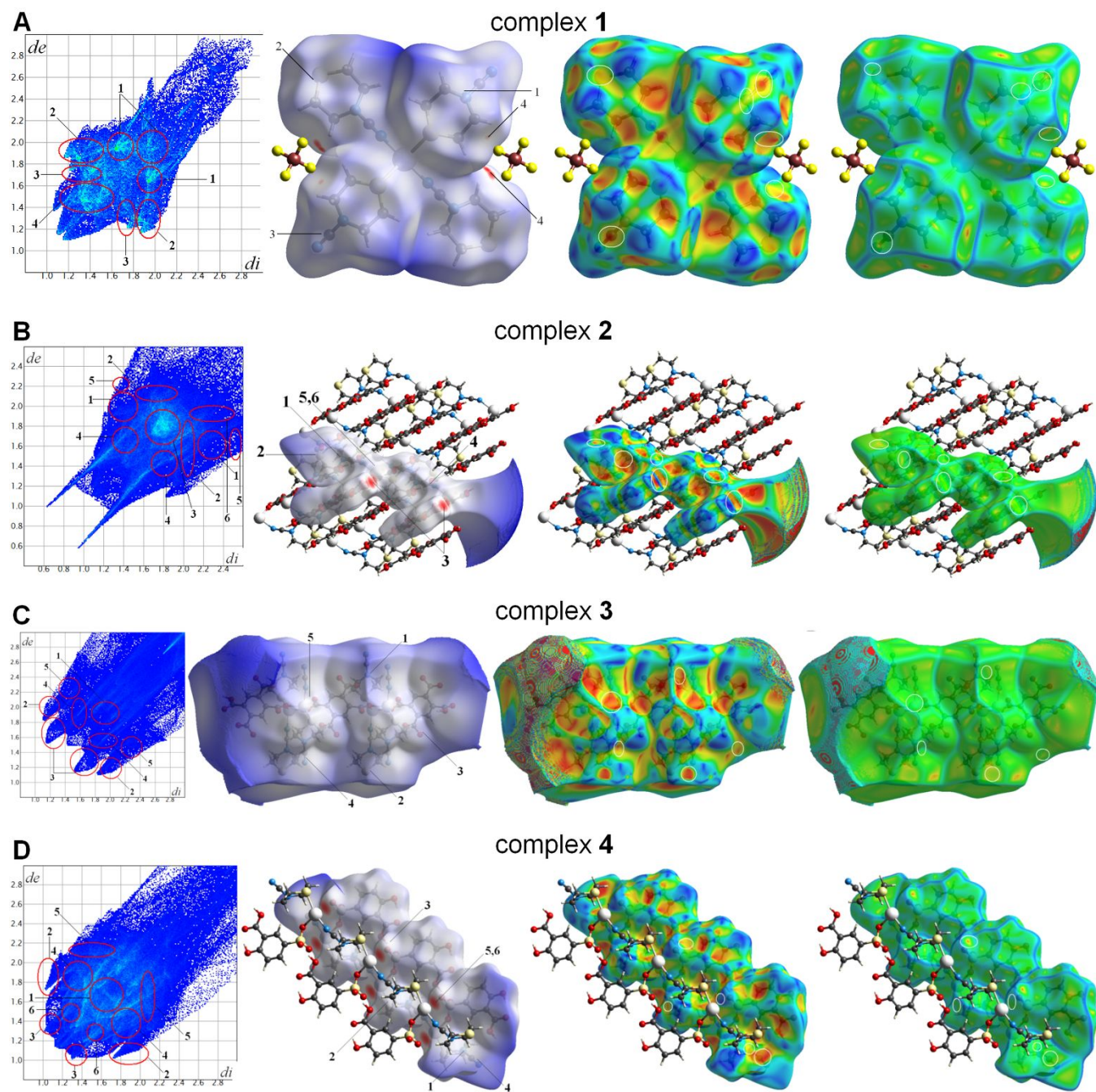


Figure 6. 2D fingerprint plot, Hirshfeld surface mapped with d_{norm} , shape index and curvedness for 1–4. For interaction types see Table 4.

The relative contributions of different types of interactions in **1–4** are shown in Table 5. As expected, the O \cdots H interactions are completely absent in **1** since it does not contain any co-ligand, and therefore no oxygen. On the other hand, the O \cdots H interactions are the most dominant type in other three complexes with aromatic polyoxoacids acids as co-ligands. Furthermore, **2** exhibits uncommonly high contribution of interactions of hydrogen and oxygen with the metal center. This can be attributed to proximity of the carboxylic group of the tricarboxylic acid to the metal (at 2.9 Å and 3.2 Å), which is just slightly longer than the Ag–O distance of the coordinated carboxylic group (2.4 Å). This indicates particularly strong interactions of the metal center with the carboxylic groups perpendicular to the plane of coordination, resulting in a quasi-3D structure for **2**, with 2D planes connected through the strong Ag \cdots O interactions on the perpendicular axis. This type of interaction is also present in **4**, where the Ag \cdots O distances are 2.6 and 3.4 Å, and the interaction comes primarily from the oxygen atoms bound to the sulfur. Absence of the Ag \cdots O interactions in **3** can be correlated with the tetrahedral coordination around the metal.

Table 5. Relative contributions (in %) and ($d_i + d_e$) values (in Å) of different interaction types in the crystal structures of **1–4**.

Interaction number	interaction type	1		2		3		4	
		relative contribution	$d_i + d_e$	relative contribution	$d_i + d_e$	relative contribution	$d_i + d_e$	relative contribution	$d_i + d_e$
1	N \cdots H	6.4	2.9	2.3	2.2	7.55	3.6	3.45	3.2
2	S \cdots H	3.5	3.0	0.75	2.3	2.35	3.6	2.0	3.4
3	C \cdots H	3.85	-	2.1	-	1.65	-	8.65	-
4	F \cdots H	4.85	2.5	-	-	-	-	-	-
4'	O \cdots H	-	-	13.6	1.2	17	3.0	12.1	2.6
5	Ag \cdots H	-	-	8.3	2.4	0.45	-	1.3	2.2
6	Ag \cdots O	-	-	5.9	2.6	-	-	2.25	2.4

3.3. Intermolecular interactions

Different types of intermolecular interactions within the crystal packing play an important part in the behavior of co-crystals, affecting their photophysical and pharmaceutical properties.¹²⁰ Table 6 shows an overview of the calculated values of intermolecular interactions

in model systems for all four complexes. These values are in a similar range for all systems – around 40 kJ/mol per monomer unit. However, the relative contributions of different types of interactions vary from one system to another (Tables S2–S5, ESI). In **1**, the intermolecular interactions are absolutely dominated by the dispersion interactions (88% contribution of attractive interactions, Table 7), while the electron interactions are almost negligible. This can be attributed to the stacking of monomer units in 2D layers. In **2**, on the other hand, electron interactions are more dominant (49% contribution to attractive interactions, Table 7), with dispersion playing an important part. In **3** and **4**, the dispersion interactions contribute 48% and 55% (Table 7), respectively, while the electron interactions contribute 35% and 31%, respectively, to the attractive interactions. This can be attributed to the increased role of hydrogen bonding, particularly between oxygen and hydrogen, in **2–4**. In addition, **2** exhibits the highest contribution of interactions between hydrogen and metal center, which can be correlated with its highest contribution of electron interactions. In all complexes, polarizations interactions contribute 11–17% (Table 7) to the overall attractive interaction energy, indicating that different composition and structure has relatively little effect on the role of this type of interactions. In **3**, slightly increased contribution of polarization interactions can be correlated with somewhat lower overall energy of intermolecular interactions. Differences in contributions of different types of interactions can be correlated to the spatial arrangement of monomer units in the lattice, with the location and orientation of hydrogen bonding being the decisive contributor to the electronic contribution to the value of the energy of attractive interactions. The negligible contribution of the electron interactions in **1** can be attributed largely to the absence of oxygen in the structure.

Table 6. Overview of calculated values for intermolecular interactions in model systems of **1–4**.

Complex	Intermolecular Interactions (kJ/mol)	monomer units	Per monomer unit (kJ/mol)
1	–84.6	2	–42.3
2	–682.2	16	–42.64
3	–288.3	8	–36.04
4	–466.9	12	–38.91

Table 7. Relative contributions (in %) to attractive interactions in the crystal structures of **1–4**.

Complex	Electron	Polarization	Dispersion
1	0.5	11.1	88.4
2	48.6	13.8	37.6
3	35.2	17.0	47.8
4	30.9	14.0	55.1

3.4. Thermal properties of 1–4

Based on the thermoanalytical data, **1–4** do not contain any lattice solvents. Complex **3** crystallizes with 3.33 water molecules per formula unit (Table 1). However, the lattice water almost completely evaporates during storage in desiccator for seven days. The thermal stability of the compounds, given by their onset temperatures, is relatively high and increases as follows: 173 °C (**3**) < 188 °C (**4**) < 192 °C (**1**) < 237 °C (**2**). The decomposition mechanism of each CP is different, in accordance with their different composition and structure. In all cases, the decomposition is a complex process which occurs in several more or less overlapped steps (Figure 7A).

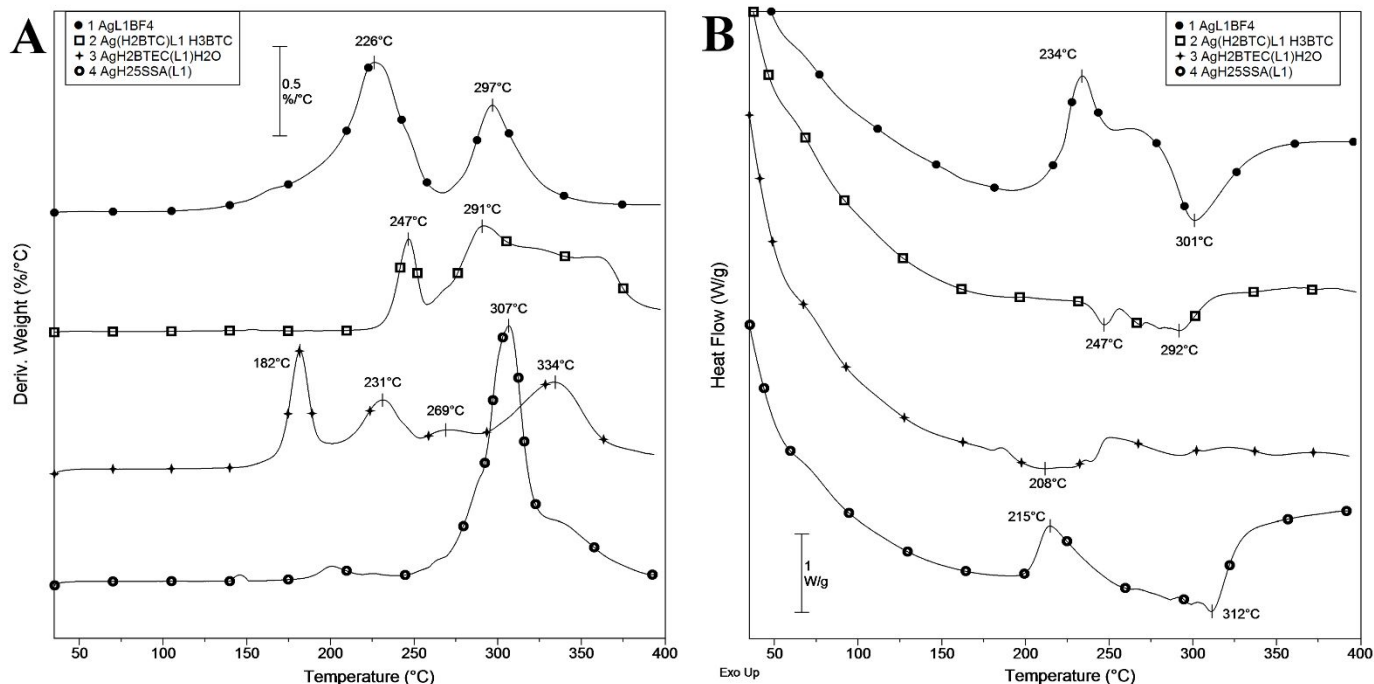


Figure 7. DTG (A) and DSC (B) curves of **1–4** in argon.

The simultaneously recorded DSC curves are shown in Figure 7B. As can be seen, the decomposition of **1** and **4** begins with an exothermic process. Although the thermal decomposition of tetrafluoroborates in most cases is followed by endothermic heat effects,^{121–123} in this case, the decomposition is exothermic. This phenomenon may be a result of intramolecular redox reactions between Ag^+ and L which are less pronounced in **2–4**, most likely because of the nature of the co-ligands. Additionally, **1** is cationic complex with BF_4^- as counter ion, and all other complexes contain the organic co-ligands coordinated to Ag(I). The oxidative properties of Ag^+ in the presence of BF_4^- are discussed in the literature.¹²⁴ The small mass loss of **4** at $\sim 200^\circ\text{C}$, followed by exothermic heat effect is most probably a CO_2 releasing process in accordance with the composition of the compound. Above $\sim 250^\circ\text{C}$ the thermal decomposition of **4** continues with endothermic processes (Figure 7B). The decomposition process of **2** and **3** is followed by endothermic effects in the whole temperature range of analysis (Figure 7B).

3.5. Photocatalytic properties

Photocatalytic properties of **1–4** were investigated in the reaction of photocatalytic degradation of MB9 dye. Since all complexes are insoluble in water, they were tested as heterogeneous catalysts in powder form for a degradation reaction in water. The progress of degradation reaction was monitored using UV/VIS spectroscopy (Figure S2, ESI) and the results are shown in Table 8. A dependence of $-\ln(C/C_0)$ on time (Figure S3, ESI), where the initial part of the curve shows linear dependence (with $R^2 > 99\%$) in all four complexes, indicates that the reaction of the photocatalytic degradation of MB9 dye can be treated as a first-order reaction. Apparent first-order rate constants for all four compounds were calculated to be in 0.036–0.056 min^{-1} range, which is comparable to the values obtained for ZnO-based photocatalysts in photocatalytic degradation of organic dyes.¹²⁵ In addition, this is also comparable to or better than the reported activities for Ag-based CPs for photocatalytic degradation of organic dyes^{126–129}. This indicates that all four complexes exhibit reasonably high photocatalytic activity. The lowest value was obtained for **1**, and the highest for **2**. It is interesting to note that **3** has more Ag atoms per monomer unit (Table 8) than **1**, **2** and **4**, therefore, the increase in photocatalytic activity cannot be attributed to higher Ag content. There is also no significant difference in the accessible free lattice volume for water (all four complexes have 0), suggesting that none of the structures exhibits porosity. Therefore, the increase in photocatalytic activity can most likely be correlated with the existence of different co-ligands in the four complexes: **1** does not contain carboxylic acid as a co-ligand and exhibits the lowest photocatalytic activity, **4** contains H₃SSA and exhibits lower photocatalytic activity than **3** and **2**, which contain H₄BTEC and H₃BTC, respectively. Complex **2** also contains free H₃BTC molecule in addition to the one coordinated to the metal center. Complex **4** contains one carboxylic group and one hydroxyl group in addition to sulfonic acid group, **3** contains one tetracarboxylic acid, while **2** contains two tricarboxylic acids. This suggests that the photocatalytic mechanism most likely includes active hydroxyl radicals ($\bullet\text{OH}$) as the main reactive species.^{126,127} The excited state of the complex reacts with water to form $\bullet\text{OH}$ which oxidizes the dye. The oxygen in the system can easily re-oxidize the reduced complex species making it active again. The presence of more reactive carboxylic groups in the system enhances the photocatalytic activity of the complexes, and the change photocatalytic reactivity of these complexes can be roughly correlated with increasing number of oxygen groups in the structure.

Table 8. Calculated apparent first-order rate constants corresponding to each compound

Compound	General formula	Empirical formula (<i>FW</i>)	Rate constant (min ⁻¹)
1	{[Ag(L) ₂](BF ₄)} _∞	C ₁₀ H ₁₆ AgBF ₄ N ₄ S ₂ (<i>FW</i> = 451.07)	0.036±0.001
2	{[Ag(H ₂ BTC)(L)]×(H ₃ BTC)} _∞	C ₂₃ H ₁₉ AgN ₂ O ₁₂ S (<i>FW</i> = 655.33)	0.056±0.003
3	{[Ag ₂ (H ₂ BTEC)(L) ₂]} _∞	C ₂₀ H ₂₀ Ag ₂ N ₄ O ₈ S ₂ (<i>FW</i> = 724.26)	0.055±0.004
4	[Ag(H ₂ 5SSA)(L)] _∞	C ₁₂ H ₁₃ AgN ₂ O ₆ S ₂ (<i>FW</i> = 453.23)	0.040±0.002

3.6. Photophysical properties

While complexes **1** and **2** do not show emissive properties in the solid state at RT or 77 K, complexes **3** and **4** display luminescent emissions in the solid state when they are irradiated with UV light. Complex **3** is not luminescent at RT, but it is luminescent at 77 K, showing an emission band centred at 522 nm (λ_{exc} 340 nm). In contrast, **4** is emissive at RT, displaying a more energetic emission located at 430 nm (λ_{exc} 330 nm). When the temperature is decreased to 77 K, a very similar emission, without any noticeable energetic shift, is detected for this complex (Figure 8).

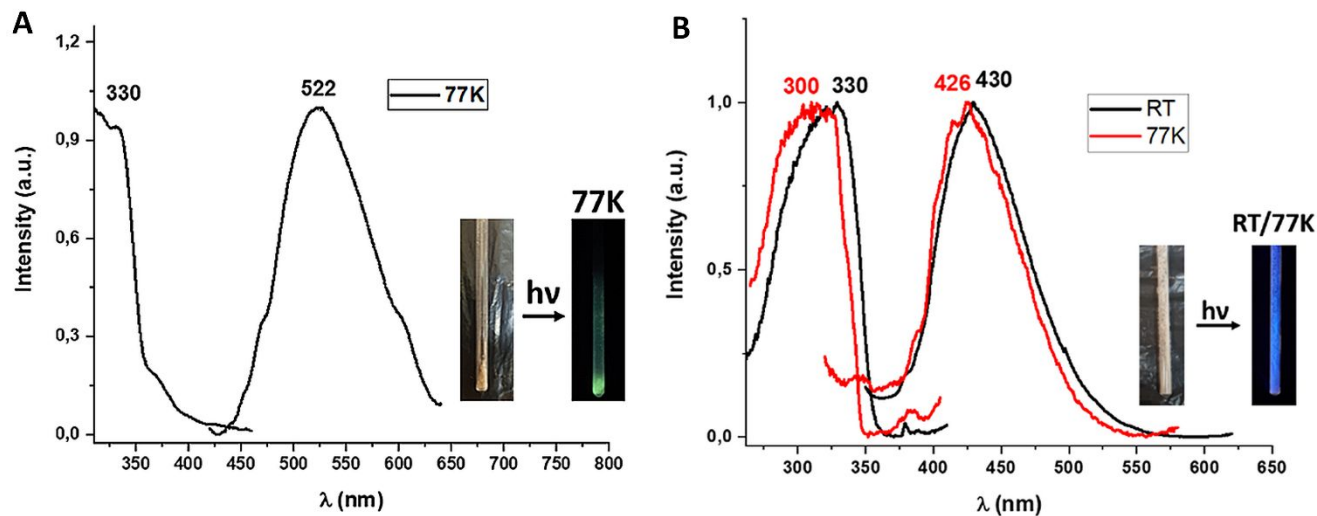


Figure 8. Excitation and emission spectra in solid state at 77K (A) and room temperature and 77 K (B) for **3** and **4**, respectively.

The lifetime obtained for the emission for **3** at 77 K is 8 ns, while for **4** it is 7 and 8 ns at room temperature and 77 K, respectively. These lifetimes seem to indicate electronic transitions of singlet parentage for the origin of the experimentally observed emissions. In fact, the excitation spectra collected in the solid state for **3** and **4** appear included within the wavelength range of the corresponding absorption spectra in the solid state, suggesting that the transitions are allowed and, therefore, related to fluorescence processes for both complexes (Figure 9).

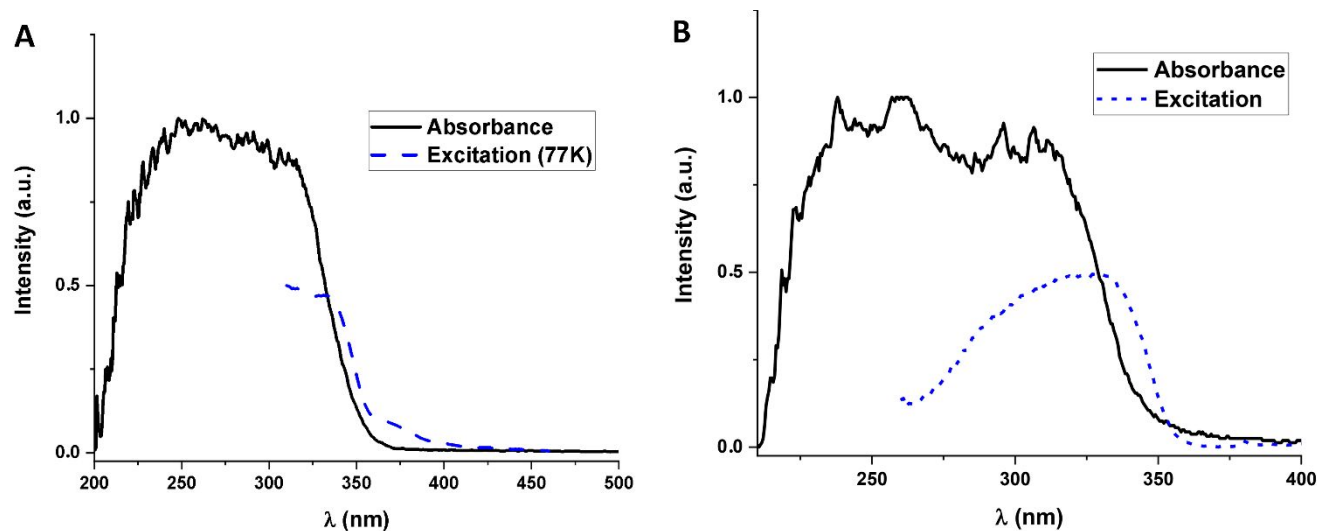


Figure 9. Absorbance (black) and excitation (blue) spectra in the solid state for **3** (A) and **4** (B).

3.7. Computational studies

DFT and TD-DFT computational calculations were carried out to elucidate the origin of the luminescent properties displayed by **3** and **4**. Tetranuclear model systems were constructed based on the experimental X-ray diffraction data, keeping all the distances and the angles fixed and representing all the bonds and interactions found in the coordination polymers (Figure 10).

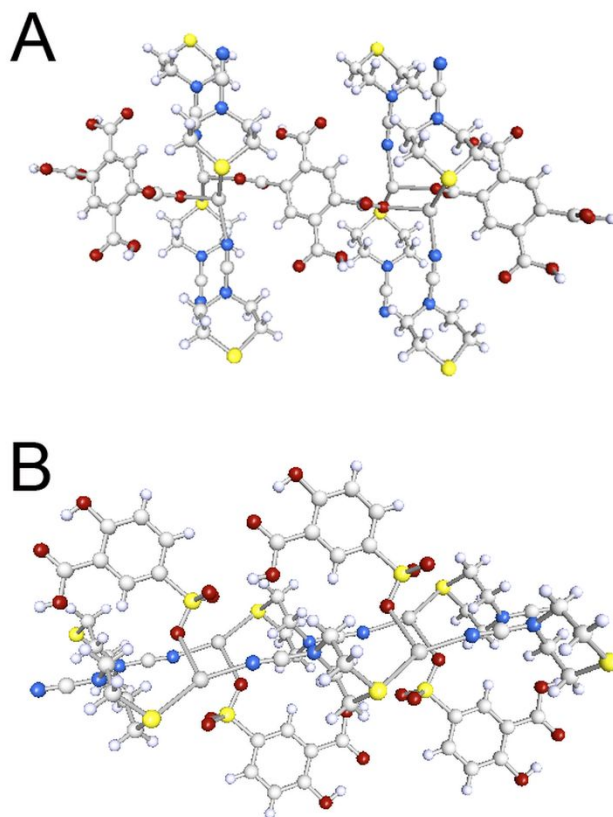


Figure 10. Theoretical model systems representing complex **3** (A) and **4** (B).

Single point DFT calculations permit the analysis of the electronic structure for these complexes. Figures 11 and 12 display the most important frontier molecular orbitals (MOs) as computed.

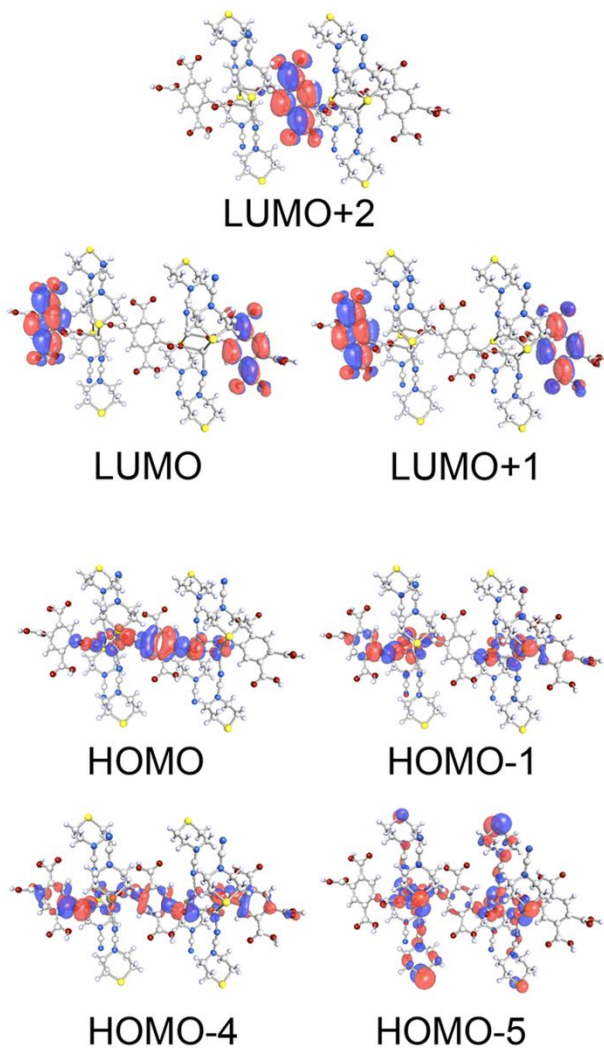


Figure 11. Frontier MOs for model system 3

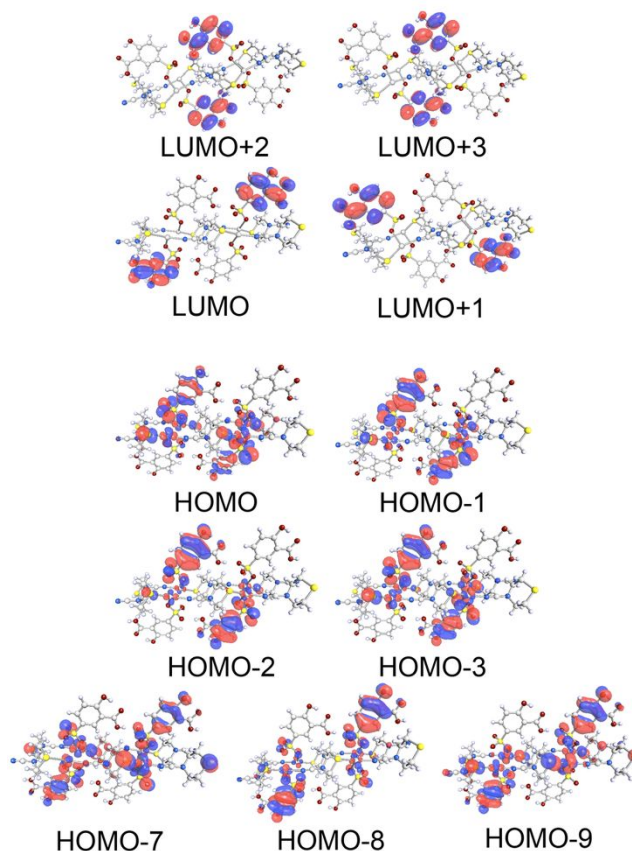


Figure 12. Frontier MOs for model system 4.

If we analyse the results obtained for the electronic structure for model 3, we observe that HOMO, HOMO-1 and HOMO-4 orbitals are located mostly at the $\text{H}_2\text{BTEC}^{2-}$ ligand (aromatic ring and carboxylate groups), with some contribution from the Ag centres. Meanwhile, HOMO-5 ligand is mostly located at L with a minor contribution from the Ag centres. On the other hand, the lowest unoccupied orbitals LUMO to LUMO+2 appear to be located mostly at the $\text{H}_2\text{BTEC}^{2-}$ ligands, without contribution from the Ag centres. In the case of model system 4, similar behaviour is computed. Thus, the molecular orbitals from HOMO to HOMO-9 appear mostly centred on the aromatic ring and the SO_3 functional group of the $\text{H}_2\text{5SAA}^-$ ligands with a minor contribution from the Ag atoms bonded to the SO_3 groups. Regarding lowest occupied molecular orbitals, from LUMO to LUMO+3 are located on the aromatic ring of the $\text{H}_2\text{5SAA}^-$ ligands with minor contributions from the COOH and OH groups bonded to the aromatic ring of the ligand. In these empty orbitals, the participation of the Ag atoms or the L ligands is, again, not detected.

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3 The TD-DFT computation of the first 25 singlet-singlet electronic excitations provides
4 same information on the origin of the fluorescent properties of **3** and **4**. Table 9 displays the
5 information of the wavelength, oscillator strength and contribution of the MOs to the
6 corresponding electronic transitions. In the case of model **3**, there are five electronic transitions
7 of large oscillator strength value between 360 and 424 nm. The computed wavelength values
8 agree well with the corresponding excitation spectrum obtained for this complex that shows a
9 maximum at 330 nm with a tail extending up to ca. 430 nm. The main contributions to these five
10 electronic transitions involve the above commented molecular orbitals, which seems to indicate
11 that the origin of the luminescent properties in **3** would be related to metal-perturbed intra ligand
12 transitions. In the case of **4**, similar behaviour was computed. The most intense electronic
13 transitions appear around 296 nm, although less intense transitions appear around 310 nm. This
14 result is also in agreement with the excitation spectrum registered for **4** between 275 and 350 nm,
15 in which a maximum at 330 nm is obtained. Again, the analysis of the orbitals involved in the
16 electronic transitions shows up a metal-perturbed intra ligand transitions as the origin of the
17 emissive properties of this complex.
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Table 9. TD-DFT singlet-singlet excitation calculations for model systems of **3** and **4**.

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Transition	λ/nm	Oscillator strength	Contributions
S_0-S_1	424.1	0.0772	HOMO→LUMO+2 (95%)
S_0-S_2	316.0	0.0404	HOMO→LUMO (54%) HOMO-1→LUMO+1 (31%)
S_0-S_5	390.9	0.0111	HOMO→LUMO (35%) HOMO-4→LUMO (30%) HOMO-1→LUMO+1 (16%)
S_0-S_7	368.4	0.0233	HOMO-5→LUMO (40%) HOMO-6→LUMO+1 (25%)
S_0-S_{10}	360.3	0.0152	HOMO-5→LUMO+2 (50%) HOMO-4→LUMO+2 (41%)
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S_0-S_4	298.9	0.0155	HOMO→LUMO+3 (46%) HOMO-1→LUMO+2 (38%)
S_0-S_7	296.4	0.133	HOMO-8→LUMO (40%) HOMO-7→LUMO+1 (18%) HOMO-9→LUMO+1 (18%)
S_0-S_8	295.7	0.124	HOMO-2→LUMO+3 (46%) HOMO-3→LUMO+2 (37%)

4. CONCLUSION

Four new Ag(I) coordination polymers with L and aromatic polyoxoacids as co-ligands were synthesized and characterized. Compounds **1** and **2** crystallize in the tetragonal $P-4_2m$ and triclinic $P-1$ space group, respectively, while **3** and **4** crystallize in the same monoclinic $P2_1/n$ space group. L behaves as a *bis*-monodentate ligand in all four structures, while the Ag(I) ion is three-coordinated in **2**, and four-coordinated in all the other complexes. Thermal analysis showed that all four complexes have good thermal stability, with the onset of the thermal decomposition in 170–240 °C temperature range. Investigation of intermolecular interactions evinced that **2** and **4** exhibit considerable contribution of interactions with the metal center, while the almost

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3 complete absence of such interactions in **3** can be attributed to the tetrahedral coordination of Ag.
4 While all compounds have similar values of the intermolecular interaction energies, the origin of
5 those interactions is different and can be correlated with the type of co-ligand in the structure.
6 Photocatalytic properties were measured for photocatalytic degradation of MB9 dye, and show
7 that all four complexes exhibit reasonable reaction rates. The differences are attributed to the
8 different co-ligands, where both the type and coordination of the co-ligand can be correlated with
9 changes in the photocatalytic reaction rate. When irradiated with the UV light, **3** and **4** show
10 photoluminescent emission, with **4** exhibiting luminescence at both RT and 77 K. The
11 luminescence lifetimes for **3** and **4** suggest electronic transitions of singlet parentage. Since the
12 excitation spectra appear to overlap with the wavelength range of the corresponding absorption
13 spectra in the solid state, these transitions are most likely allowed and related to fluorescence
14 processes. TD-DFT study determined the relative contributions of individual singlet-singlet
15 electronic excitations to the fluorescence properties of both complexes, indicating that metal-
16 perturbed intra ligand transitions is responsible in both cases.
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29 ASSOCIATED CONTENT

30 Supporting information available

31 Supplementary information contains crystallographic data and refinement parameters for
32 SQUEEZED structure **3**, pairwise interaction energies in the crystal structure of **1–4** based on
33 B3LYP/ DGDZVP energy model, overlapped experimental and theoretically obtained powder X-
34 ray diffractograms and photocatalytic degradation of MB9 dye using the complexes **1–4**
35 monitored by UV-Vis spectroscopy. This information is available free of charge via the Internet
36 at <http://pubs.acs.org/>.
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45 Accession Codes

46 CCDC 1987944, 1987947–1987949 and 1990303 contain the supplementary crystallographic
47 data for this paper. These data can be obtained free of charge via
48 www.ccdc.cam.ac.uk/data_request/cif or by emailing data_request@ccdc.cam.ac.uk, or by
49 contacting The Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ,
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Notes

The authors declare no competing financial interest.

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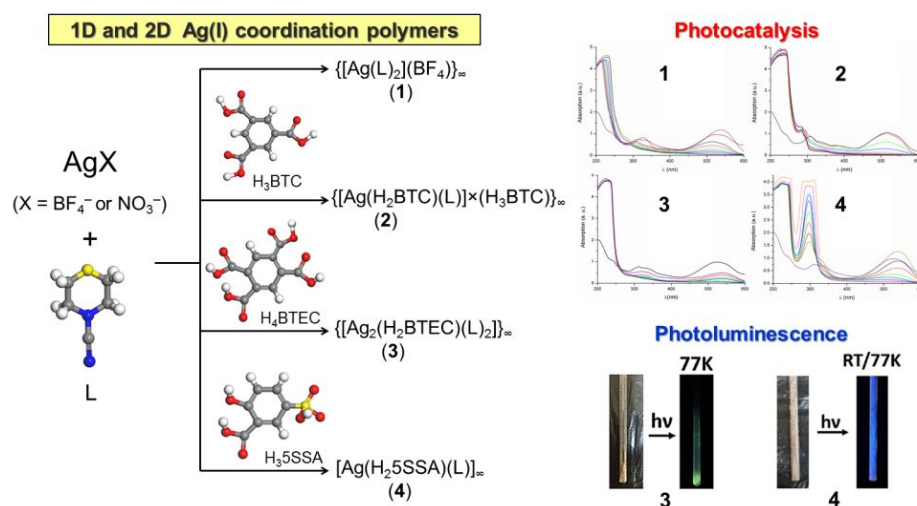
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For Table of Contents Use Only

1D and 2D silver-based coordination polymers with thiomorpholine-4-carbonitrile and aromatic polyoxoacids as co-ligands: structure, photocatalysis, photoluminescence and TD-DFT study

Predrag Ristić, Tamara R. Todorović*, Vladimir Blagojević, Olivera R. Klisurić, Ivana Marjanović, Berta Barta Holló, Predrag Vulić, Mihaela Gulea, Morgan Donnard, Miguel Monge, María Rodríguez-Castillo, José M. López-de-Luzuriaga, Nenad R. Filipović



Ag(I) coordination polymers **1–4** exhibit reasonable reaction rates in photocatalytic degradation of MB9 dye. When irradiated with the UV light, **3** and **4** show photoluminescent emission. The luminescence lifetimes suggest electronic transitions of singlet parentage. TD-DFT study determined the relative contributions of individual singlet-singlet electronic excitations to the fluorescence properties, indicating that metal-perturbed intra ligand transitions is responsible in both cases.

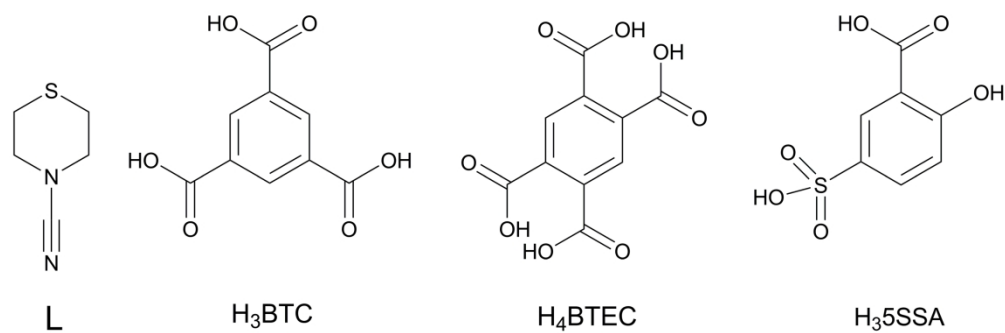


Figure 1. Structures of L and aromatic polyoxoacids co-ligands.

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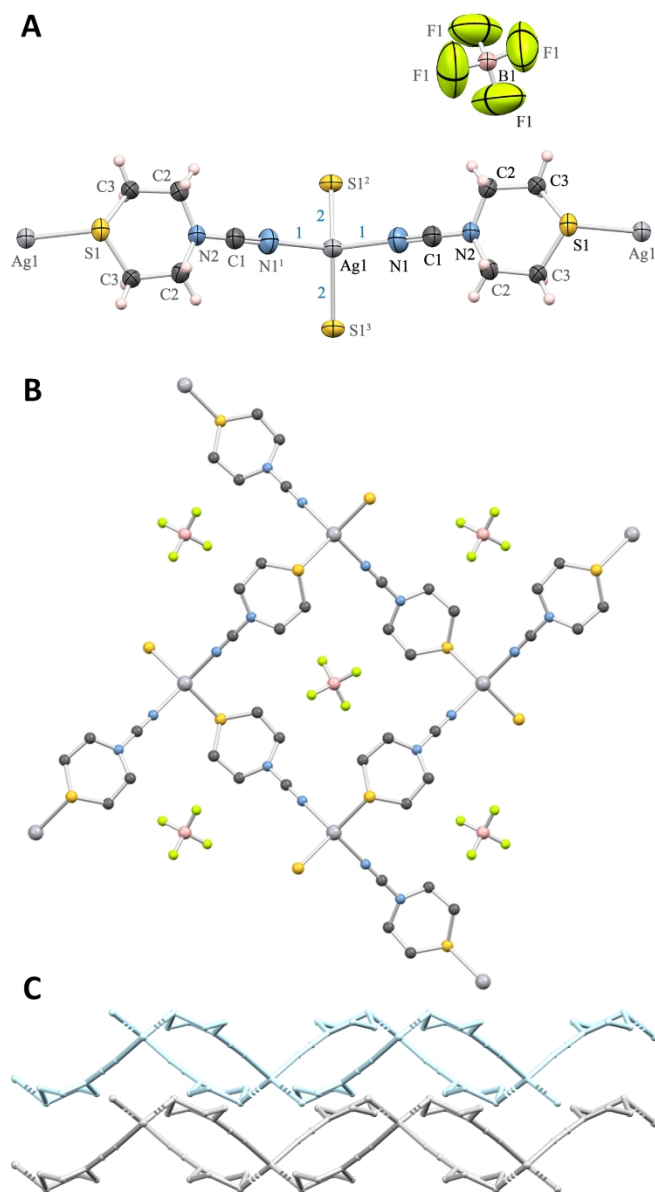


Figure 2. (A) ORTEP drawing (generated by MERCURY93) of the part of infinite structure of 1 with labeled non-H atoms. The atoms of the asymmetric unit are labeled in black. Displacement ellipsoids are shown at the 50% probability level, while the H atoms are drawn as spheres of arbitrary radii. Symmetry codes: (1) $-x+1, -y, z$; (2) $y, -x+1, -z$; (3) $-y+1, x-1, -z$. Lengths of bonds labeled as 1 and 2 (in blue) are given in Table 2. (B) The crystal packing of 1 viewed along c-axis. (C) Stacked layers viewed along b-axis. All hydrogen atoms (B, C) and tetrafluoroborate anions (C) are omitted for clarity.

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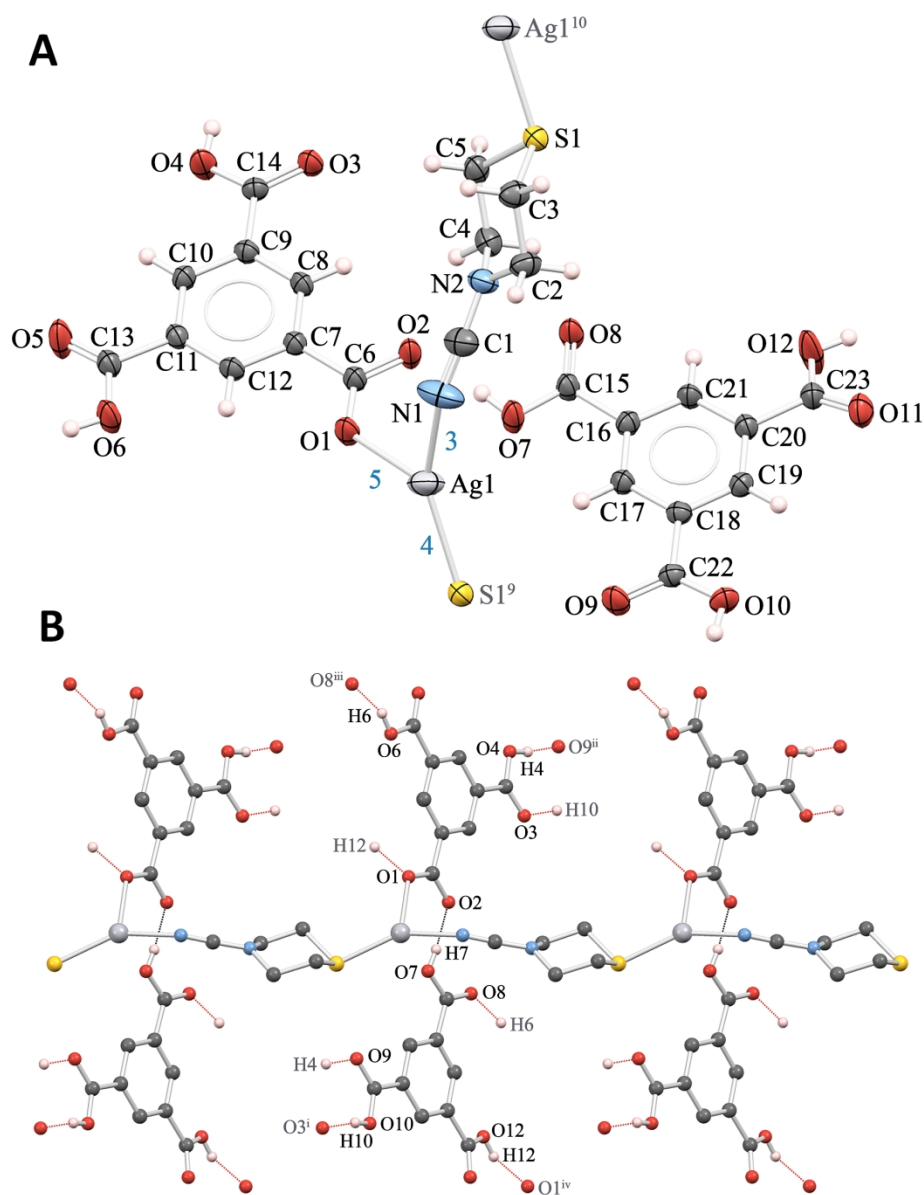


Figure 3. (A) ORTEP drawing (generated by MERCURY93) of the part of infinite structure of 2 with labeled non-H atoms. The atoms of the asymmetric unit are labeled in black. Displacement ellipsoids are shown at the 50% probability level, while the H atoms are drawn as spheres of arbitrary radii. Symmetry codes: (9) $x-1, y, z$; (10) $x+1, y, z$. Lengths of bonds labeled as 3–5 (in blue) are given in Table 2. (B) The crystal packing of 2 viewed along c -axis. Selected hydrogen bonds are shown as dashed lines. The hydrogen atoms not involved in the selected hydrogen bonds are omitted for clarity.

84x110mm (600 x 600 DPI)

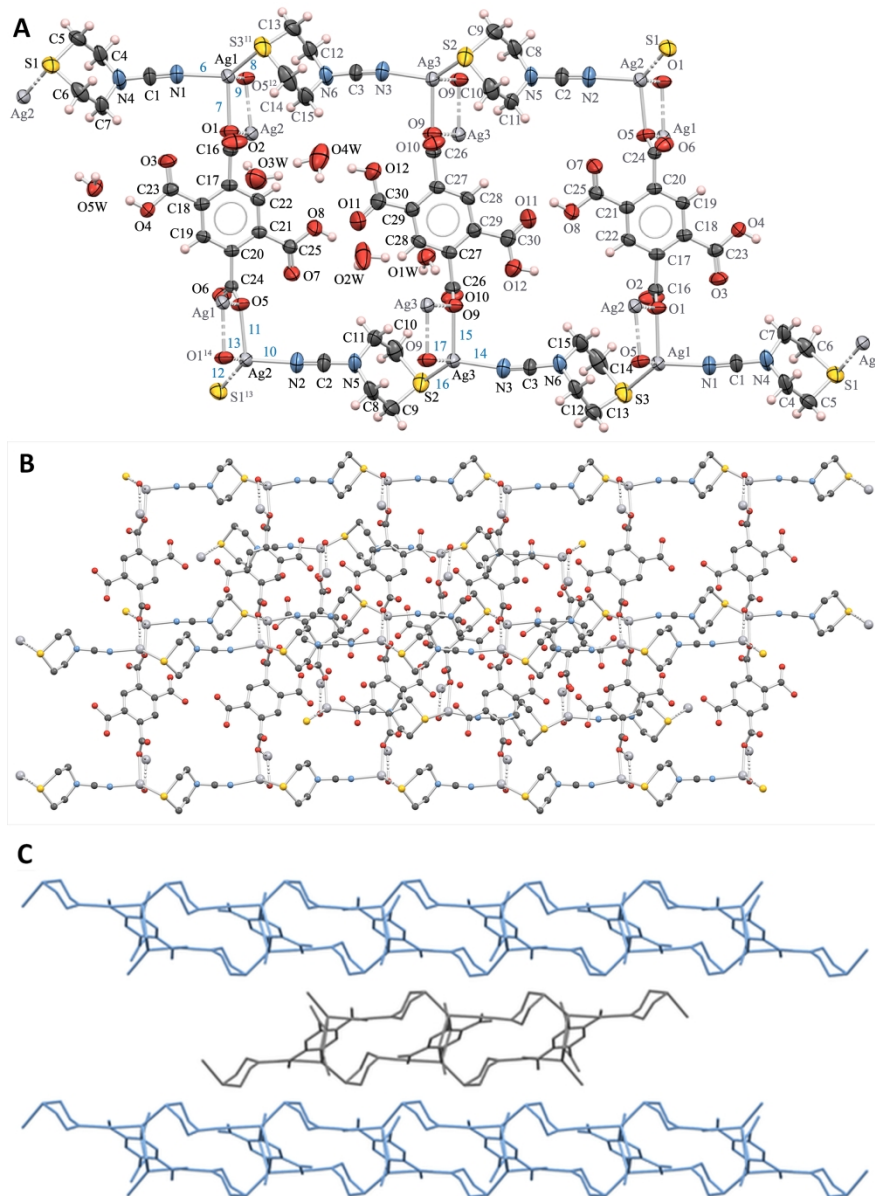


Figure 4. (A) ORTEP drawing (generated by MERCURY93) of the part of infinite structure of 3 with labeled non-H atoms. The atoms of the asymmetric unit cell are labeled in bold. Displacement ellipsoids are shown at the 50% probability level, while the H atoms are drawn as spheres of arbitrary radii. Lengths of bonds labeled as 6–17 (in blue) are given in Table 2. (B) The extended structure of 3 viewed parallel to c-axis. (C) The extended structure of 3 viewed along a-axis showing two-dimensional layers. All hydrogen atoms are omitted for clarity (B, C).

134x184mm (600 x 600 DPI)

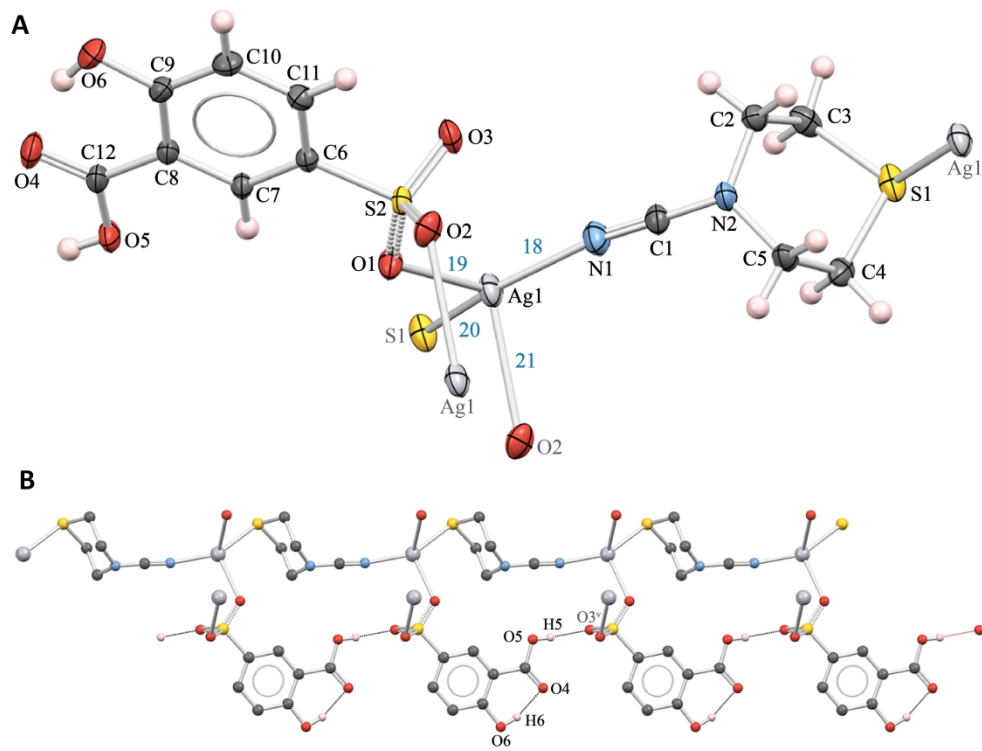


Figure 5. (A) ORTEP drawings (generated by MERCURY93) of the part of infinite structure of 4 with labeled non-H atoms. The atoms of the asymmetric unit cell are labeled in black. Displacement ellipsoids are shown at the 50% probability level, while the H atoms are drawn as spheres of arbitrary radii. Lengths of bonds labeled as 18–21 (in blue) are given in Table 2. (B) The crystal packing of 4 viewed along c-axis. Selected hydrogen bonds are showed as dashed lines. The hydrogen atoms not involved in the selected hydrogen bonds are omitted for clarity.

152x115mm (600 x 600 DPI)

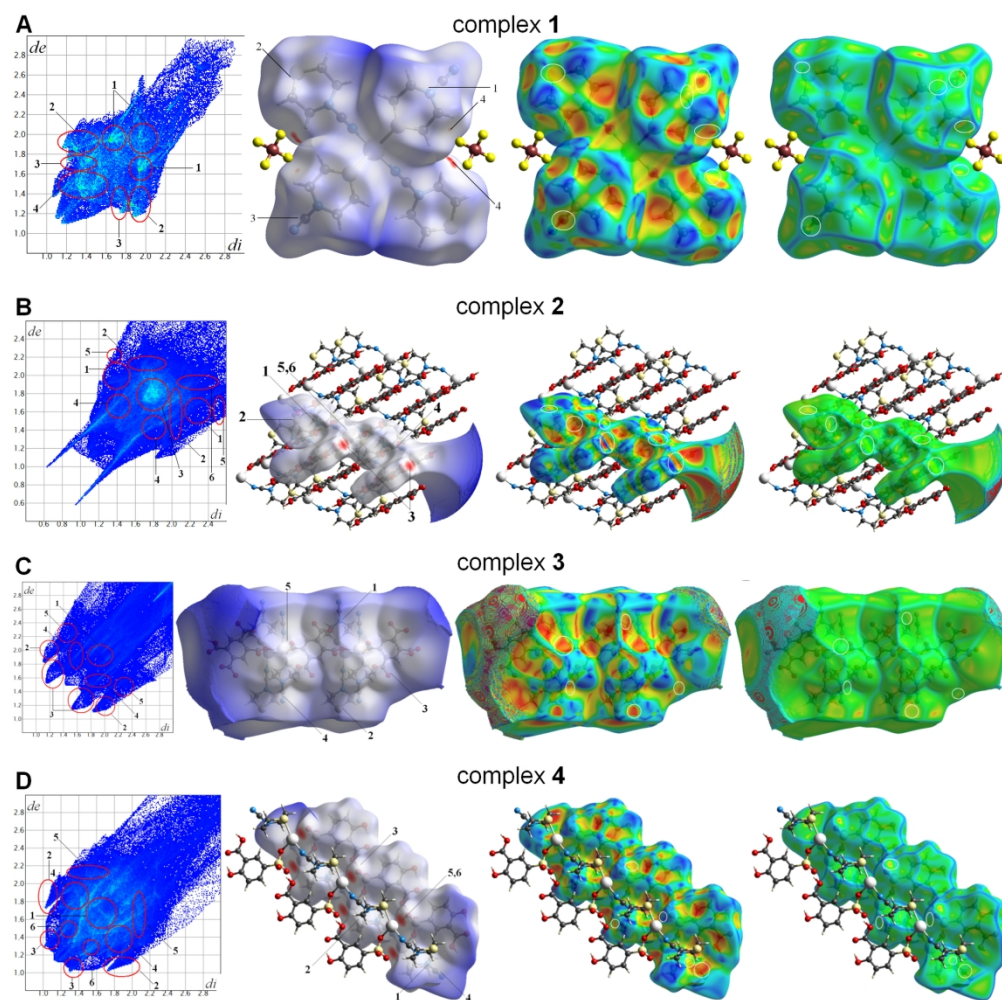


Figure 6. 2D fingerprint plot, Hirshfeld surface mapped with d_{norm} , shape index and curvedness for 1–4. For interaction types see Table 4.

177x176mm (600 x 600 DPI)

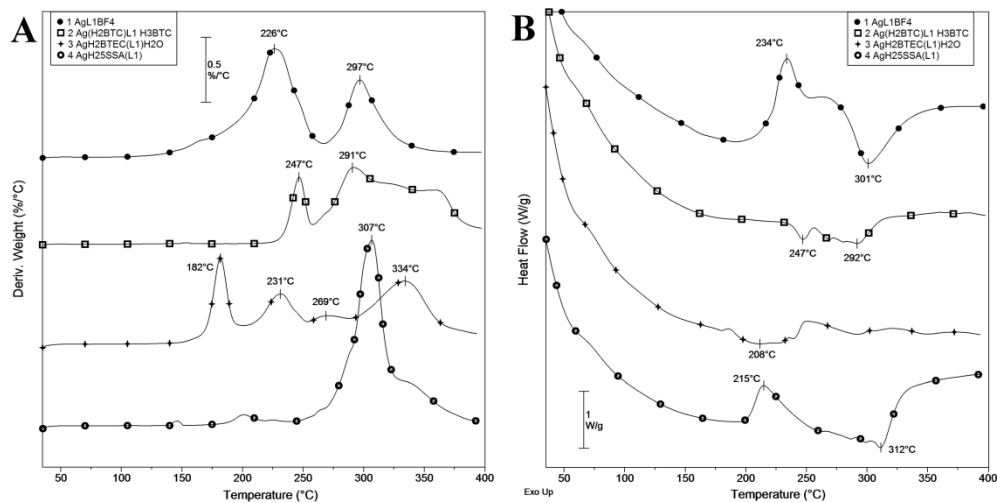


Figure 7. DTG (A) and DSC (B) curves of 1–4 in argon.

182x92mm (600 x 600 DPI)

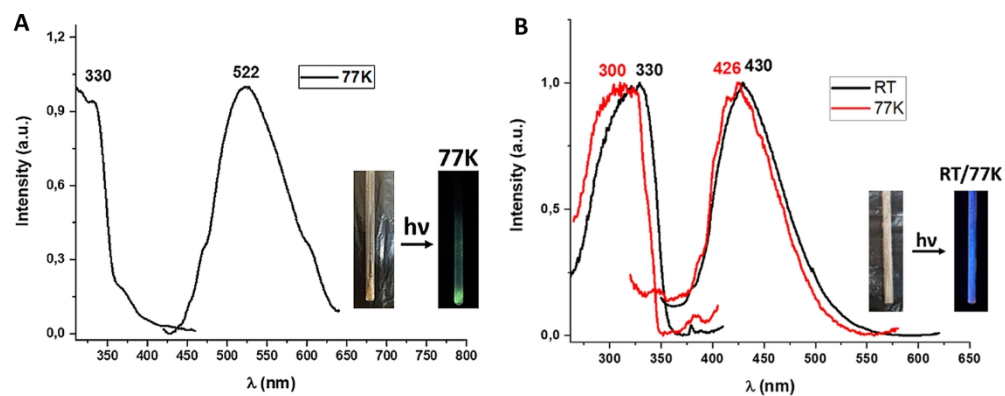


Figure 8. Excitation and emission spectra in solid state at 77K (A) and room temperature and 77 K (B) for 3 and 4, respectively.

174x68mm (600 x 600 DPI)

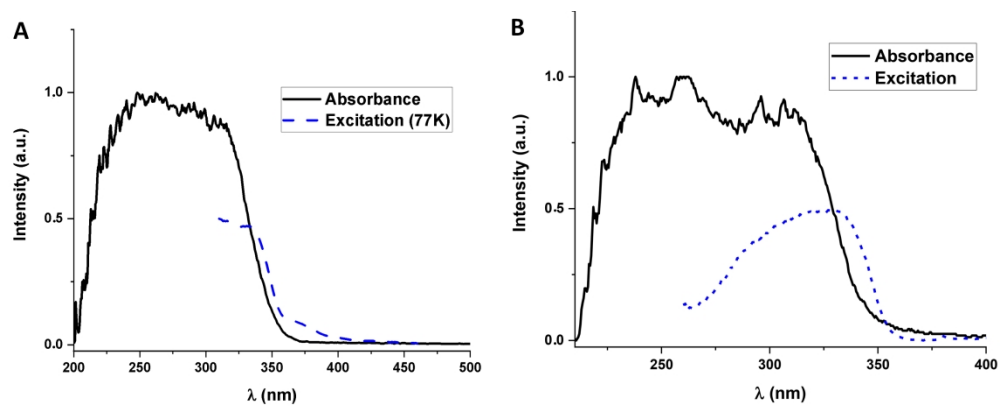
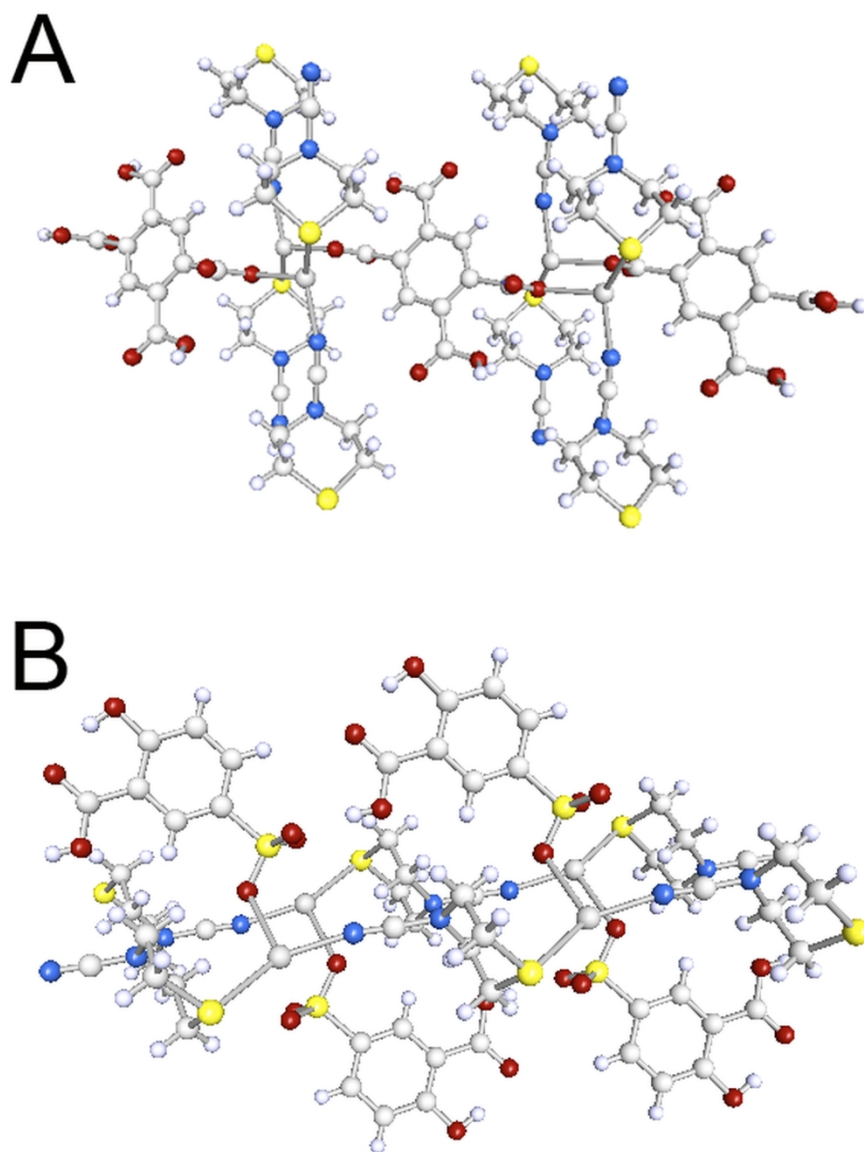


Figure 9. Absorbance (black) and excitation (blue) spectra in the solid state for 3 (A) and 4 (B).

174x69mm (600 x 600 DPI)



45 Figure 10. Theoretical model systems representing complex 3 (A) and 4 (B).

46 84x112mm (600 x 600 DPI)

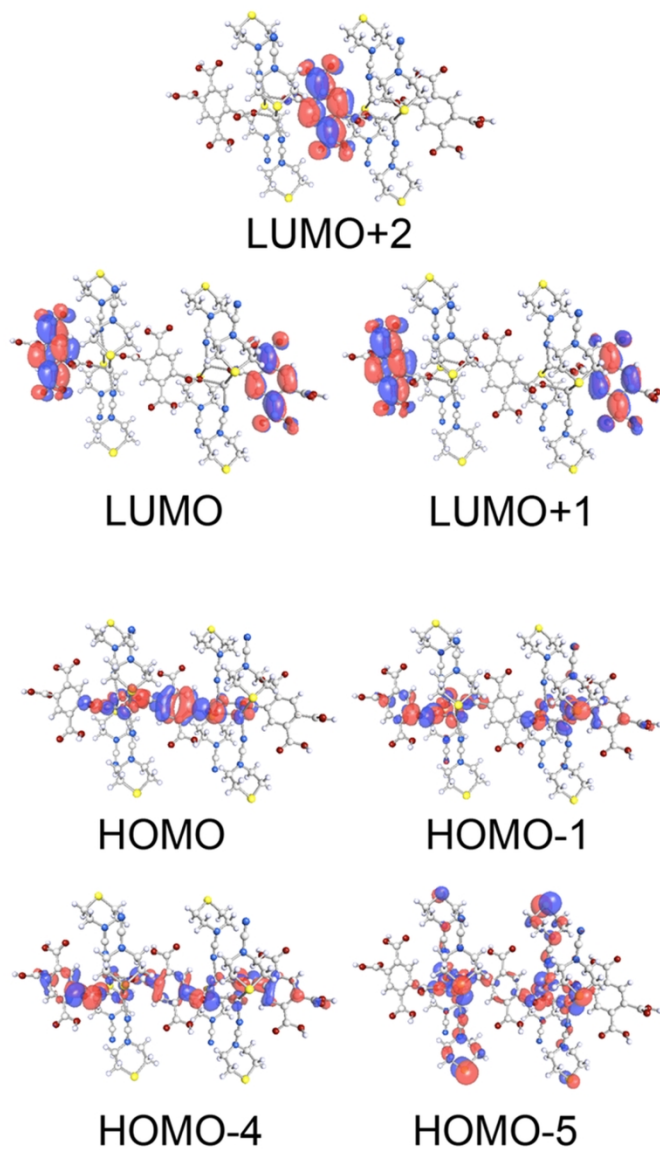
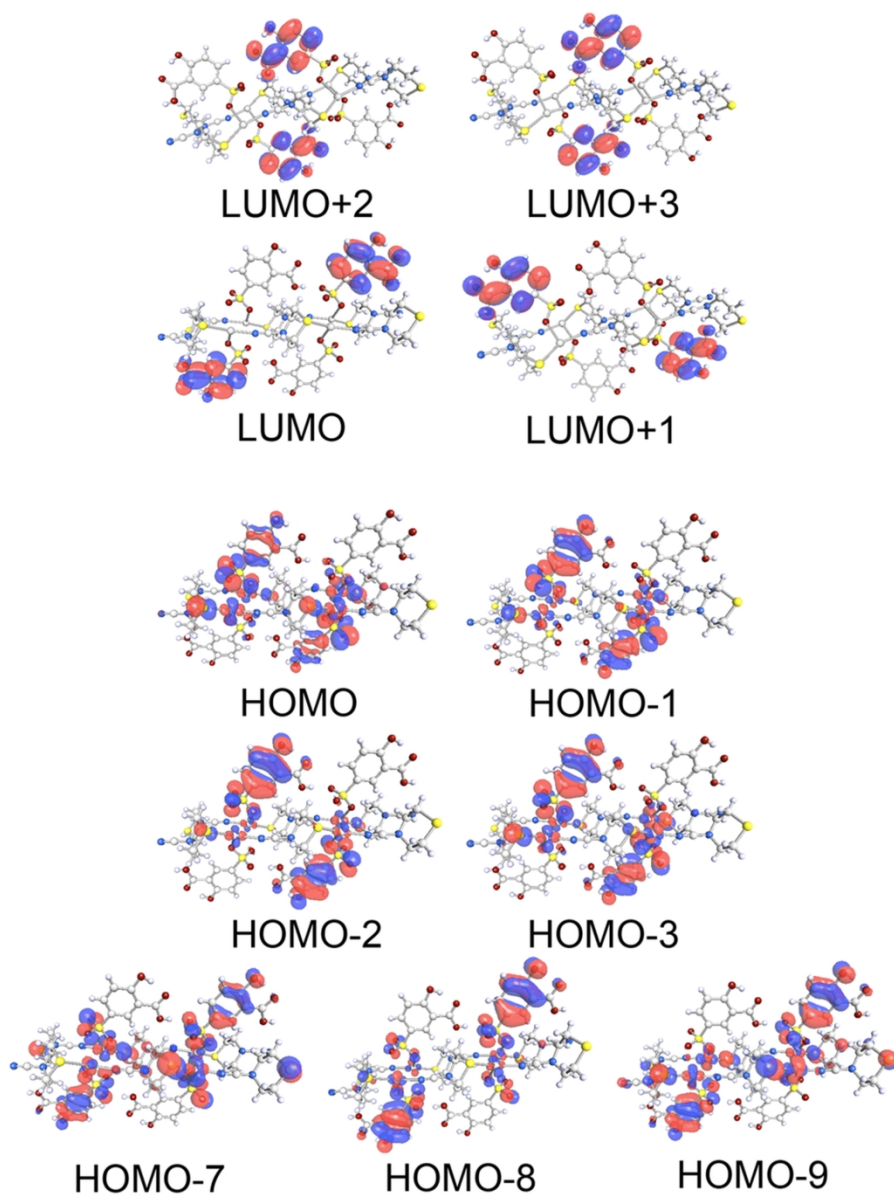


Figure 11. Frontier MOs for model system 3

84x144mm (600 x 600 DPI)



45 Figure 12. Frontier MOs for model system 4.

46 84x112mm (600 x 600 DPI)