Conversion of Azomethine Moiety to Carboxamido Group at Cobalt(III) Center in Model Complexes of Co-Containing Nitrile Hydratase

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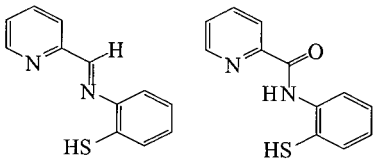
The Co(III) complex of the Schiff base ligand *N*-2-mercaptophenyl-2′-pyridylmethyl-enimine (PyASH), namely, $[Co(PyAS)_2]Cl$ (**1**), has been synthesized via an improved method and its structure has been determined by X-ray crystallography. The two deprotonated ligands are arranged in *mer* configuration around the Co(III) center and the overall coordination geometry is octahedral. The coordinated azomethine function in **1** is rapidly converted into carboxamido group upon reaction with OH^-. The product is the bis carboxamido complex $(Et_4N)[Co(PyPepS)_2]$ (**2**), reported by us previously. Reaction of H_2O_2 with **1** in DMF affords $[Co(PyASO_2)(PyPepSO_2)]$ (**3**), a species with mixed imine and carboxamido-N donor centers as well as S-bound sulfinates. Further reaction with H_2O_2 in the presence of $NaClO_4$ converts **3** into the previously reported bis carboxamido/sulfinato complex $Na[Co(PyPepSO_2)_2]$ (**4**). The reaction conditions for the various transformation reactions for complexes **1**−**4** and the structure of **3** are also reported. The mechanism of the −CH═NR + [O] → −C(═O)NHR transformation has been discussed. The reactions reported here provide convenient alternate routes for the syntheses of Co(III) complexes with coordinated carboxamide, thiolate, and/or sulfinate donors as models for the Co-site in the Co-containing nitrile hydratase(s).

Introduction

The enzyme nitrile hydratase (NHase), which catalyzes the conversion of nitriles to amides, has received much attention in recent years. This attention, in part, is due to its successful use in the industrial production of selected amides.[1−5] Interest in NHase also stems from the unusual active site of the enzyme, which is novel for a hydrolytic enzyme. The active site of NHase contains either a low spin non-heme Fe (III) or a noncorrin Co (III) center. Recent crystallographic studies of two Rhodococcus NHases have revealed that the single low spin Fe (III) is coordinated to two deprotonated carboxamido nitrogens and three Cys-S centers[6] two of which are modified to Cys-sulfenic and -sulfinic group.[7] The posttranslational oxidation of the Cys-S centers has recently been shown to be essential for activity of the Fe-containing enzyme.[8] Although no crystallographic studies have been reported for a Co-containing NHase, spectroscopic evidences indicate that the coordination of the Co(III) center in the enzyme is very similar to that of Fe(III) in Fe−NHase.[9,10]

Attempts to model the biological Co(III) site in NHases have so far included Schiff base ligands[11] and ligands with built-in carboxamide groups.[12] Previously, we reported the first examples of Co (III) complexes containing both carboxamido nitrogens and thiolato sulfurs and conversion of the bound thiolates in such complexes to S-bonded sulfinates.[13] In our continuing effort to investigate the role of the unusual metal coordination in Co-containing NHases, we have now studied the Co(III) complexes of the Schiff base ligand *N*-2-mercaptophenyl-2′-pyridylmethylenimine (PyASH) which resembles our previous ligand *N*-2-mercaptophenyl-2′-pyridinecarboxamide ($PyPepSH_2$) except for the imine group replacing the carboxamide moiety. We intended to determine the susceptibility of the ligand frame in such complexes toward oxidative and hydrolytic conditions.



PyASH $PyPepSH_2$

Only a few Co (III) complexes with both imino and thiolato donor atoms have been reported and the available information on their reactivity is quite limited.[14] It is well-known that

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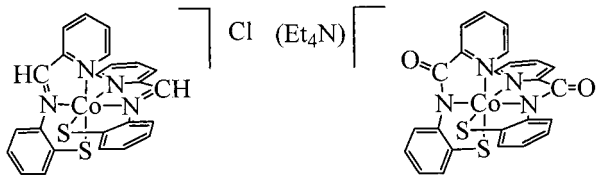
inductive effects of electropositive metals make coordinated imines more susceptible to nucleophillic attack.[15] The reaction of coordinated imine with OH^- or H_2O therefore usually yields free aldehyde (or ketone) and amine.[16] Such reactions also generate coordinated alcohols,[16] amines and amides.[17] In a few cases, oxidation of the coordinated imine group to carboxamide group has also been noted.[18−23] The reported complexes that do undergo ligand imine oxidation to carboxamide are of interest for several reasons. For example, selective oxidation of ligand framework provides a valuable route to complexes otherwise difficult to synthesize. Since NHases contain $M-N_{amido}$ linkage, the thrust of modeling in this area is more directed toward studies on species with $Co(III)-N_{amido}$ bonds. Complexes with both thiolato-S and carboxamido-N donors are difficult to synthesize and hence alternate synthetic routes are of value. Also, the mechanisms of oxygen atom incorporation into organic moieties, assisted by metal complexation, are of general interest. Studies so far have led to a general mechanism for such transformations. It appears that for imine to carboxamide oxidation to occur, the metal center must have two easily accessible oxidation states.[18] The complexes undergo concomitant ligand and metal oxidation and are thought to proceed via a mechanism involving oxidative radical formation on the ligand framework.[18−25]

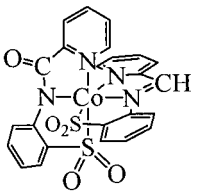
In this paper we report the first example of oxidation of ligated imine to carboxamido moiety in a Co(III) complex. Unlike previously reported cases of ligand oxidation leading to carboxamide, the reaction presented here is unique since the initial and final oxidation states of the metal center remain the same. Reaction of the Co(III) complex of PyASH namely, $[Co(PyAS)_2]Cl$ (**1**) with OH^- readily affords the previously reported carboxamido complex $(Et_4N)[Co(PyPepS)_2]$ (**2**) while reaction with H_2O_2 gives rise to $[Co(PyASO_2)(PyPepSO_2)]$ (**3**) a species with mixed imine and carboxamido-N donor centers as well as S-bound sulfinato groups. Complex **3** further reacts with H_2O_2 to afford $Na[Co(PyPepSO_2)_2]$ (**4**) in which the two ligand frames are fully oxidized.

We have reported conversion of **2** to **4** in a previous account.[13] The structures of **1** and **3** are reported here for the first time. Results of the oxidation reactions are described here in detail. It is also important to note that the reactions reported here proceed cleanly and in nearly quantitative fashion with no ligand dissociation. This is in contrast to hitherto known studies, which usually lead to the carboxamido complex among other decomposition products.[17, 24−26]

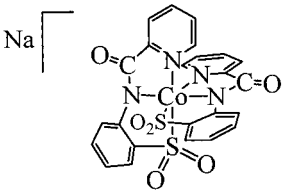


$[Co(PyAS)_2]Cl$ (**1**)

$(Et_4N)[Co(PyPepS)_2]$ (**2**)



$[Co(PyASO_2)(PyPepSO_2)]$ (**3**)



$Na[Co(PyPepSO_2)_2]$ (**4**)

Experimental Section

Materials. 2-Pyridinecarboxaldehyde, 2-aminothiophenol, tetraethylammonium hydroxide, and picolinic acid were purchased from Aldrich Chemical Co. Hydrogen peroxide (30%) was purchased from Fisher Scientific Co. $[Co(NH_3)_5Cl]Cl_2$ was synthesized by following the published procedure.[27] All manipulations were carried out on Schlenk lines except otherwise noted and the solvents were dried and distilled before use.

Preparation of Compounds. PyASH and $PyPepSH_2$. The two ligands, $PyPepSH_2$ and PyASH, have been synthesized by following published procedures.[13,28]

$[Co(PyAS)_2]Cl$ (1). A batch of 298 mg (1.4 mmol) of PyASH was dissolved in 10 mL of degassed dimethylformamide (DMF). To the resulting light yellow solution, 27.3 mg (1.2 mmol) of solid NaH was added. The deep red solution was allowed to react for 10 min and then a batch of 142 mg (0.57 mmol) of $[Co(NH_3)_5Cl]Cl_2$ was added with an additional 10 mL of DMF. The reaction mixture was gently heated for 15 min and the resultant deep blue solution was stirred at room temperature for 2 h. Next, the DMF was removed under vacuum and the blue residue was dissolved in 100 mL of methanol (MeOH). The deep blue solution was filtered and the volume reduced to 20 mL by rotary evaporation and stored at −28 °C for 16 h. The microcrystalline solid was collected and dried under vacuum for 10 h. Yield: 405 mg (65%). Single crystals suitable for X-ray diffraction were obtained by slow diffusion of acetone into a dilute solution of **1** in methanol. ^1H NMR (d_6-DMSO, 500 MHz, δ from TMS, 35 °C): 7.13 (2H, t), 7.20 (1H, t), 7.47 (1H, t), 7.99 (1H, d), 8.09 (1H, t), 8.18 (2H, t), 9.39 (1H, imine). Selected IR bands: (KBr pellet, cm^{-1}) 1603, 1572 ($\nu_{C=N}$). Electronic absorption spectrum in DMF, λ_{max}, nm (ϵ, $M^{-1}cm^{-1}$): 678 sh (1 620), 593 (2 360), 400 sh (5 100), 360 (7 970).

Addition of $NaClO_4$ to the methanolic solution of **1** allows a nearly quantitative precipitation of the complex as the perchlorate salt.

$(Et_4N)[Co(PyPepS)_2]$ (2). A batch of 93 mg (0.16 mmol) of **1** was dissolved in 15 mL of DMF and to it was added 0.79 mL of 1M Et_4NOH under aerobic conditions. After 20 min, a deep red color developed. The solution was stirred for another 20 min and then the solvent was removed in vacuo. The brick red precipitate was washed 3 times with 5 mL of H_2O and 2 times with 5 mL of Et_2O. ^1H NMR and electronic absorption data confirmed the identity of the complex. Yield: 104 mg (93%). The structure and spectroscopic properties of this compound have been reported previously.[13]

$[Co(PyASO_2)(PyPepSO_2)]$ (3). A batch of 0.5 mL of 30% H_2O_2 was slowly added to a solution of 170 mg (0.33 mmol) of **1** in 30 mL of MeOH and the solution was stirred in air at room temperature for 2 days. The reaction mixture afforded **3** as a light orange solid in nearly quantitative yield, which was collected and dried under vacuum for 10 h. Single crystals were obtained by slow diffusion of THF into a DMF

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Table 1. Summary of Crystal Data and Intensity Collection and Structure Refinement Parameters for $[Co(PyAS)_2]Cl\cdot 2CH_3OH$ (**1**·$2CH_3OH$), and $[Co(PyASO_2)(PyPepSO_2)]\cdot THF$ (**3**·THF)

	$[Co(PyAS)_2]Cl\cdot 2CH_3OH$	$[Co(PyASO_2)(PyPepSO_2)]\cdot THF$ (**3**·THF)
formula	$C_{26}H_{26}ClCoN_4O_2S_2$	$C_{28}H_{25}CoN_4O_6S_2$
mol wt	585.01	636.57
cryst color, habit	black needle	red plate
T, K	90(2)	91(2)
cryst syst	triclinic	monoclinic
space group	$P\bar{1}$	$P2_{1/c}$
a, Å	8.5683(4)	12.0000(10)
b, Å	11.3700(5)	10.0651(8)
c, Å	13.4224(6)	23.2750(17)
α, deg	84.9070(10)	90
β, deg	84.7950(10)	104.243(2)
γ, deg	84.0370(10)	90
V, A^3	1291.03(10)	2727.8(4)
Z	2	4
d_{calcd}, g cm^{-3}	1.505	1.552
abs coeff, μ, mm^{-1}	0.962	0.835
GOF[a] on F^2	1.038	1.016
R1,[b] %	3.15	6.79
wR2,[c] %	8.61	16.46

[a] GOF = $[\sum[w(F_o^2 - F_c^2)^2]/M - N)]^{1/2}$ (M = number of reflections, N = number of parameters refined). [b] $R1 = \sum||F_o| - |F_c||/\sum|F_o|$. [c] $wR2 = [\sum[w(F_o^2 - F_c^2)^2]/\sum[w(F_o^2)^2]]^{1/2}$.

solution of **3**. ^{1}H NMR (d_6-DMSO, 500 MHz, δ from TMS, 25 °C) 7.10 (1H, t), 7.32 (1H, d), 7.45 (2H, m), 7.65 (3H, m), 7.77, (1H, t), 7.94 (1H, s), 8.07 (1H, d), 8.10 (2H, d), 8.18 (1H, d), 8.21 (1H, t), 8.32 (1H, d), 8.48 (1H, d), 10.20 (1H, imine). Selected IR bands: (KBr pellet, cm^{-1}) 1669, 1631 ($\nu_{C=O}$), 1604 ($\nu_{C=N}$), 1076, 1048 ($\nu_{S=O}$). Electronic absorption spectrum in DMF, λ_{max}, nm (ϵ, $M^{-1}cm^{-1}$): 564 (380), 418 sh (3 440), 367 (6 690).

Conversion of $[Co(PyASO_2)(PyPepSO_2)]$ (3) to $Na[Co(PyPepSO_2)_2]$ (4). A batch of 100 mg (0.18 mmol) of **3** was gently heated in 20 mL of MeOH with 33 mg (0.27 mmol) of $NaClO_4$ until the entire solid dissolved. The orange solution was then mixed with excess H_2O_2 (30%) and the mixture was stirred for 10 h. Next, the solvent was removed in vacuo and the orange precipitate was redissolved in 10 mL MeOH. It was then filtered to remove any unreacted material. The filtrate, upon evaporation, afforded the desired complex as a light orange powder. Comparison of the ^{1}H NMR, electronic absorption and IR data confirmed the identity of this complex.

X-ray Data Collection and Structure Solution and Refinement. Black needles of $[Co(PyAS)_2]Cl$ (**1**) suitable for X-ray analysis were obtained by slow diffusion of acetone into a methanolic solution of **1**. Red plates of $[Co(PyASO_2)(PyPePSO_2)]$ (**3**), suitable for X-ray analysis were obtained by slow diffusion of tetrahydrofuran (THF) into a DMF solution of **3**. Diffraction data for complexes **1** and **3** were collected on a Bruker SMART 1000 diffractometer. All structures were solved by direct methods (SHELXS-97). The data were corrected for absorption effects.[29] Machine parameters, crystal data, and data collection parameters are summarized in Table 1. Selected bond distances and angles are listed in Table 2. The two sets of crystallographic data have been submitted as Supporting Information.

Other Physical Measurements. Infrared spectra were obtained with a Perkin-Elmer 1600 FTIR spectrophotometer. Absorption spectra were measured on a Perkin-Elmer Lambda 9 spectrophotometer. ^{1}H NMR spectra were recorded on a Varian Unity Plus 500 running Solaris 2.6/VNMR 6.1B. Electrochemical measurements were performed with Princeton Applied Research instrumentation (model 273A) and a Beckman platinum inlay electrode. Potentials were measured with reference to saturated calomel electrode (SCE). DMF and $(Et_4N)(ClO_4)$ were used as the solvent and the supporting electrolyte, respectively. The value of the ferrocene/ferrocenium couple in DMF is 0.46 V vs SCE.

Table 2. Selected Bond Distances (Å) and Angles (deg)

$[Co(PyAS)_2]Cl\cdot 2CH_3OH$

Bond Distances

Co(1)−N(3)	1.9034(11)	S(1)−C(1)	1.7430(14)
Co(1)−N(1)	1.9089(12)	S(2)−C(13)	1.7541(15)
Co(1)−N(2)	1.9749(11)	N(1)−C(7)	1.2957(17)
Co(1)−N(4)	1.9813(11)	N(3)−C(19)	1.3000(17)
Co(1)−S(1)	2.2366(4)	C(15)−C(16)	1.398(2)
Co(1)−S(2)	2.2437(4)	C(22)−C(23)	1.385(2)

Bond Angles

N(3)−Co(1)−N(1)	177.23(5)	N(4)−Co(1)−S(1)	91.69(3)
N(3)−Co(1)−N(2)	99.23(5)	N(3)−Co(1)−S(2)	87.85(3)
N(1)−Co(1)−N(2)	82.44(5)	N(1)−Co(1)−S(2)	94.40(4)
N(3)−Co(1)−N(4)	82.66(5)	N(2)−Co(1)−S(2)	89.24(3)
N(1)−Co(1)−N(4)	95.15(5)	N(4)−Co(1)−S(2)	170.31(4)
N(2)−Co(1)−N(4)	90.36(5)	S(1)−Co(1)−S(2)	90.248(14)
N(3)−Co(1)−S(1)	90.00(3)	C(1)−S(1)−Co(1)	96.20(5)
N(1)−Co(1)−S(1)	88.37(4)	C(6)−C(1)−S(1)	120.53(10)
N(2)−Co(1)−S(1)	170.73(3)	C(13)−C(18)−C(17)	121.37(12)

$[Co(PyASO_2)(PyPepSO_2)]\cdot THF$

Bond Distances

Co(1)−N(3)	1.925(5)	C(22)−C(23)	1.372(9)
Co(1)−N(1)	1.931(5)	S(2)−O(3)	1.460(4)
Co(1)−N(4)	1.957(5)	S(2)−C(13)	1.779(7)
Co(1)−N(2)	2.002(5)	O(5)−C(19)	1.247(7)
Co(1)−S(1)	2.1769(16)	N(1)−C(7)	1.293(7)
Co(1)−S(2)	2.1800(16)	N(3)−C(19)	1.329(8)
S(1)−O(2)	1.446(5)	C(3)−C(4)	1.375(9)
S(1)−O(1)	1.457(4)	C(8)−C(9)	1.373(9)
S(1)−C(1)	1.785(6)	C(15)−C(16)	1.353(11)
S(2)−O(4)	1.445(4)		

Bond Angles

N(3)−Co(1)−N(1)	177.6(2)	O(2)−S(1)−O(1)	113.3(3)
N(3)−Co(1)−N(4)	83.6(2)	O(2)−S(1)−Co(1)	117.4(2)
N(1)−Co(1)−N(4)	97.68(19)	C(1)−S(1)−Co(1)	98.0(2)
N(3)−Co(1)−N(2)	100.5(2)	O(4)−S(2)−O(3)	114.1(3)
N(1)−Co(1)−N(2)	81.6(2)	O(3)−S(2)−C(13)	110.1(3)
N(4)−Co(1)−N(2)	86.01(19)	C(13)−S(2)−Co(1)	98.8(2)
N(3)−Co(1)−S(1)	89.96(15)	C(2)−C(1)−S(1)	121.1(5)
N(1)−Co(1)−S(1)	87.99(15)	C(1)−C(2)−C(3)	118.3(6)
N(4)−Co(1)−S(1)	90.58(14)	N(1)−C(7)−C(8)	116.6(5)
N(2)−Co(1)−S(1)	168.54(16)	N(2)−C(8)−C(7)	113.5(5)
N(3)−Co(1)−S(2)	86.82(16)	C(14)−C(13)−S(2)	120.1(5)
N(1)−Co(1)−S(2)	92.00(14)	C(13)−C(18)−C(17)	117.3(6)
N(4)−Co(1)−S(2)	169.95(15)	O(5)−C(19)−C(20)	119.0(6)
N(2)−Co(1)−S(2)	92.78(14)	N(3)−C(19)−C(20)	113.5(5)
S(1)−Co(1)−S(2)	92.44(6)	N(4)−C(20)−C(19)	114.2(5)

Results and Discussion

Synthesis. Although complex **1** was reported in an earlier paper by Jones and McCleverty,[30] no structural data are available and to date, no reactivity studies have been performed with this complex. The reported synthesis involves in situ condensation of 2-pyridinecarboxaldehyde with 2-aminothiophenol and subsequent addition of $CoCl_2\cdot 6H_2O$ to the reaction mixture. The reaction was carried out in air and the Co(III) complex was isolated as the hexafluorophosphate salt from a blue-green solution. The synthesis reported in this paper utilizes a Co(III) starting material namely, $[Co(NH_3)_5Cl]Cl_2$ and NaH to deprotonate the preformed Schiff base ligand PyASH. The synthesis is performed in an air-free flask and the complex is isolated from a dark blue solution. It is important to note that if air is not excluded during the complexation reaction, the reaction mixture turns more green (like the original report) and the yield of **1** is significantly decreased.

Rapid transformation of **1** to **2** by simple presence of OH^- is the most noteworthy observation in the present work. The

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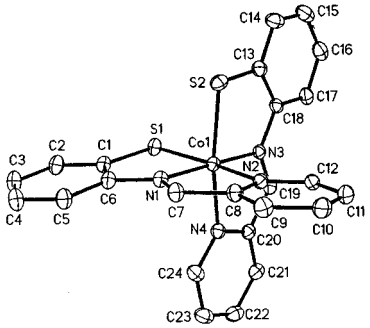

Figure 1. Thermal ellipsoid (probability level 50%) plot of $[Co(PyAS)_2]^+$ (cation of **1**) with the atom-labeling scheme. H atoms are omitted for the sake of clarity.

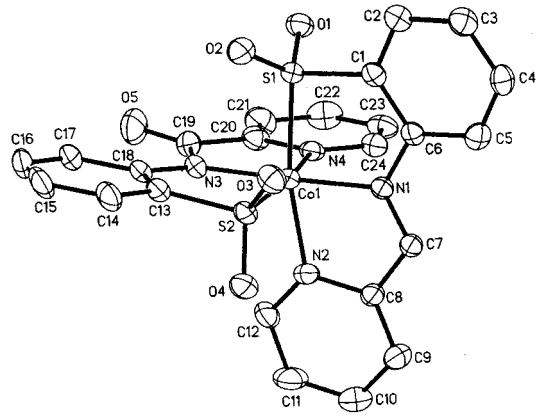

Figure 2. Thermal ellipsoid (probability level 50%) plot of $[Co(PyASO_2)(PyPepSO_2)]$ (**3**) with the atom-labeling scheme. H atoms are omitted for the sake of clarity.

conversion is complete within 20 min upon addition of 5 equiv of OH^- to a solution of **1** in MeOH or DMF in the presence of air. This conversion of imine nitrogen to carboxamido nitrogen, reported here for the first time for a Co(III)−imine complex, is of particular interest since it occurs on a ligand frame bound to a metal center that retains its original oxidation state. All previously reported examples of formation of ligated carboxamido group from bound imine involve concurrent oxidation of the metal centers resulting in an increase in the metal oxidation state. The present reaction is unique in this regard.

Attempts to oxidize **1** with H_2O_2 to produce the sulfinato species produced unexpected results. In no case, a Co(III) species with two coordinated imine nitrogens and sulfinato group(s) was isolated. Instead, addition of H_2O_2 to solutions of **1** in MeOH or DMF results in clean and nearly quantitative production of complex **3** in which one of the imine nitrogens is converted to a carboxamido nitrogen and both thiolato sulfurs are oxidized to S-bonded sulfinate groups. This neutral complex is readily precipitated from the reaction mixture and hence further oxidation does not take place. However, if one dissolves **3** in warm MeOH in the presence of $NaClO_4$ and adds more H_2O_2, the oxidation reaction proceeds further to afford the previously reported complex **4**.[13] In **4**, both the ligand frames are completely oxidized to the amide-sulfinate forms. Since the overall charge of the complex changes as one transforms the imine nitrogen to carboxamido nitrogen, the presence of $NaClO_4$ is a requirement.

In the present work, all efforts to synthesize the di-imine/di-sulfinato complex were unsuccessful. Addition of 2 equiv of H_2O_2 (30%) to solutions of **1** in MeOH or DMF resulted in a green solution that did not afford any pure compound. In an effort to exclude H_2O from the reaction mixture, the reaction was repeated with 2 equiv of 95% H_2O_2 in MeOH. Once again, a green solution was obtained and no pure solid was isolated. When solutions of **1** in MeOH or DMF were stirred in air with the addition of freshly activated charcoal, similar green solutions were obtained. Further work up did not afford any crystalline material in any case. ^1H NMR spectra of the residues from these green solutions indicate the presence of a mixture of products including complex **3**.

Structure of $[Co(PyAS)_2]Cl\cdot 2CH_3OH$ ($1\cdot 2CH_3OH$). The structure of $[Co(PyAS)_2]^+$ is shown in Figure 1. The coordination geometry around cobalt is distorted octahedral and the deprotonated $PyAS^-$ ligands are ligated to the Co(III) in a *mer* fashion. The two thiolato sulfurs occupy positions that are cis to each other with the mean Co(III)−S bond length of 2.2401(9) Å. These Co−S bond lengths are within the range of previously reported Co(III) complexes of aromatic thiolates.[31,32] The average Co(III)−N_{py} and Co(III)−N_{imine} bond distances (1.9781(1) Å and 1.90616(15) Å respectively) are also within the range of distances observed in other reported complexes.[33−35]

Structure of $[Co(PyASO_2)(PyPepSO_2)]\cdot THF$ ($3\cdot THF$). The ligand arrangement in the neutral $[Co(PyASO_2)(PyPepSO_2)]$ is very similar to that of complex **1**. (Figure 2). The N_{amido} and N_{imine} donor centers occupy positions that are trans to each other and the Co(III)−N bond distances are 1.925(5) Å and 1.931(5) Å respectively. There is a slight increase in the Co(III)−N_{imine} bond distance presumably due to the stronger donor ability of the trans amido nitrogen. The average Co(III)−S(sulfinato) bond distance (2.1784(66) Å) in **3** is shorter compared to the Co(III)−S(thiolato) distance in **1**. Similar shortening of the Co(III)−S distance upon oxidation has been observed before.[13,36,37] The average S−O bond distance for the two ligands are very similar with an average value of 1.452(4) Å. This distance is well within the range noted for other Co(III) complexes with S-bonded sulfinato groups.[36,37]

Spectral Properties. The electronic absorption spectra of complexes **1** and **2** are very similar (Figure 3) with one exception: the λ_{max} of complex **2** (∼500 nm) is blue shifted compared to that of **1** (∼600 nm). The ∼500 nm band in complex **2** has been previously assigned to a thiolate-to-Co(III) charge transfer (LMCT).[13,36,37] The band in complex **1** also arises from a similar thiolate-to-Co(III) charge transfer since conversion of **1** to **3** results in the disappearance of the band (Figure 3). The blue shift of the charge-transfer band by ∼100 nm upon conversion of the imine group to carboxamide indicates that the electronic properties of the thiolato moiety are affected by the nature of the nitrogen donor in the ligand frame. Since the Co(III) (d^6 low spin) center in octahedral crystal field has filled t_{2g} orbitals, the thiolate-to-Co(III) charge transfer is directed toward the empty e_g orbitals. Therefore, as the ligand strength increases upon conversion of the imine group to

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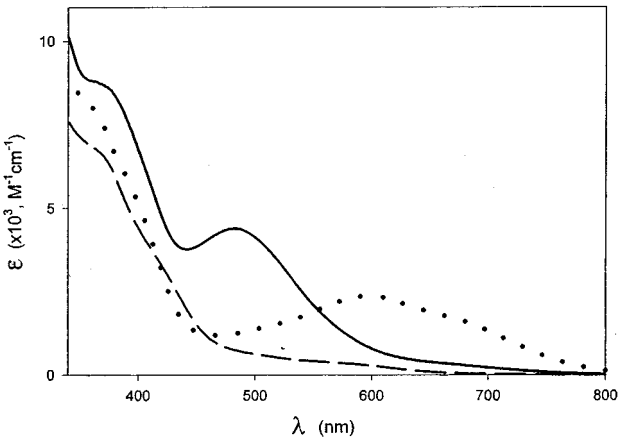

Figure 3. Electronic absorption spectra of $(Et_4N)[Co(PyPepS)_2]$ (**2**) (solid line), $[Co(PyAS)_2]Cl$ (**1**) (dotted line), and $[Co(PyASO_2)(PyPepSO_2)]$ (**3**) (broken line) in DMF.

carboxamide, one would expect to see a blue shift in the thiolate-to-Co(III) charge-transfer band. Overall, these spectral data confirm that the carboxamido nitrogen is a much stronger donor compared to imine nitrogen.

The ^{1}H NMR spectrum of **1** is shown in Figure 4a. The spectrum is similar to that of **2** (Figure S1, Supporting Information) with aromatic protons grouped around 7 and 8 ppm and a triplet near 7.5 ppm. Complex **1** also exhibits a singlet at 9.7 ppm arising from the α-hydrogen of the imine moiety. Conversion of the imine nitrogen to carboxamido nitrogen (**1** → **2** transformation) results in disappearance of this peak and appearance of a doublet at 9.1 ppm. As shown in Figure 4, the various complexes can be easily identified by their ^{1}H NMR spectra. Oxidation of **2** affords **4** which exhibits a downfield shift of the doublet from 9.1 to 9.3 ppm (Figure 4c). As shown in Figure 4b, complex **3**, an intermediate in the **1** → **4** conversion, displays a ^{1}H NMR spectrum which consists of two sets of peaks corresponding to the aromatic protons of the two differently oxidized ligands.

Reactivity of the Complexes. Conversion of coordinated azomethine group to bound carboxamido moiety in the presence of oxidants has been reported for a few metal complexes. In case of Ru(II) complexes with coordinated imine groups, oxidation with H_2O_2 or Ce(IV) affords similar imine-amide complexes.[19,21] Oxidation of Mn(II) Schiff base complexes with O_2 also affords imine-amide species.[20] However, in all such cases, the metal center is one-electron oxidized in the imine-amide case compared to the bis(imine) species. Also, even when excess oxidant is used, only one imine function in one of the ligands is oxidized to amide; the second imine group remains unaffected in all cases. Contrary to these results, the Co(III) center in **1** does not change its oxidation states in the ligand-oxidized species and also the bis(amide) complex **2** is readily obtained from the bis(imine) species **1** upon reaction with OH^-.

Studies on the conversion of azomethine function to carboxamide group in rhenium and ruthenium complexes have provided insight into the mechanism of such transformation.[21] Conversion of **1** to **2** in the present case appears to follow similar pathways (Scheme 1). The first step (step a) is the addition of water to the imine function, a well-documented step that leads to an α-hydroxy amine moiety. The adduct undergoes rapid oxidation, like other cases,[18,21,22] to form a radical on the ligand framework (step b).[38] An internal redox (step c) and proton loss (step d) results in the formation of the carboxamido N center. Since carboxamido nitrogens are strong donors, the Co(II) center becomes susceptible to oxidation[39] and is finally converted back into a Co(III)-amido species **2** (step e) in the presence of O_2. The overall reaction involves loss of two protons and therefore is facilitated by the presence of OH^-. The reaction also stops at **2** since O_2 cannot oxidize the thiolato S centers to sulfinates. However, if one uses H_2O_2 in the reaction mixture, one obtains **3** and ultimately **4** as the final product. In the last two complexes, the thiolato S terminals are oxidized to S-bonded sulfinato moieties, a transformation reported by us in a previous account.[13] Support for this mechanism comes from the facts that (a) **1** is rapidly converted into **4** when the reaction mixture contains both OH^- and H_2O_2 and (b) the transformation of **1** into **2** upon addition of OH^- does not proceed unless O_2 is present.

Both the azomethine function and the thiolato sulfur donors in complex **1** are susceptible to oxidation. Thus as one adds H_2O_2 to a solution of **1**, concurrent oxidation leads to formation of carboxamido moieties and S-bound sulfinato groups and one obtains **4** as the only product. However, this process requires the presence of $NaClO_4$ since conversion of the azomethine function to carboxamido group necessitates change in the overall charge of the complex. If the reaction mixture does not contain $NaClO_4$, the intermediate neutral species **3** precipitates from the reaction mixture in almost quantitative yield. In this complex, both thiolato sulfurs are oxidized to sulfinates while only *one* of the azomethine functions is converted to carboxamido group. It thus appears that the sulfur end of the ligand $PyAS^-$ is oxidized first. Such oxidation of bound thiolates to sulfinates in **1** removes electron density from the Co−S bonds. This in turn makes the cobalt center more electropositive. The increased electrophilicity of the metal center further activates the imine function toward nucleophillic attack by H_2O (or OH^-) in the reaction mixture. A summary of the reactivity of complex **1** is shown in Scheme 2.

Interestingly, some Co(III) complexes with ligated imine groups have been synthesized via oxidation of their Co(II) counterparts by careful addition of H_2O_2.[40] These studies did not report any reaction of the ligand frame with the oxidant and in all cases, the Co(III) Schiff base complexes were isolated as the major products. Also, the Co(III) model complex reported by Kovacs and co-workers is converted to the corresponding sulfenato/sulfinato species upon reaction with H_2O_2.[11] The imine portion of the ligand in this complex does not undergo any change despite prolonged stirring in the presence of excess H_2O_2. It must be noted that unlike **1**, the ligands in these complexes do not contain an aromatic ring *next* to the azomethine function. This suggests that coordinated imine moieties undergo oxidation to carboxamido groups when they are next to an aromatic ring.[18,19,21−23]

To check whether internal transfer of an electron from the ligand-based radical to the Co(III) center of **1** (step c in Scheme 1) is feasible, we have determined the $E_{1/2}$ value of the Co(III)/Co(II) couple in complex **1**. In DMF, complex **1** exhibits a quasireversible cyclic voltammogram with $E_{1/2}$ at −0.64 V vs SCE. This value is in the range of M(III)/M(II) potential of bis complexes of ruthenium containing azomethine moieties which undergo similar internal redox processes.[21] The $E_{1/2}$ value

(38) When aqueous Et_4NOH is added to a solution of **1** in DMF and the mixture is rapidly frozen, the radical formed on the ligand frame exhibits an ESR signal with $g = 2.009$ and 2.125.

(39) All attempts to isolate the Co(II) intermediate have however been unsuccessful so far.

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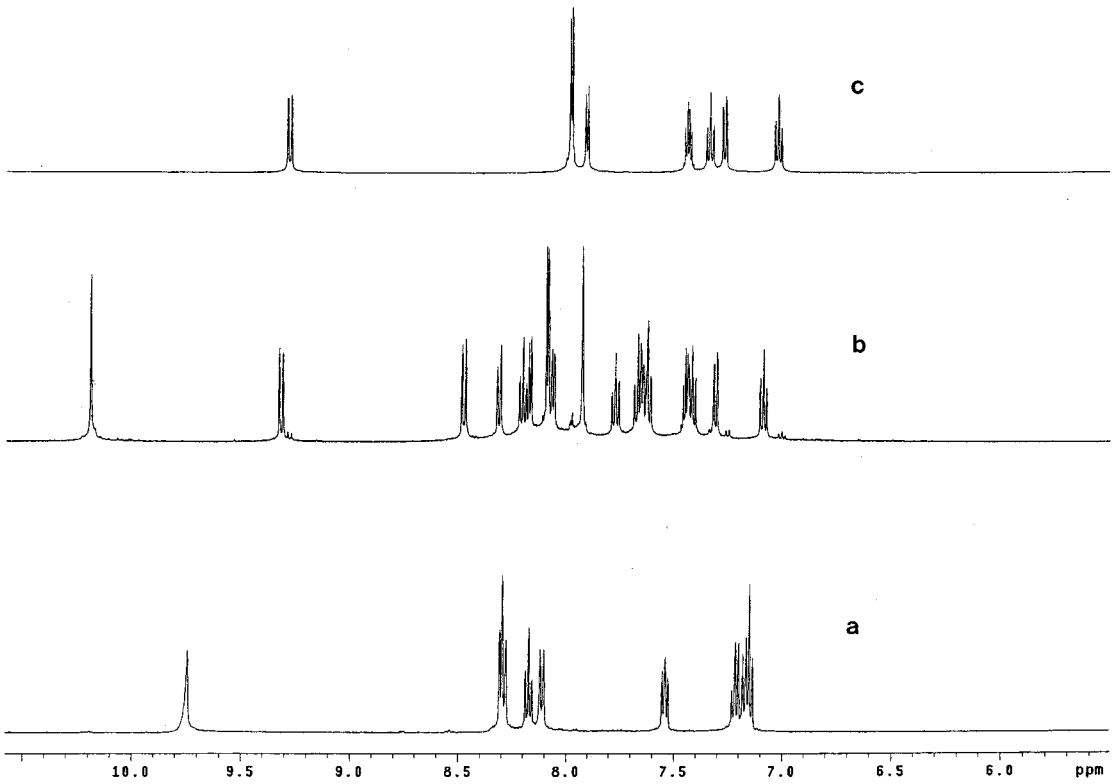
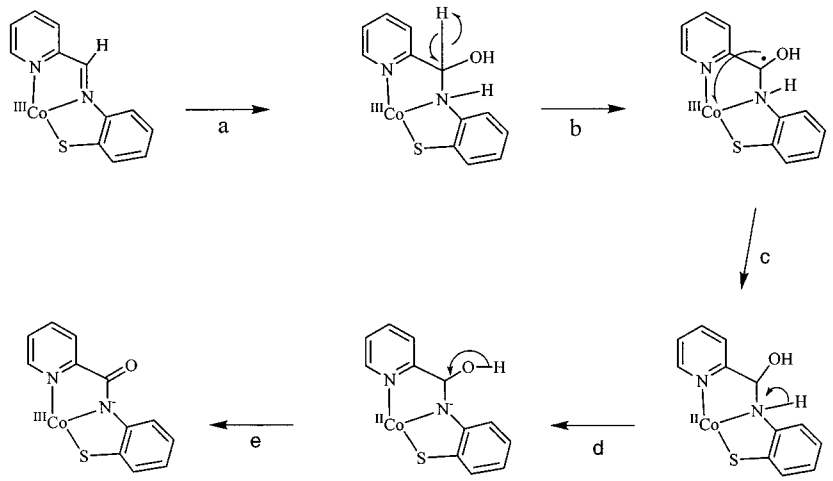


Figure 4. ^{1}H NMR spectra (6−10 ppm) of (a) $[Co(PyAS)_2]Cl$ (**1**), (b) $[Co(PyASO_2)(PyPepSO_2)]$ (**3**), and (c) $Na[Co(PyPepSO_2)_2]$ (**4**) in d_6-DMSO. The singlet at ∼7.9 ppm in the spectrum of **3** (panel b) arises from lattice DMF.

Scheme 1



of **1** thus provides additional support to the proposed mechanism in Scheme 1.

The $E_{1/2}$ values of the sulfinato complexes **3** and **4** clearly indicate that the carboxamido nitrogens provide extra stability to the Co(III) centers in these complexes. In DMF, the reduction potential of complex **3** (with one imine N and one carboxamido N) is −0.61 V (vs SCE) while that of **4** (with two carboxamido N) is −1.3 V (vs SCE). It thus appears each imine-to-carboxamide change shifts the reduction potential by −0.69 V. Indeed, the Co(III) center in complex **2** is highly stabilized and does not exhibit any reduction wave in DMF up to −1.8 V vs SCE.

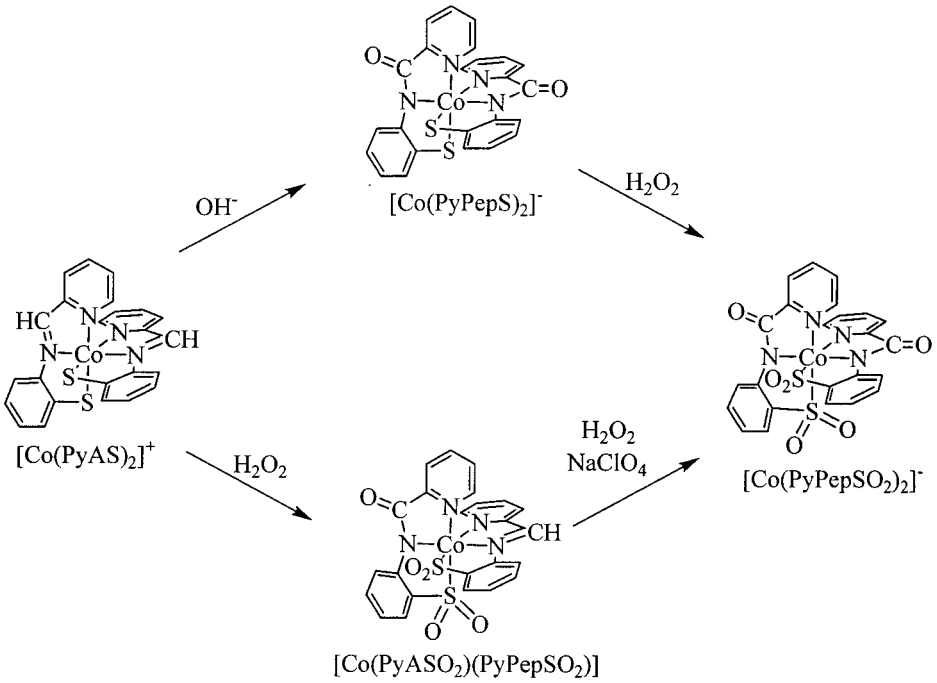
The present work provides an important clue toward modeling the Co-site in NHases. It is evident that if one selects a designed ligand with azomethine function(s) next to an aromatic system, the resulting Co(III) complex could be easily converted into the corresponding carboxamido species upon reaction with OH^-. Furthermore, one could conveniently oxidize both the azomethine function (to carboxamido group) and the thiolato sulfurs (to sulfinato moieties) with H_2O_2. The presence of OH^- in such reaction will accelerate the transformation. Since structural models of the Co-containing NHases require the presence of both carboxamido nitrogens and thiolato sulfurs/sulfinates,[41] the reactions reported in this paper will provide alternate routes to their syntheses.

Summary and Conclusions. The following are the summary and conclusions of this investigation.

(a) The Co(III) complex of the Schiff base *N*-2-mercaptophenyl-2′-pyridylmethylenimine (PyASH) namely, $[Co(PyAS)_2]Cl$ (**1**) has been isolated and structurally characterized. Although

(41) Noveron, J. C.; Olmstead, M. M.; Mascharak, P. K. *J. Am. Chem. Soc*. **1999**, *121*, 3553.

Scheme 2



this complex was reported briefly in a previous account, the present synthesis affords the complex in pure form and in high yield.

(b) When complex **1** is reacted with OH^- in DMF under aerobic conditions, it is quantitatively converted to $(Et_4N)[Co(PyPepS)_2]$ (**2**) in which both imine groups are oxidized to carboxamido moieties. Complex **2**, as reported by us before, is converted into $Na[Co(PyPepSO_2)_2]$ (**4**) upon reaction with H_2O_2.

(c) Reaction of **1** with H_2O_2 in DMF leads to the formation of $[Co(PyASO_2)(PyPepSO_2)]$ (**3**), a species with mixed imine and carboxamido-N donor centers as well as S-bound sulfinato groups Addition of $NaClO_4$ and excess H_2O_2 to **3** in methanol affords $Na[Co(PyPepSO_2)_2]$ (**4**) in which the two ligand frames are fully oxidized. We have reported the structure of **4** previously while the structure of **3** is reported here for the first time.

(d) The mechanism of the imine-to-carboxamide ($-CH{=}NR + [O] \rightarrow -C(=O)NHR$) conversion in complex **1** includes addition of water across the imine C═N bond, formation of a ligand-based radical and an internal redox reaction with proton loss (Scheme 1). Implications of these reactions in modeling of the Co-containing NHases have been discussed.

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Supporting Information Available: ^1H NMR spectra of **1** and **2** in d_6-DMSO (Figure S1) and the X-ray crystallographic files (in CIF format) and tables for the structure determination of complexes **1·2CH$_3$OH** and **3·THF**. This material is available free of charge via the Internet at http://pubs.acs.org.

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