Synthesis and Crystal Structure of a Water-soluble Gold(I) Complex, $\{K_3[Au(mba)_2]\}_2$ Formed by 2-Mercaptobenzoic Acid (H_2mba), with Aurophilic Interaction in the Solid-State

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Medicinally active, water-soluble and anionic gold(I) complex $\{K_3[Au(mba)_2]\}_2$ **1** formed by 2-mercaptobenzoic acid (H_2mba) was isolated and its crystal structure determined. The molecular structure in the solid-state comprised a dimeric $(AuS_2)_2$ core through a short gold(I)-gold(I) contact (3.1555(7) Å), i.e., the aurophilic interaction.

One recently highlighted topic in the coordination chemistry of the gold(I) atom is the d^{10}-d^{10} interaction between two closed shell cations, or the aurophilic interaction, many examples of which have been recently reported.[1] The weak gold(I)-gold(I) interaction, whose energy is similar to that of hydrogen bonds, has been rationalized by using relativistic and correlation effects.[1a] As a matter of fact, particular attention has been paid to compounds which contain weak metal-metal interactions with gold(I)-gold(I) separations in the range less than twice the van der Waals radii for gold, 3.32 Å.[1,2]

On the other hand, the studies of gold(I) complexes with biological or medicinal activities have been focused mostly on their antiarthritic activities,[3] antitumor activities,[3a] and also, recently, antimicrobial activities.[4] We have so far prepared water-soluble, anionic gold(I) complexes with thiolate ligands such as $\{Na_2[Au(tma)]\cdot 1.75H_2O\}_n$ (**3**, H_3tma = thiomalic acid),[5a] and $Na_3[Au(mba)_2]\cdot 5H_2O$ (**2**, H_2mba = 2-mercaptobenzoic acid).[5b] In fact, complexes **2** and **3** have shown effective antiarthritic activities,[5c] and **2** has also shown selective and modest antibacterial activities.[5d] X-Ray structure determination of these complexes has not been successful, because crystallization of **3** was difficult while as regards for **2**, the problem was in getting crystals suitable for X-ray analysis. However, in relation to **3**, the commercial $\{Na_{2-x}H_x[Au(tma)]\cdot nH_2O\}_n$ as an antiarthritic drug (myochrisine), which has been believed to be most difficult to crystallize, has been recently crystallized by hanging-drop vapor diffusion and its crystal structure determined.[6] In this work, with respect to **2**, we were successful in determining the crystal structure of $\{K_3[Au(mba)_2]\}_2$ **1**, being a dimer in the solid-state through the aurophilic interaction. Herein, we report the synthesis and structure of **1**.

The complex **1** with 3 hydrated water and one solvated EtOH was prepared by the $AuCl_4^-$: H_2mba : KOH = 1 : 4 : 8 molar ratio reaction in aqueous solution, purified by Sephadex G-10 gel filtration and crystallized from a solvent mixture of water and excess EtOH in a sealed flask.[7] The molecular formula of $\mathbf{1}\cdot 3H_2O\cdot$EtOH, obtained in 68.3% (0.34 g) yield, was consistent with all data of elemental analysis, TG/DTA, FT-IR, and ^{1}H and ^{13}C NMR spectroscopies.[8] The formation of **1** is shown in Eq 1.

$$NaAuCl_4\cdot 2H_2O + 4\ H_2mba + 8\ KOH \rightarrow 1/2\ \mathbf{1} + 3\ KCl + NaCl + 10\ H_2O + K_2(mba)_2 \quad (1)$$

where $K_2(mba)_2$ is a disulfide form (RS-SR) of mba^{2-}. The H_2mba plays the role of a reducing agent and a coordinating ligand, and all byproducts were removed by Sephadex G-10 gel filtration.

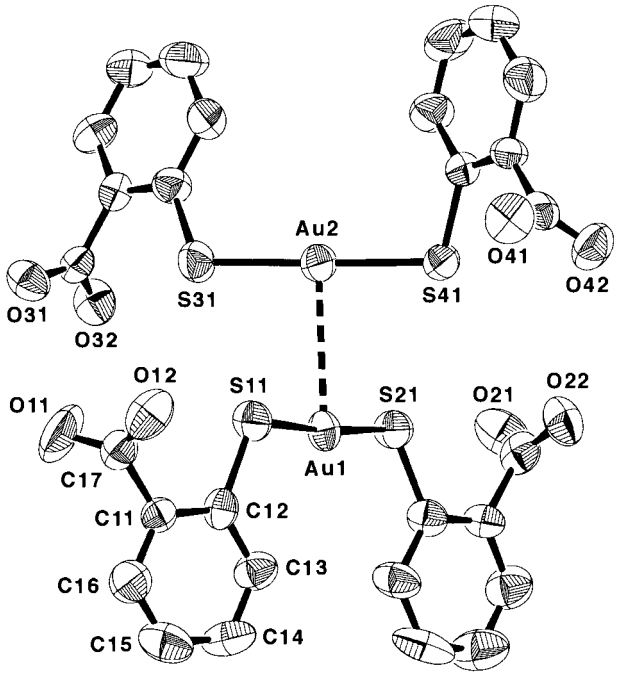

Figure 1. Molecular structure of complex **1**. Potassium ions, solvated EtOH and H_2O molecules, and hydrogen atoms are omitted for clarity. Selected bond distances (Å) and angles (°): Au1···Au2 3.1555(7), Au1-S11 2.288(3), Au1-S21 2.277(3), Au2-S31 2.276(3), Au2-S41 2.285(3), S11-Au1-S21 174.5(1), S31-Au2-S41 177.1(1), Au1-Au2-S31 92.27(8), Au1-Au2-S41 88.13(8), Au2-Au1-S11 92.26(8), Au2-Au1-S21 82.31(8).

The molecular structure of **1** (Figure 1) was determined with single-crystal X-ray diffraction analysis.[9] The most interesting feature in **1** is the presence of a short intermolecular Au1-Au2 distance of 3.1555(7) Å, which is significantly less than twice the van der Waals radii for gold, indicating a weak interaction between the two AuS_2 cores. The gold(I)-gold(I) distance of **1** is compared with those of the recent gold(I)-thiolate complexes with the aurophilic interaction, *e.g.*, $[Au_2(3,4\text{-}S_2C_6H_3CH_3)(PPh_3)_2]$ [3.096(2) Å],[1j] $[Au_2\{S_2CN(C_2H_4OMe)_2\}_2]$ [2.7902(6) (intramolecular) and 3.1572(7) Å (intermolecular)],[10a] and $[Au_2(SCH_2CH_2PEt_2)_2]$ [3.104 Å].[10b] The complex **1** in the crystals had a discrete dimeric unit without any intermolecular interaction; there were neither π-π stacking interactions between the ligands nor any hydrogen-bonding interactions. In the dimeric complex **1**, each gold(I) atom had a T-shaped geometry with the Au-S distances [2.288(3), 2.277(3), 2.276(3), 2.285(3) Å] and the S-Au-S angles [174.5(1), 177.1(1)°]. Six potassium cations were observed around the gold(I)-gold(I)

bond, but one potassium ion was disordered. The aurophilic interaction in **1** may be related to electrostatic interactions among potassium ions, carboxyl oxygen atoms and thiolate groups [K-O distances 2.52(1)-3.52(1) Å, K-S distances 3.228(4)-3.591(4) Å]. Similar aurophilic interaction has been also suggested in **2**.[5e] It has been pointed out that steric effects play a decisive role, since the weak forces associated with the gold(I)-gold(I) contacts are easily overruled by steric repulsion and other factors such as packing forces and also, by solvation with solvent molecules in solution.[1d]

The systems where the hydrogen bonding and the aurophilic interactions are cooperative forces have been reported in the neutral complexes $[Ph_2P(OH)AuCl]_2$[10c] and $[R_2P(OH)AuP(O)R_2]_2$.[10d] We have recently found the systems where the hydrogen bonding and the aurophilic interactions are competitive forces in the neutral complexes [Au(3-Hmba)(PPh_3)] (3-H_2mba = 3-mercaptobenzoic acid) and [Au(3-Hmba)(PCy_3)] (PCy_3 = tricyclohexylphosphine).[5f] On the other hand, the cationic complexes with the aurophilic interaction, $[Au(NH_2Bu^t)(PMe_3)]^+ BF_4^-$ and $[\{Au(PMe_3)\}_2NH(CH_2Ph)]^+BF_4^-$ [gold(I)-gold(I) distances 3.047(1) and 3.143(1) Å, respectively], have been so far reported.[1d] Thus, the aurophilic interaction observed in the water-soluble, anionic complex **1** is a rare example.

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7 Synthesis of **1**: To 1.54 g (10 mmol) of H_2mba dissolved in 10 mL EtOH, 20 mL of 1 M aqueous KOH solution (20 mmol) was added. The resulting clear yellow solution was dropwise added to a stirred solution of 1.00 g (2.5 mmol) $NaAuCl_4 \cdot 2H_2O$ in 10 mL water. The yellow solution was filtered through a folded filter paper (Whatman No. 2), followed by evaporating the filtrate to ca 2 mL by a rotary evaporator at 45 °C. To vigorously stirred 250 mL EtOH, the yellow concentrated solution was dropwise added to give a white precipitate. After washing it with EtOH (50 mL x 2) and thorough drying for 2 h, the white powder was redissolved in 10 mL water, filtered through a folded filter paper (Whatman No. 2), and the filtrate was evaporated to ca 2 mL by a rotary evaporator at 45 °C. The concentrated solution was passed through a Sephadex G-10 gel filtration column (ϕ 1.5 cm x 90 cm), and the fraction of the solution which gives a yellow precipitate by adding one drop of saturated $AgNO_3$ aqueous solution was collected by a fraction collector. The solution collected was evaporated to dryness by a rotary evaporator at 45 °C and dried *in vacuo* at 50 °C overnight. At this stage, a white solid was obtained in 1.23 g (73.4%) yield.
Crystallization of **1**: 0.50 g (0.7 mmol) of the white solid was dissolved in 5 mL water and the colorless solution was filtered through a folded filter paper (Whatman No. 2). The filtrate was evaporated by a rotary evaporator at 45 °C to just before the crystals deposit. To the clear colorless filtrate in a 100-mL round-bottom flask, 95 mL of EtOH was slowly added over 3 h. The flask was tightly sealed with a glass stopper and parafilm, and placed in the dark. The colorless cubic crystals were washed with (50 mL x 2) EtOH and dried *in vacuo* for 2 h. The thermally and light-stable and hygroscopic white powder obtained in 0.34 g (68.3%) yield was soluble in water, but insoluble in most organic solvents. From similar work-ups, colorless needle crystals of **2** were obtained in 0.15 g (30.4%) yield.

8 **1**: Anal. Found: C, 26.87; H, 1.87%. Calcd for $C_{15}H_{14}O_6S_2K_3Au$ or $K_3[Au(mba)_2]\cdot 1.5H_2O\cdot 0.5EtOH$ as a monomeric unit: C, 26.94; H, 2.11%. TG/DTA data: weight loss of 7.67% was observed below 239 °C (calcd for $1.5H_2O$ + 0.5EtOH: 7.49%) with an endothermic point at 79.4 °C and exothermic points at 284.3 and 400.2 °C; decomposition began around 365 °C. IR bands in 1700 - 400 cm^{-1} region (KBr disk): 1587vs, 1568vs, 1456m, 1425s, 1400vs, 1254m, 1158w, 1120w, 1054m, 1031m, 844m, 743m, 709m, 652m, 463w, 419w cm^{-1}. ^{1}H NMR (399.65 MHz, D_2O, 25 °C): 1.19 (EtOH, CH_3), 3.66 (EtOH, CH_2), 7.07 (1H, dd, H14, *J* 5.6 Hz), 7.13 (1H, dd, H15, *J* 7.6 Hz), 7.16 (1H, d, H16, *J* 7.1 Hz), 7.90 (1H, d, H13, *J* 7.6 Hz) ppm. ^{13}C NMR (100.40 MHz, D_2O, 25 °C): 19.6 (EtOH, CH_3), 60.1 (EtOH, CH_2), 181.3 (C17), 144.8 (C11), 137.9 (C12), 137.0 (C13), 129.8 (C14), 128.5 (C16), 126.5 (C15) ppm. Numbering of ^{1}H and ^{13}C NMR resonances is designated to Figure 1.

9 Crystal data for **1:** $C_{14}H_{14}O_7S_2K_3Au$. *M* = 672.7, monoclinic, *a* = 15.964(6) Å, *b* = 26.868(4) Å, *c* = 11.865(4) Å, β = 90.23(3)°, *V* = 5089(2) Å^3, space group $P2_1/n$ (#14), *Z* = 8 (monomers), *F(000)* = 2576.0, Mo-Kα radiation, room temperature. D_{cal} = 1.756 g cm^{-3}. μ = 64.83 cm^{-1}. A colorless cubic crystal of **1** (0.2 x 0.2 x 0.1 mm^3) was sealed in a glass capillary. All crystallographic measurements were made using RIGAKU AFC5S diffractometer. The structure was solved by direct method and refined by full-matrix least-squares using TEXSAN software package.[11] The *R* and R_w factors after refinement using 6038 observed reflections ($I > 2\sigma(I)$) among 11671 unique reflections were 0.044 and 0.063, respectively. Hydrogen atoms and solvated EtOH and water molecules were refined with isotropic temperature factor. Other atoms were refined with anisotropic thermal factors.

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11 TEXSAN: Crystal Structure Analysis Package, Molecular Structure Corporation 1985 and 1992.