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An Alternate Route to Disulfanido Complexes by Nucleophilic Attack of Thiolates on Ruthenium-Bound Thiosulfonato Ligands

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The reaction of the thiosulfonato complexes $[(p\text{-cym})Ru(bipy)(S\text{-}SO_2R)]^+$ (R = Ph, *p*-Tol) with the thiolates $R'S^-$ (R′ = alkyl or aryl) leads to S−S bond cleavage and to the quantitative formation of the corresponding disulfanido derivatives $[(p\text{-cym})Ru(bipy)(S\text{-}SR')]^+$. The aryldisulfanido complexes also react with benzyl thiolate by S−S bond cleavage to give $[(p\text{-cym})Ru(bipy)(SSCH_2Ph)]^+$.

The recent report of crystal structures that reveal persulfides directly ligated to a transition-metal center in biological systems[1] has opened a new field of investigation for coordination chemists. To provide a rational synthesis of disulfanido complexes and to study their chemical reactivity, however, still remain challenges. With three potential reactive centers, namely, the metal cation and the two sulfurs of the S−S bond, these species are indeed highly reactive. We have recently reported the first direct synthesis of alkyldisulfanido complexes by the simple reaction between a hydroxo zinc complex and a synthetic persulfide.[2] However, this strategy requires a stable persulfide and is therefore limited to bulky and electron-rich derivatives. It also absolutely requires the presence of a base in the metal coordination sphere of the starting complex, to avoid the known degradation of hydrodisulfides in a basic solution. Other rational strategies found in the literature use the nucleophilicity of sulfur ligands like hydrogen (sulfido)[3] (HS^-) or disulfido[4] (S_2^{2-}) and their subsequent reaction with electrophilic sulfur or carbon centers, respectively. Herein, we propose an alternate route toward disulfanido complexes, resulting from the nucleophilic attack of a thiolate on a metal-bound thiosulfonate moiety. Interestingly, the thiolate does not react at the metal center by ligand exchange but selectively on the thiosulfonate ligand itself, leading to cleavage of the $S-S(O)_2$ bond and to the formation of a new S−S bond.

The new complexes $[(p\text{-cym})Ru(bipy)(S\text{-}SO_2(p\text{-Tol})]^+$ (**1a**) and $[(p\text{-cym})Ru(bipy)(S\text{-}SO_2(Ph)]^+$ (**1b**) were synthesized and isolated as their PF_6 salts by first reacting the complex $[(p\text{-cym})Ru(bipy)(Cl)](PF_6)$ with $AgNO_3$ in methanol, followed by the addition of the thiosulfonate salt *p*-$TolSO_2SK$ or $PhSO_2SNa$. Thiosulfonato complexes of ruthenium, based on the Cp ligand, have already been reported, but they were obtained either by oxygen transfer from the thiosulfinato derivatives $CpRu(PPh_3)(CO)(SS(O)R)$[5] or by reaction between the hydrogen (sulfido) compounds CpRu(dppe)(SH) or CpRu(dppm)(SH) and sulfonyl chlorides.[6] The X-ray crystal structure of $\mathbf{1b\cdot PF_6}$ is displayed in Figure 1, and it shows bond lengths and angles in the range observed in related derivatives of ruthenium[5,6] or other metals.[7]

Upon the addition of a methanolic solution of sodium benzyl thiolate to a solution of **1a** or **1b** in methanol or dimethyl sulfoxide (DMSO), the color of the mixture immediately turned from yellow to orange. Careful analysis of the ^1H NMR spectrum of the crude reaction mixture (Figure 2) of **1a**

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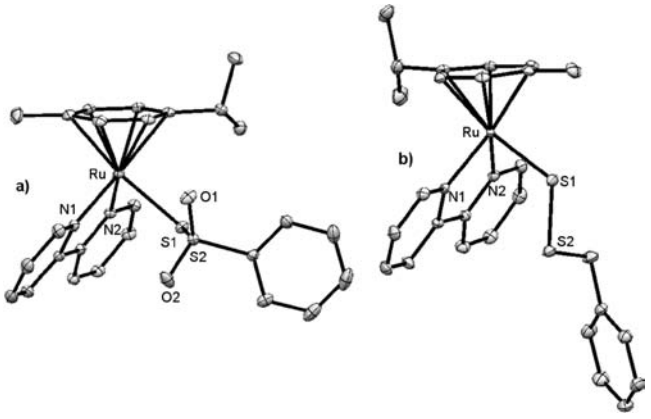


Figure 1. ORTEP views of complexes **1b·PF$_6$** (a) and **2c·BPh$_4$** (b) showing thermal ellipsoids at 50% probability and atom labeling. The hydrogen atoms and the anions have been omitted for clarity. Selected bonds lengths for **1b·PF$_6$** (**2c·BPh$_4$**): Ru1−S1, 2.401 (2.384); Ru1−N1, 2.082 (2.078); Ru1−N2, 2.075 (2.084); S1−S2, 2.040 (2.042).

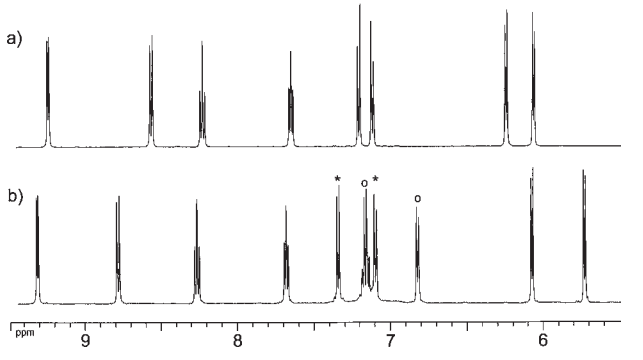
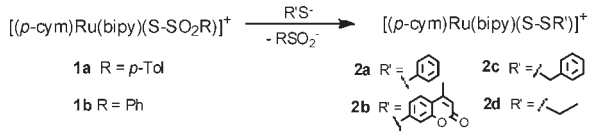


Figure 2. Aromatic region of the ^{1}H NMR spectra recorded at 500 MHz of **1a·PF$_6$** (0.02 M in DMSO-d_6) before (a, top) and after (b, bottom) the addition of 1 equiv of sodium benzyl thiolate (*, *p*-TolSO$_2$Na; ○, PhCH$_2$SS-Ru).

Scheme 1. Synthesis and Notation of the Disulfanido Complexes



indicates the release of *p*-TolSO$_2^-$ in solution, along with the replacement of the initial signals of the thiolate anion by a new set of more shielded peaks ($\Delta\delta$ = 1.35 ppm for the benzylic protons), attributed to the introduction of the benzyl group within the coordination sphere of the metal.

This is in agreement with the reaction proposed in Scheme 1, in which the S−S(O)$_2$ bond is cleaved by a nucleophilic attack of the thiolate on the internal sulfur atom of the metal thiosulfonate ligand. Further evidence for the formation of the disulfanido species, Ru−S−SCH$_2$Ph, comes from analysis of the mass spectrometry spectrum (ESI$^+$ mode) of the crude reaction mixture, which displays a peak at *m*/*z* 547 (**2c**, 100%), and from X-ray structure analysis of **2c** crystallized as the BPh$_4$ salt, shown in Figure 1. The Ru−S bond length in **2c** is slightly shorter (Δ = 0.017 Å) than that in **1a**, and this correlates with an increase of the average Ru−N distance (Δ = 0.023 Å). The structure also clearly shows that the benzylic protons of the disulfanido moiety lie above one of the aromatic rings of the bipy ligand, accounting for the strong shielding of these protons

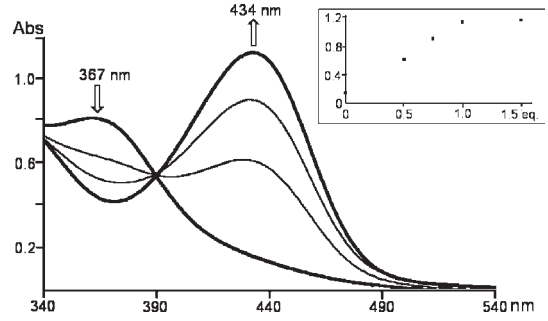


Figure 3. Titration of complex **2b·PF$_6$** in DMSO (4×10^{-5} M) by sodium benzyl thiolate (inset: variation of the absorbance at 434 nm with the amount of added thiolate).

observed by ^{1}H NMR. Again, the Ru−S distance is similar to that observed in the CpRu(PPh$_3$)(CO)(SSR) complexes.[5]

The reaction is general, and aromatic as well as aliphatic thiolates can be successfully used (Scheme 1), with the only complexes detected at the end of the reaction being the disulfanido derivatives **2a**−**2d**.

A similar reaction takes place between the aryldisulfanido complexes **2a** and **2b** and sodium benzyl thiolate. The reaction, in DMSO, can easily be monitored by ^{1}H NMR. The addition of 1 equiv of benzyl thiolate to either **2a** or **2b** leads to the immediate and complete formation of **2c** as a single complex (see Figure S1 in the Supporting Information). With **2b**, which bears a coumarin chromophore, the reaction can conveniently be monitored by UV−visible spectroscopy. While **2b** (λ_{max} = 367 nm) is stable for hours in solution, it immediately reacts with benzyl thiolate with concomitant release of 4-methyl-2-oxo-2*H*-chromene-7-thiolate (λ_{max} = 434 nm). In both cases, the reactions are not equilibrated, showing that the released aryl thiolate is not able to attack the alkyldisulfanido ligand by UV−visible spectroscopy (Figure 3).

The conversion of complex **1** into complex **2** is related to the reaction of organic thiosulfonates RSO$_2$SR′ with thiols R″SH, which is known to yield the disulfides R′SSR″ along with the release of the sulfinic acid RSO$_2$H.[8] More interestingly, this conversion shares some similarities with the reaction catalyzed by rhodanese-like enzymes[9] or thiosulfate reductase,[10] which assist cleavage of the S−S bond of thiosulfate ($S_2O_3^{2-}$) or thiosulfonate (RSO_2S^-) anions by a thiolate. The active sites of these enzymes are characterized by an intense electrostatic field generated by basic amino acid residues such as arginines and histidines, which provide a strong anion binding site for the substrate.[11] When the electron density is reduced from the terminal sulfur of the thiosulfate or thiosulfonates, this field favors the nucleophilic attack of the thiolate and the formation of a persulfide, which can subsequently react with a sulfur acceptor, such as cyanide or thiols.

From the few precedents found in the literature,[12] it appears that sulfur-containing nucleophiles do not promote

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the $S-S(O)_2$ bond cleavage of thiosulfonato metal complexes but lead to ligand exchange.[12] Similarly, very recently, we reported that the reaction between alkyldisulfanido tris(pyrazolyl)borate zinc complexes and thiols in the presence of a base results in a metal-based reaction rather than in sulfur attack of the S−S bond.[2] In the case of octahedral Ru^{II} d^6complexes, ligand-exchange reactions are usually slow compared with those of other divalent metal complexes,[13] and this results in an unprecedented reaction leading to **2a**−**2d** and to the specific conversion of **2a** or **2b** into **2c**. Indeed, we can expect a slow exchange of the thiosulfonato or disulfanido ligands in **1** and **2** because in similar derivatives thiolate substitution is slow[14] and the Ru−S bond strength is rather insensitive to the sulfur oxidation state.[15] This drives the reaction with the nucleophilic thiolates toward cleavage of the S−S bonds, although the reaction is only feasible in the presence of good leaving groups such as sulfinates or aryl thiolates.

In conclusion, we successfully controlled the heterolytic cleavage of the S−S bond of a metal-coordinated thiosulfonate. The versatile chemoselective nucleophilic attack at the internal sulfur of $Ru-\underline{S}-S(O_2)R$ by thiolates gives access to alkyl- or aryldisulfanido complexes, $Ru-\underline{S}-S-R'$, with release of the sulfinate anion $RS(O_2)^-$. This reaction is highly reminiscent of the thiolate cleavage of organic thiosulfonates $R_1-S-S(O_2)R_2$ by a selective attack at the sulfenyl sulfur to give a disulfide $R_1-S-S-R'$.

Supporting Information Available: Synthetic procedures for all of the complexes described, Figure S1, and crystallographic data of complexes **1b·PF$_6$** and **2c·BPh$_4$** in CIF format. This material is available free of charge via the Internet at http://pubs.acs.org.

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