

# Kinetics and mechanism of the Co(II)-assisted oxidation of thioureas by dioxygen†

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Catalytic oxidation of *N,N'*-dimethylthiourea and thiourea by dioxygen in water using a new cobalt(II) complex of octasulfophenyltetrapyrazinoporphyrazine was performed under mild conditions. The reaction is shown to include the formation of an intermediate anionic five-coordinate complex followed by an unusual two-electron oxidation to produce the corresponding urea and elemental sulfur (S<sub>8</sub>). Kinetic and thermodynamic parameters for the different reaction steps of the process were determined. Drastic differences in catalytic activity of cobalt and iron octasulfophenyltetrapyrazinoporphyrazines were observed.

## Introduction

Thiourea (TU) and *N,N'*-dimethylthiourea (DMTU) are widely used in chemistry, biochemistry and technology.<sup>1,2</sup> Thus, thiourea is an extremely versatile chemical with applications involving melamine resins, catalysis, stabilization of textiles, pharmaceuticals, flame retardants, and complex reactions involved in electrolytic processes.<sup>1</sup> *N,N'*-dimethylthiourea, a highly permeate molecule, decreases injury in a wide variety of biological systems.<sup>2,3</sup> The protective effect of DMTU has been ascribed to its capacity to inactivate reactive oxygen species.<sup>2–6</sup> Both TU<sup>7</sup> and DMTU<sup>8</sup> are known to be toxic compounds. It has been argued that the degree of desulfurization during the metabolic processes may determine the level of toxicity of each thiourea.<sup>7</sup> Desulfurization of thioureas *in vivo* probably occurs *via* oxygenation, followed by nucleophilic substitution or elimination reactions.<sup>7</sup> Oxidative desulfurization of thiourea also plays an important role in industry.<sup>9,10</sup> High concentrations of TU in industrial wastes are not acceptable due to the toxicity of this compound.<sup>9</sup> Thus environmental concerns have promoted studies on the destruction of TU.

The desulfurization of thioureas has been achieved by use of a number of different reagents, including hydrogen peroxide,<sup>11</sup> chlorine dioxide,<sup>12</sup> ferrate(VI)<sup>10</sup> and other substances. Frost tested the oxidative degradation of TU in an alkaline medium using air on an activated charcoal surface;<sup>13</sup> major products were dicyandiamide and thiosulfate, whereas urea and sulfur were the minor products. Cyanamide and dicyandiamide were found to be the major products of photo-catalysed destruction of TU over TiO<sub>2</sub> powder.<sup>9</sup> Unfortunately, since dicyandiamide is resistant to biodegradation,<sup>14</sup> high concentrations are not acceptable in waste water. Much more promising would be oxidation by air (O<sub>2</sub>) leading to urea. It is known that catalytic oxidation of the reduced sulfur-containing compounds can be achieved by use of metallophthalocyanines as catalysts.<sup>15</sup> Due to their high stability, specificity, and strong catalytic activity, metallophthalocyanines have been engaged in many studies in recent years.<sup>16–18</sup> In contrast to phthalocyanines (Pc), their aza analogues, tetrapyrazinoporphyrazines, remain much less studied although they are receiving rapidly increasing attention due to their effectiveness as photo-sensitizers in photodynamic

therapy of cancers,<sup>19</sup> as molecular scaffolds<sup>20</sup> and as highly conducting films.<sup>21</sup>

Published data show that the properties of tetrapyrazinoporphyrazines and their metal complexes are quite different from their phthalocyanine analogues. The observed redox potentials of metallotetrapyrazinoporphyrazines appear to be markedly shifted to the cathodic region when compared with those of metallophthalocyanines. This behaviour is consistent with the enhanced  $\pi$ -acceptor properties of the pyrazine annulated porphyrazines.<sup>22</sup> These peculiarities may be manifested in other properties of the mentioned macrocyclic compounds, for example, the mechanism of catalytic oxidations by dioxygen in the presence of these metallocomplexes. Such reactions have received significant attention, since several critical processes in biology involve dioxygen,<sup>23,24</sup> and most of these processes are promoted by transition metal ions and complexes.

In this paper we report kinetic and mechanistic information for the oxidation of *N,N'*-dimethylthiourea by dioxygen in the presence of Co(II)-octasulfophenyltetrapyrazinoporphyrazine, [Co<sup>II</sup>{PyzPz(PhSO<sub>3</sub>)<sub>8</sub>}(H<sub>2</sub>O)<sub>2</sub>]<sup>8–</sup>, that exhibits distinct differences compared to the other catalytic oxidations of thioureas. Some experiments were also performed with thiourea.

## Experimental

### Materials

All chemicals were of p.a. grade and used as received. CAPS, TRISINE and BIS-TRIS buffers were purchased from Sigma. Pure thiourea and *N,N'*-dimethylthiourea (Aldrich) were used. Ultrapure water was used in all measurements.

**(Octaphenyltetrapyrazinoporphyrazine)cobalt(II) (1).** 2 g (7.1 mmol) 2,3-dicyano-5,6-diphenylpyrazine<sup>25</sup> and 0.8 g (3.2 mmol) cobalt(II) acetate tetrahydrate were added to a quartz tube. This mixture was stirred at 250 °C under inert atmosphere for 20 min. After cooling the crude product was dissolved in 50 ml of conc. H<sub>2</sub>SO<sub>4</sub> and precipitated by addition of 200 ml of distilled water. The green precipitate was filtered and washed with water. Complex **1** was purified by washing with hot acetone. Yield 1.40 g (66%). Anal. Calcd. for [Co<sup>II</sup>{PyzPzPh<sub>8</sub>}(H<sub>2</sub>O)<sub>2</sub>], C<sub>72</sub>H<sub>44</sub>CoN<sub>16</sub>O<sub>2</sub>; C, 70.64; H, 3.62; N, 18.31%. Found: C, 70.13; H, 3.62; N, 18.04%. M 1224 (FD-MS).

**(Octasulfophenyltetrapyrazinoporphyrazine)cobalt(II) (2).** Complex **1** (1.0 g, 0.82 mmol) was dissolved in HSO<sub>3</sub>Cl (5 ml), and the mixture was refluxed for 1 h under stirring. After cooling,

† Electronic supplementary information (ESI) available: Five figures including Eyring plots and plots of  $k_{\text{obs}}$  as a function of pressure. See <http://www.rsc.org/suppdata/dt/b4/b417775d/>

the mixture was added to an ice cold saturated NaCl solution in water and the precipitate was filtered off and washed with cold distilled water to neutrality. After filtration, the green paste was heated at 100 °C. The final solid material was washed with conc. HCl. After drying, this sample was used as catalyst. For analysis the complex can be purified using column chromatography. Yield 0.89 g. 0.1 g of the complex was dissolved in 2 ml of water and chromatographed twice, firstly on a column with 'Dowex' (eluent: water) and secondly using gel permeation chromatography (Molselect G9, eluent: water). The final product was precipitated from solution in water by addition of ethanol, filtered off, washed with ethanol and dried under vacuum for 2 h (0.073 g). UV-vis,  $\lambda$ /nm (H<sub>2</sub>O): 351, 636. <sup>1</sup>H NMR,  $\delta$  (D<sub>2</sub>O): 8.40–7.42 (q). Anal. Calcd. for [Co<sup>II</sup>{PyzPz(PhSO<sub>3</sub>H)<sub>8</sub>}(H<sub>2</sub>O)<sub>2</sub>], C<sub>72</sub>H<sub>44</sub>CoN<sub>16</sub>S<sub>8</sub>O<sub>24</sub>; C, 47.19; H, 2.42; N, 12.23; S, 14.00%. Found: C, 46.76; H, 2.42; N, 12.11%.

### Separation and identification of the products of catalytic oxidation

Sulfur S<sub>8</sub> was separated from solution by filtration. Analytical data: EI-MS (70 eV) 256 (100%); elemental analysis (%) calculated for S<sub>8</sub>: S 100%; found: S 99.33%. *N,N'*-Dimethylurea was separated by evaporation of the filtrate and purified by double crystallization from aqueous ethanol. <sup>1</sup>H NMR (300 MHz, CDCl<sub>3</sub>):  $\delta$  = 5.80–5.91 (s, 2H), 2.62–2.80 (t, 6H); <sup>13</sup>C NMR (75 MHz)  $\delta$  = 163.4, 27.8. Urea was separated by evaporation of the filtrate. The precipitate was dissolved in a minimum quantity of water and urea precipitated as nitrate after addition of nitric acid. Mp = 151–152 °C (dec.) following crystallization from water.

### Instrumentation

pH measurements were performed on a Mettler Delta 350 pH meter. The pH meter was calibrated with standard buffer solutions at pH 4.0 and 10.0. The UV-vis spectra were recorded on a Cary 1 spectrophotometer. IR spectra were recorded on an AT1 Mattson FTIR Infinity spectrophotometer. NMR measurements were performed on a Bruker Avance DPX 300 NB spectrometer operating at 300.13 MHz for <sup>1</sup>H NMR. EPR spectra were recorded on a Bruker ESR 300 E spectrometer (9.96 GHz) in H<sub>2</sub>O and DMSO at 177 K. MS spectra were recorded on a Jeol M700 instrument. Cyclic voltammetric measurements on complex 2 were carried out on an AUTOLAB (Eco Chemie B.V.) instrument at 25 °C in a 0.1 M aqueous solution of NaBF<sub>4</sub>. Cyclic voltammograms were recorded by potential scanning rates of 50, 100, 300, 500 and 1000 mV s<sup>-1</sup>. The working electrode was gold (Metrohm), the counter electrode was platinum wire (Metrohm), and the reference electrode was Ag/AgCl, KCl (sat.). The system was calibrated with K<sub>3</sub>[Fe(CN)<sub>6</sub>] as standard before the measurements.

### Stopped-flow kinetics

Kinetic measurements were performed on a thermostated ( $\pm$  0.1 °C) stopped-flow spectrophotometer (SX-17MV, Applied Photophysics) under pseudo-first order conditions. The changes in absorbance were monitored at 515 nm. High-pressure stopped-flow experiments were performed at pressures up to 130 MPa on a custom-built instrument described previously.<sup>26</sup> Kinetic traces were recorded on an IBM-compatible computer and analysed with the OLIS KINFIT (Bogart, GA, 1989) and Origin 7.0 set of programs.

### Determination of p*K*<sub>a</sub> values

Two methods were used for determination of p*K*<sub>a</sub> values: spectrophotometric titration and kinetic determination. (1–4)  $\times$  10<sup>-5</sup> M solutions of 2 in water (pH = 6.1–6.3) were titrated with

NaOH. Kinetic p*K*<sub>a</sub> was determined from the dependence of *k*<sub>obs</sub> on pH in the reaction of 2 with KOH.

## Results and discussion

Our previous studies on octasulfophenyltetrapyrzineporphyrane–iron(II) showed<sup>27</sup> that the introduction of four electron accepting pyrazine units into the macrocycle stabilizes the Fe<sup>II</sup> cation to oxidation and makes the complex a promising electron scavenger. The reaction of the complex with either weak (hydrochloric acid, bromine) or strong (SO<sub>3</sub><sup>2-</sup>, Ce<sup>4+</sup>) oxidants did not lead to the formation of the Fe(III) complex. Contrary to the oxidation, the Fe(II) complex can easily be reduced chemically with weak reductants such as TU or Na<sub>2</sub>SO<sub>3</sub>. It was assumed that octasulfophenyltetrapyrzineporphyrane–iron(II) will be an effective catalyst for oxidation of TU. Unfortunately, the catalytic oxidation of TU did not proceed with measurable rates at room temperature and pH 5–9. This prompted us to synthesize octasulfophenyltetrapyrzineporphyrane–cobalt(II) and to study its properties.

### Properties of complex 2

Fig. 1 reports cyclic voltammograms of complex 2 at pH 5.0. Only one reduction at –0.819 mV and two successive oxidations at +951 and 1091 mV were observed for this complex. The reduction is an irreversible multi-electron process and assigned to the reduction of the porphyrane macrocycle, accompanied by its destruction. The first oxidation is a pseudo-reversible process with a corresponding anodic maximum at +667 mV assigned to the Co<sup>III</sup>/Co<sup>II</sup> couple. The second is an irreversible one-electron oxidation of the ligand. By comparison, the cyclic voltammogram of octasulfophenyltetrapyrzineporphyrane–iron(II) consists of two reductions at +545 and –890 mV, and an oxidation at +1019 mV.<sup>27</sup> For both iron and cobalt complexes, no peaks were observed for the Fe<sup>II</sup>/Fe<sup>I</sup> or Co<sup>II</sup>/Co<sup>I</sup> couples, probably as a result of slow heterogeneous electron

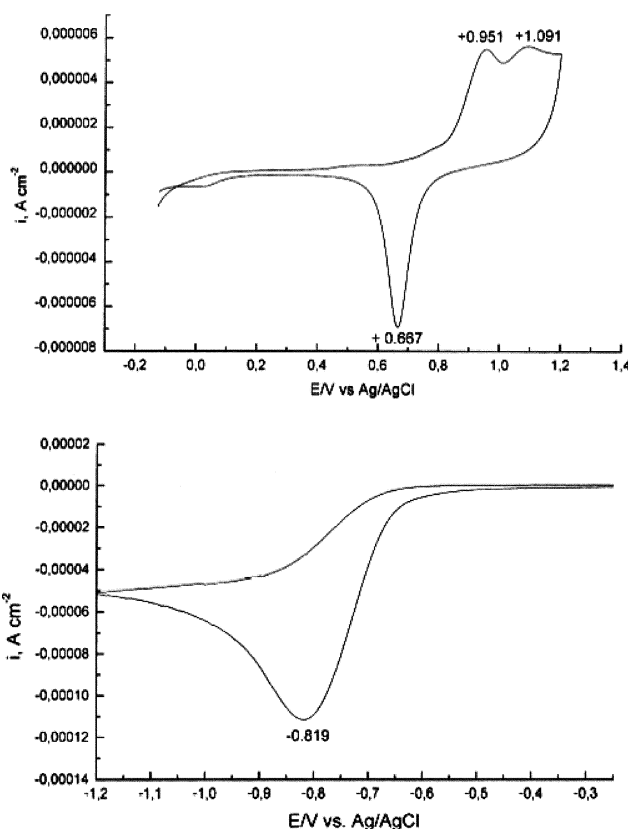
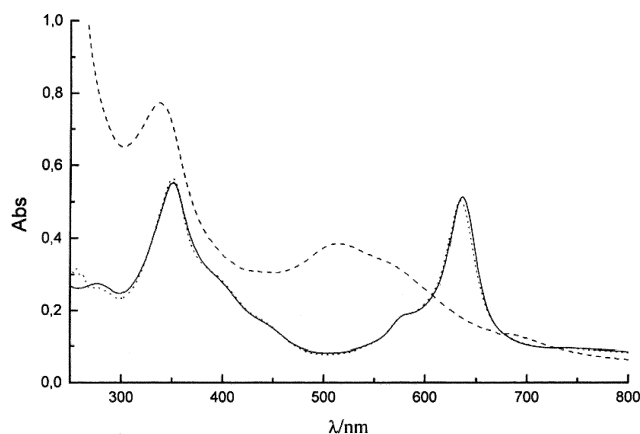


Fig. 1 Cyclic voltammograms for [Co<sup>II</sup>{PyzPz(PhSO<sub>3</sub>H)<sub>8</sub>}(H<sub>2</sub>O)<sub>2</sub>]<sup>8-</sup> (10<sup>-3</sup> M) at 25.0 °C, pH = 5.0. Scan rate 0.1 V s<sup>-1</sup>.

transfer kinetics for these couples. A comparison of the voltammograms for the cobalt and iron complexes shows that  $[\text{Co}^{\text{II}}\{\text{PyzPz}(\text{PhSO}_3)_8\}(\text{H}_2\text{O})_2]^{8-}$  can be easier reduced and oxidized than the iron complex, but differences in electrochemical behaviour are relatively small. However, they lead to drastic differences in catalytic activity of the complexes (see below).

Complex **2** is soluble in water and hence the UV-vis spectra were recorded in water. Fig. 2 shows that spectra of **2** under aerobic and anaerobic conditions differ slightly. The electronic spectrum of complex **2** under anaerobic conditions is typical for metal porphyrazines and comprises of intense  $\pi$ - $\pi^*$  transition bands in the Soret (351 nm) and Q (636 nm) regions (Fig. 2).



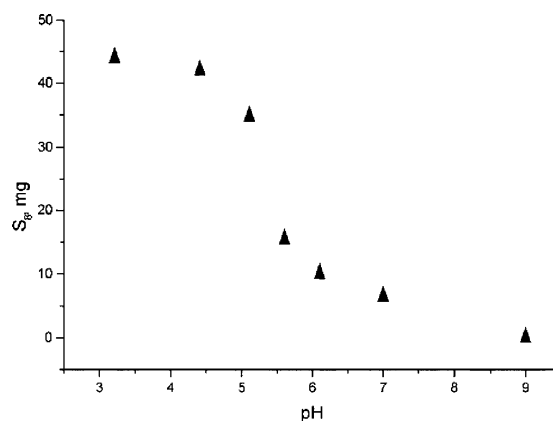
**Fig. 2** UV-Vis spectra of  $[\text{Co}^{\text{II}}\{\text{PyzPz}(\text{PhSO}_3)_8\}(\text{H}_2\text{O})_2]^{8-}$  ( $8 \times 10^{-6}$  M) in  $\text{H}_2\text{O}$  in air saturated solution (dotted line), after bubbling with argon (solid line), after addition of an excess of DMTU (broken line); last spectrum was recorded for  $[\text{Co}^{\text{II}}\{\text{PyzPz}(\text{PhSO}_3)_8\}(\text{H}_2\text{O})_2]^{8-} = 1.1 \times 10^{-5}$  M.

### Interaction of complex **2** with TU and DMTU

On addition of TU or DMTU to a solution of **2**, the colour changes from green to red. Fig. 2 shows that in the presence of reductant a new intense band at 515 nm appears, whereas the Q-band completely disappears. Similar spectral changes were observed in the reaction with either strong (sodium dithionite) or weak reductants (diethylamine in water with complex **2** or in DMSO with complex **1**). Therefore, it is reasonable to assume that in all cases the reduction of complex **2** leads to the formation of the same product. It is important to note that addition of  $\text{Na}_2\text{S}_2\text{O}_4$  to a solution of  $\text{Co}^{\text{II}}$  tetrasulfophthalocyanine  $[\text{Co}^{\text{II}}(\text{TSPc})^{4-}]$  leads to very different changes than observed for octasulfophenyltetrapyrrolineporphyrazine-cobalt(II). In the case of  $\text{Co}^{\text{II}}(\text{TSPc})^{4-}$ , an intense absorption maximum at 450 nm appears,<sup>18</sup> and simultaneously the Q-band is red shifted. The observed spectrum is identical to that reported for  $\text{Co}^{\text{I}}(\text{TSPc})^{5-}$ . If the reduction of complex **2** would also lead to formation of a  $\text{Co}^{\text{I}}$  complex, the appearance of a blue shifted band compared to 450 nm is expected, since metalloporphyrazines always absorb at lower wavelengths than the corresponding metallophthalocyanines.<sup>28</sup> Obviously, the dramatic changes in UV-vis spectrum of complex **2** after reduction indicate strong changes in the  $\pi$ -system of the ligand. Additional data on the structure of the reaction products can be obtained from  $^1\text{H}$  NMR. The overlap of signals from  $\text{CH}_3$  groups in free and coordinated DMTU does not allow the determination of the structure of reduced complex **2**. Fortunately, no such overlap has been observed for free and coordinated diethylamine (at least 10-fold excess of  $(\text{C}_2\text{H}_5)_2\text{NH}$  was used in the mixture of complex **1** and diethylamine in  $\text{DMSO}_{d6}$ ). It was therefore possible to determine the correlation between integral intensities of the signals of aromatic protons in eight phenyl groups of complex **1** and  $\text{CH}_2$  groups in coordinated diethylamine which was equal to 10 : 1. This result shows that the formation of a 1 : 1 complex

takes place. Obviously, similar complexes are formed also in the case of thioureas. It should be noted that the final complex is stable under anaerobic conditions for at least a few hours independently of the nature of the reductant.

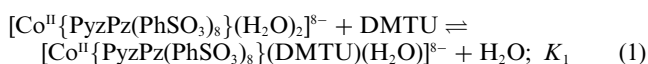
Attempts to obtain the UV-vis spectra of TU or DMTU solutions in the presence of complex **2** under aerobic conditions were unsuccessful due to rapid formation of a precipitate. Data from EI-MS analysis clearly showed that this precipitate is elemental sulfur ( $\text{S}_8$ ). The desulfurization of thioureas proceeds in acidic and neutral media (pH 1–8), but not in alkaline solutions presumably due to deactivation of the catalyst (see below). The rate of desulfurization increases with decreasing pH and does not depend on the type of acid ( $\text{HCl}$ ,  $\text{H}_2\text{SO}_4$ ,  $\text{CH}_3\text{COOH}$ ). Besides sulfur, other products of the catalytic oxidative desulfurization are urea and  $N,N'$ -dimethylurea (DMU), respectively. It is known that one-electron oxidation of thiourea in acidic media leads to formamidedisulfide.<sup>29</sup> The carbamidinothiyl radical,  $\text{NH}_2(=\text{NH})\text{CS}^\bullet$ , is the first product of a one-electron oxidation of TU.<sup>30</sup> The use of a spin trap 5,5-dimethyl-1-pyrroline- $N$ -oxide (DMPO), allows the detection of this radical. The stability of the carbamidinothiyl radical was found to depend substantially on pH; the most intense EPR signal being observed at pH 2.5–3.0.<sup>30</sup> However, in the present study we were unable to detect any formation of this radical upon oxidation of TU with dioxygen in acidic solutions in the presence of complex **2** and DMPO. Additional evidence for the absence of formamidedisulfide in the intermediate steps of TU oxidation comes from the pH dependence of the rate of sulfur formation (due to difficulties with kinetic measurements of sulfur formation, Fig. 3 shows the pH dependence of the quantity of sulfur formed in the same time from thiourea under aerobic conditions). It is known that formamidedisulfide is unstable at high pH,<sup>30</sup> and the rate of its decomposition to sulfur increases in more alkaline solutions. In contrast to this, in the present study the rate of sulfur formation increases in more acidic solutions (Fig. 3). Thus, all available data confirm a two-electron mechanism for the oxidative desulfurization of thioureas catalysed by complex **2**.



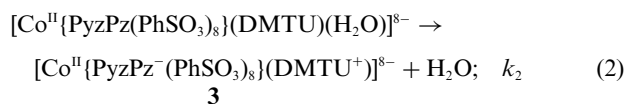
**Fig. 3** pH dependence of quantity of  $\text{S}_8$  formed from thiourea under aerobic conditions,  $[\text{Co}^{\text{II}}\{\text{PyzPz}(\text{PhSO}_3)_8\}(\text{H}_2\text{O})_2]^{8-} = 1.2 \times 10^{-5}$  M,  $[\text{TU}] = 0.48$  M,  $25.0^\circ\text{C}$ , reaction time 24 h, reaction volume 5 ml.

### Kinetic and mechanistic studies

The kinetic study of the catalytic desulfurization of DMTU involved two series of experiments. In the first series the reaction of an excess of DMTU with complex **2** under anaerobic conditions and pH 7 was studied. A straight line plot of  $1/k_{\text{obs}}$  vs  $1/[\text{DMTU}]_0$  (Fig. 4) shows that the reaction follows Michaelis-Menten kinetics which is characteristic for intramolecular electron transfer involving a rapid pre-equilibrium. The corresponding rate law is given in (3).

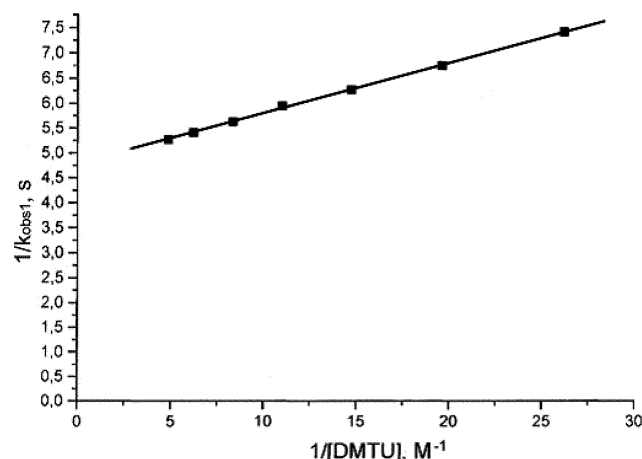






$$k_{\text{obs1}} = k_2 K_1 [\text{DMTU}] / \{1 + K_1 [\text{DMTU}]\} \quad (3)$$

The values of  $K_1$  and  $k_2$  from Fig. 4 are  $2.1 \pm 0.2 \text{ M}^{-1}$  and  $0.21 \pm 0.01 \text{ s}^{-1}$  at 298 K, respectively. It should be noted that no sulfur formation was observed during the experiments under anaerobic conditions. This indicates that no disulfide is formed from DMTU and an oxidized form of DMTU does not leave the coordination sphere of the complex. The results for TU were comparable to the results obtained with DMTU, but in this case rates of reduction were approx. 5 times slower than with DMTU under the same conditions.

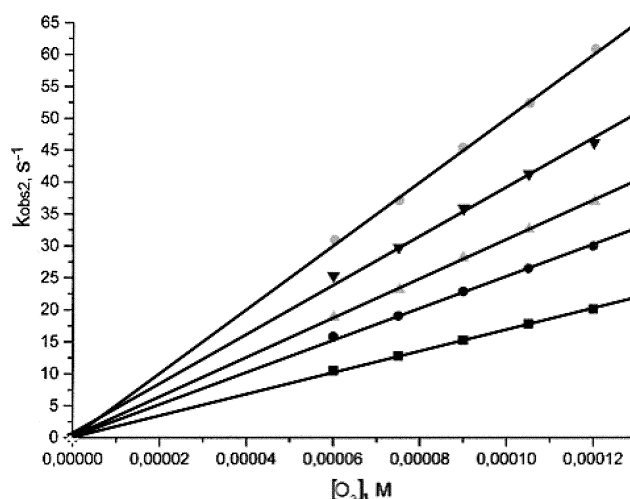


**Fig. 4** Plot of  $1/k_{\text{obs1}}$  vs.  $1/[\text{DMTU}]$ . Experimental conditions: 0.1 M BIS-TRIS buffer, pH = 7.0, 25.0 °C,  $[\text{Co}^{\text{II}}\{\text{PyzPz}(\text{PhSO}_3)_8\}(\text{H}_2\text{O})_2]^{8-} = 1.46 \times 10^{-5} \text{ M}$ .

The determination of the activation volume for this reaction was performed for a high excess of DMTU to prevent the influence of the pre-equilibrium, *i.e.* where  $k_{\text{obs1}} = k_2$ . The obtained data for  $\Delta V^\ddagger = +14.1 \pm 0.6 \text{ cm}^3 \text{ mol}^{-1}$  (Fig. S1†) confirms the conclusion that the second step is a dissociation of the six-coordinate complex to the five-coordinate product and water (it is known that dissociation of coordinated water *via* a dissociative mechanism has a  $\Delta V^\ddagger$  value of *ca.*  $+13 \text{ cm}^3 \text{ mol}^{-1}$  for an octahedral complex<sup>31</sup>). The formation of the five-coordinate complex is accompanied by inner-sphere electron transfer from DMTU to the macrocyclic ligand as shown in (2).

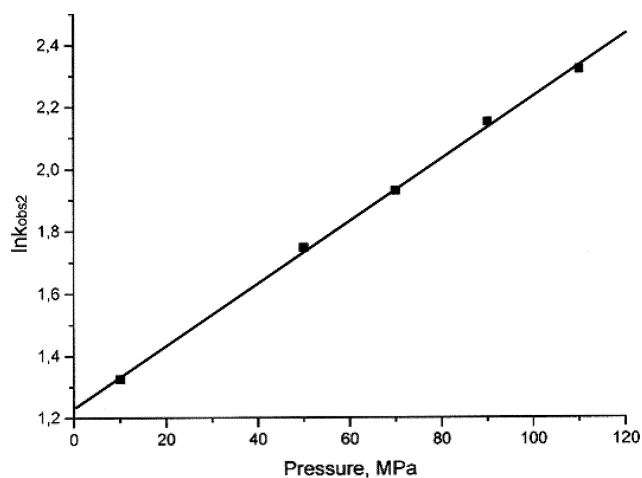
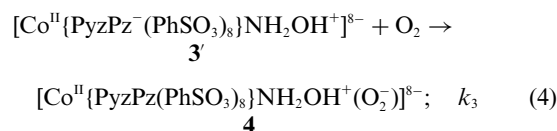
As mentioned above, the reaction of complex **2** with TU or DMTU under aerobic conditions leads to formation of sulfur that makes it difficult to study the second part of the catalytic process, *viz.* oxidation of the five-coordinate complex by dioxygen. On assuming that the mechanism of this reaction does not depend on the type of reductant taken for preparing of the five-coordinate complex, hydroxylamine sulfate was used instead of TU or DMTU. A solution of the five-coordinate complex in neutral buffer was prepared in a syringe. The end of the reduction process (formation of the red complex  $[\text{Co}^{\text{II}}\{\text{PyzPz}^-(\text{PhSO}_3)_8\}\text{NH}_2\text{OH}^+]^{8-}$ , **3'**) was determined on the basis of spectral data. The second syringe contained a buffered solution (pH 7) with different concentrations of dioxygen. In all experiments an excess of dioxygen was used.

The decrease in concentration of complex **3'** with time is satisfactorily described by an exponential law. A plot of  $k_{\text{obs2}}$  vs.  $[\text{O}_2]_0$  is linear over the selected concentration range of dioxygen (Fig. 5). The oxidation of complex **3'** was found to be irreversible. The overall reaction is characterized by a relatively small activation enthalpy ( $29.3 \pm 0.9 \text{ kJ mol}^{-1}$ , Fig. S2†). This result shows that the reaction is not accompanied by the breakage of any strong bonds. On the other hand, the reaction is characterized by a negative activation entropy ( $-40 \pm$



**Fig. 5** Plots of  $\ln k_{\text{obs2}}$  vs.  $[\text{O}_2]$  at different temperatures. Experimental conditions: 0.1 M TRIS buffer, pH = 7,  $[\text{Co}^{\text{II}}\{\text{PyzPz}(\text{PhSO}_3)_8\}(\text{H}_2\text{O})_2]^{8-} = 2.1 \times 10^{-6} \text{ M}$ , 6.0 °C (black squares), 15.0 °C (black circles), 20.0 °C (white triangles), 25.0 °C (black triangles), 30.0 °C (white circles).

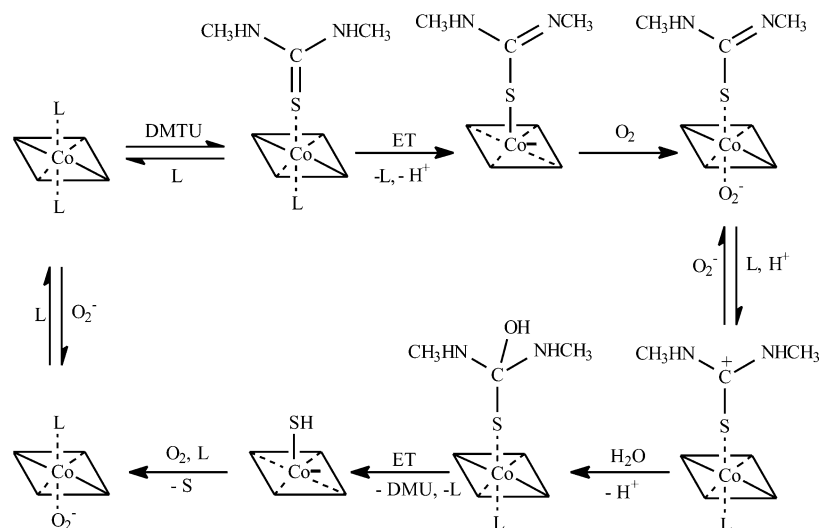
$4 \text{ J K}^{-1} \text{ mol}^{-1}$ , Fig. S2) and an unusually large negative activation volume ( $-23.9 \pm 0.5 \text{ cm}^3 \text{ mol}^{-1}$ , Fig. 6). The activation data show that oxidation of complex **3'** is an associative process accompanied by addition of dioxygen to cobalt, followed by fast intramolecular electron transfer. The first step of this process may be represented as follows:



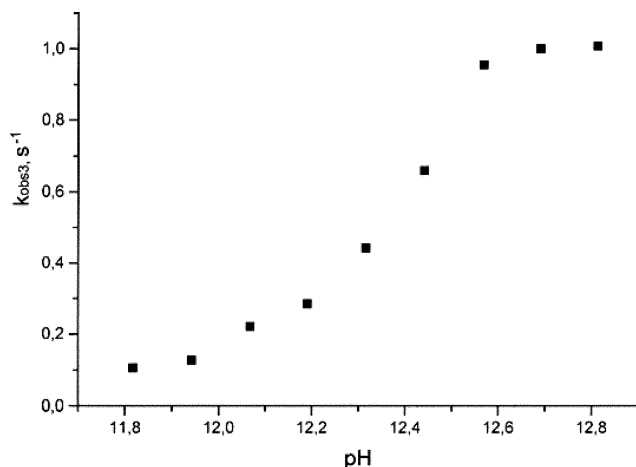
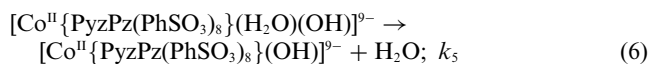
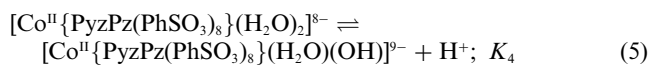
**Fig. 6** Plot of  $k_{\text{obs2}}$  vs. pressure. Experimental conditions: 0.1 M TRIS buffer, pH = 7, 25.0 °C,  $[\text{Co}^{\text{II}}\{\text{PyzPz}(\text{PhSO}_3)_8\}(\text{H}_2\text{O})_2]^{8-} = 2.1 \times 10^{-6} \text{ M}$ ,  $[\text{O}_2] = 1.2 \times 10^{-4} \text{ M}$ .

In the case of hydroxylamine sulfate, the subsequent reduction of the six-coordinate complex **4** proceeds slowly ( $\tau_{1/2}$  is approx. 2 h at pH 7). This creates the possibility of determining the rate constant  $k_3 = (3.07 \pm 0.15) \times 10^5 \text{ M}^{-1} \text{ s}^{-1}$  at 25 °C.

Studies on the influence of pH on the catalytic oxidation of thioureas show that the higher the pH, the slower the reaction, and in strongly alkaline solutions the oxidation practically does not proceed at all. It should be noted that this is valid for both steps of the catalytic process, *viz.* reduction of complex **2** and oxidation of complex **3** (Fig. 3). Therefore, it is reasonable to assume that **2** forms a stable complex with  $\text{OH}^-$ , which is inert in the redox process. The interaction of complex **2** with  $\text{OH}^-$  is well described by pseudo-first-order kinetics and proceeds quite slowly. This indicates that the rate-determining step is not an



acid–base interaction. The UV-vis spectra show that the product of this reaction is a complex similar to that in the case of the thioureas (Fig. 2). The pH dependence of  $k_{\text{obs}}$  is given in Fig. 7. The activation parameters for this reaction at pH 13 are:  $\Delta H^\ddagger = 77 \pm 4 \text{ kJ mol}^{-1}$ ,  $\Delta S^\ddagger = -29 \pm 13 \text{ J K}^{-1} \text{ mol}^{-1}$  and  $\Delta V^\ddagger = +14.1 \pm 0.6 \text{ cm}^3 \text{ mol}^{-1}$  (Fig. S3 and S4, respectively<sup>†</sup>). A high positive value of  $\Delta V^\ddagger$  and the saturation of  $k_{\text{obs}}$  at high pH indicate that the most plausible mechanism is rapid formation of the aquahydroxo complex, followed by rate-determining dissociation of a water molecule to form the five-coordinate hydroxo complex. The observed volume of activation is very typical for the dissociation of water from an octahedral complex.<sup>31</sup>



**Fig. 7** Plot of  $k_{\text{obs3}}$  vs. pH. Experimental conditions: 25.0 °C,  $[\text{Co}^{\text{II}}\{\text{PyzPz}(\text{PhSO}_3)_8\}(\text{H}_2\text{O})_2]^{8-} = 1.46 \times 10^{-5}$  M.

For the determination of the  $\text{pK}_a$  of coordinated water in complex **2**, a standard spectrophotometric titration was performed (Fig. S5†). The  $\text{pK}_4$  value ( $12.4 \pm 0.1$ ) is in good agreement with the observed kinetic results (see Fig. 7).

From a combination of the data for the reaction between complex **2** and DMTU under anaerobic conditions and for the reaction of the five-coordinate complex **3'** with dioxygen at pH 7, the overall scheme given above for the catalytic desulfurization of DMTU can be postulated.

This scheme is also applicable for TU. The scheme shows that oxidation of five-coordinate complex **3** by dioxygen involves

two consecutive steps without the intermediate formation of disulfide. Seemingly, a rate-limiting step is the addition of water to a product of a one-electron reduction of DMTU (TU). Since the rate of the overall reaction significantly increases in acidic solutions and does not depend on the type of acid used, it is reasonably to conclude that the reaction is catalysed by protons. Indeed, water is known to be a weak nucleophile and for its addition to a C=N bond a preliminary activation of the substrate by specific catalysis is mandatory. Furthermore, the product formed is oxidized to sulfur and the corresponding urea. A regeneration of the catalyst involves one-electron oxidation of the five-coordinate complex by a second molecule of dioxygen. Importantly, in contrast to a majority of catalytic oxidations by dioxygen, here the catalyst does not activate a molecule of O<sub>2</sub> but the substrate itself. Due to its extremely strong electron accepting properties, (octasulfophenyltetrapyrazinoporphyrazine)-cobalt(II) easily accepts an electron from the substrate (DMTU or TU). After that, the complex formed is also easily oxidized by dioxygen. The product of dioxygen reduction, *viz.* superoxide, seems to disproportionate to dioxygen and hydrogen peroxide. The latter disproportionates to dioxygen and water (it is well known that metallophthalocyanines and metalloporphyrazines catalyse this reaction<sup>32</sup>). In the case of (octasulfophenyltetrapyrazinoporphyrazine)iron(II), dioxygen cannot oxidize a corresponding five-coordinate complex. This explains the very weak catalytic activity of the iron complex in the studied processes.

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