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Coordination of Methyl Coenzyme M and Coenzyme M at Divalent and Trivalent Nickel Cyclams: Model Studies of Methyl Coenzyme M Reductase Active Site

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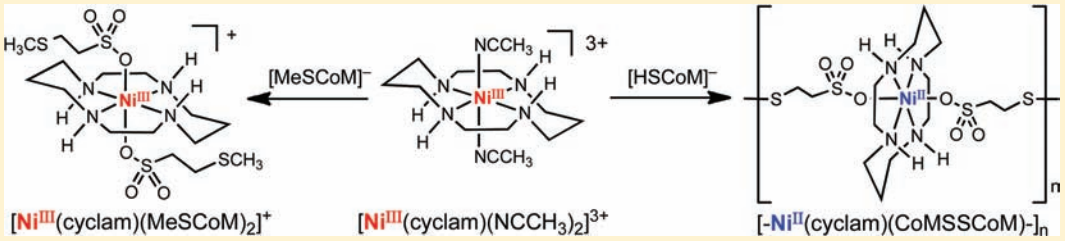
Supporting Information



ABSTRACT: Divalent and trivalent nickel complexes of 1,4,8,11-tetraazacyclotetradecane, denoted as cyclam hereafter, coordinated by methyl coenzyme M ($MeSCoM^-$) and coenzyme M ($HSCoM^-$) have been synthesized in the course our model studies of methyl coenzyme M reductase (MCR). The divalent nickel complexes Ni(cyclam)$(RSCoM)_2$ (R = Me, H) have two trans-disposed $RSCoM^-$ ligands at the nickel(II) center as sulfonates, and thus, the nickels have an octahedral coordination. The $SCoM^{2-}$ adduct Ni(cyclam)(SCoM) was also synthesized, in which the $SCoM^{2-}$ ligand chelates the nickel via the thiolate sulfur and a sulfonate oxygen. The trivalent MeSCoM adduct [Ni(cyclam)$(MeSCoM)_2$](OTf) was synthesized by treatment of [Ni(cyclam)$(NCCH_3)_2$]$(OTf)_3$ with (^{n}Bu$_4$N)[MeSCoM]. A similar reaction with (^{n}Bu$_4$N)[HSCoM] did not afford the corresponding trivalent $HSCoM^-$ adduct, but rather the divalent nickel complex polymer $[-Ni^{II}$(cyclam)(CoMSSCoM)$-]_n$ was obtained, in which the terminal thiol of $HSCoM^-$ was oxidized to the disulfide $(CoMSSCoM)^{2-}$ by the Ni(III) center.

INTRODUCTION

Methyl coenzyme M reductase (MCR) is a key enzyme that catalyzes formation of methane and the heterodisulfide (CoBSSCoM) from methyl−CoM ($MeSCoM^-$) and *N*-7-mercaptoheptanoyl threonine phosphate (HSCoB) in the final step of methanogenesis (eq 1).[1] X-ray structures of two inactive forms of MCR from *M. thermoautrophicum*, designated as MCR_{silent} and $MCR_{ox1\text{-}silent}$, have been determined. As depicted in Figure 1, the active sites have in common a nickel tetrahydrocorphinoid cofactor F430 (Figure 2).[2,3] One of the axial coordination sites of the nickel in F430 is occupied by a sulfonate oxygen of the heterodisulfide CoBSSCoM in MCR_{silent} or a thiolato (or thiol) sulfur of coenzyme M for $MCR_{ox1\text{-}silent}$, while Gln147 interacts weakly with the nickel at the other axial site.[2,3] These inactive forms contain a divalent nickel and are EPR silent. The EPR-active forms such as MCR_{red1} and MCR_{ox1} have also been characterized by spectroscopic analyses.[4] While the active site of MCR_{red1} was assigned as Ni(I), MCR_{ox1} has been suggested to take a Ni(III) state with a similar coordination geometry to that of the $MCR_{ox1\text{-}silent}$ as shown in Figure 3.[5,6]

$$\text{MeSCoM} + \text{HSCoB} \rightarrow \text{CH}_4 + \text{CoBS} - \text{SCoM} \quad \Delta G^{\circ\prime} = 30\ \text{kJ mol}^{-1} \qquad (1)$$

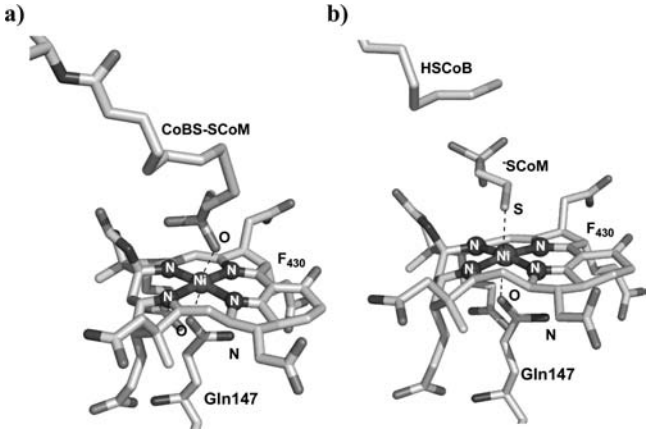


Figure 1. Active site structures of MCR: (a) MCR_{silent} and (b) $MCR_{ox1\text{-}silent}$.

Previously, we reported the reactions of $MeSCoM^-$ and $HSCoM^-$ with Ni(II) triflates having tmc and pyc as auxiliary ligands (Chart 1, tmc = 1,4,8,11-tetramethyl-1,4,8,11-tetraaza-cyclotetradecane, pyc = 5-oxo-7-(2-pyridyl)-1,4,8,11-tetraazacy-

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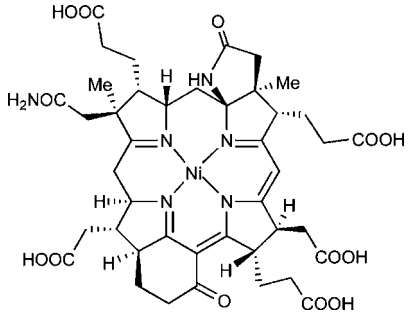


Figure 2. Cofactor F430 in MCR.

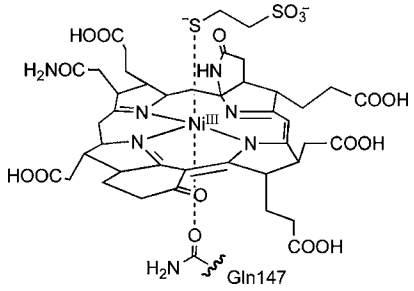
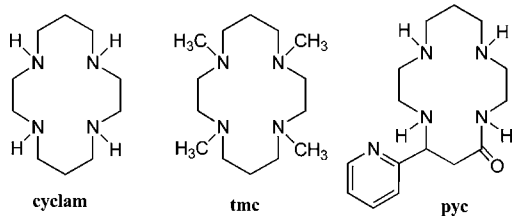


Figure 3. Proposed structure of the MCR_{ox1} active site.

Chart 1



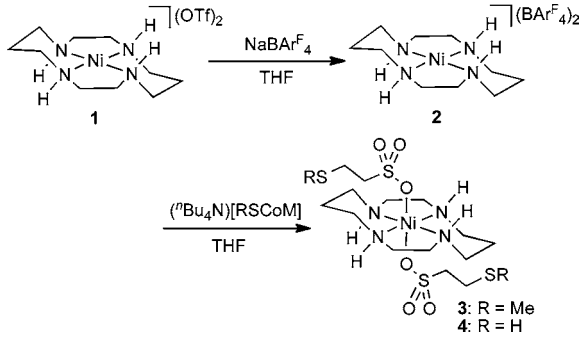
clotetradecane), which gave the coenzyme adducts $[Ni^{II}(L)(MeSCoM)](OTf)$ and $[Ni^{II}(L)(HSCoM)](OTf)$ (L = tmc, pyc) as models of the active site of MCR_{silent}.[7]

Now we extend the scope of our study to the oxidized Ni(III) states. We attempted chemical oxidation of $[Ni^{II}(tmc)]^{2+}$ and $[Ni^{II}(pyc)]^{2+}$, because the Ni(III) complexes of pyc and tmc have not been reported. However, treatments of these tetraaza complexes of Ni(II) with oxidants such as ammonium peroxodisulfate resulted in a complex mixture, probably due to the high oxidation potentials of these Ni(II) complexes as suggested by Barefield et al.[8] Thus, we employed 1,4,8,11-tetraazacyclotetradecane, denoted as cyclam hereafter (Chart 1), in place of tmc and pyc, because the Ni(III) cyclam complexes $[Ni^{III}(cyclam)(Cl)_2](X)$ (X = Cl, ClO_4) and $[Ni^{III}(cyclam)(NO_3)_2](ClO_4)$ are known.[9−11] We herein report the synthesis of the Ni(II) and Ni(III) cyclam complexes of coenzyme M derivatives such as $MeSCoM^-$, $HSCoM^-$, and $SCoM^{2-}$.

RESULTS AND DISCUSSION

Synthesis and Structures of $Ni^{II}(cyclam)(MeSCoM)_2$ (3) and $Ni^{II}(cyclam)(HSCoM)_2$ (4). The divalent nickel cyclam, $[Ni(cyclam)](OTf)_2$ (**1**), was synthesized according to the literature,[12] and anion exchange with $NaBAr^F{}_4$ (Ar^F = 3,5-$(CF_3)_2C_6H_3$) gave $[Ni(cyclam)](BAr^F{}_4)_2$ (**2**). The MeSCoM complex $Ni(cyclam)(MeSCoM)_2$ (**3**) was synthesized in 68% yield as light purple crystals by reaction of **2** and 2 equiv of $(^nBu_4N)[MeSCoM]$ in THF. A similar reaction of **2** with $(^nBu_4N)[HSCoM]$ gave $Ni(cyclam)(HSCoM)_2$ (**4**) in 57% yield (Scheme 1).

Scheme 1



The molecular structures of **3** and **4** as determined by X-ray analysis are shown in Figure 4a and 4b, and selected bond

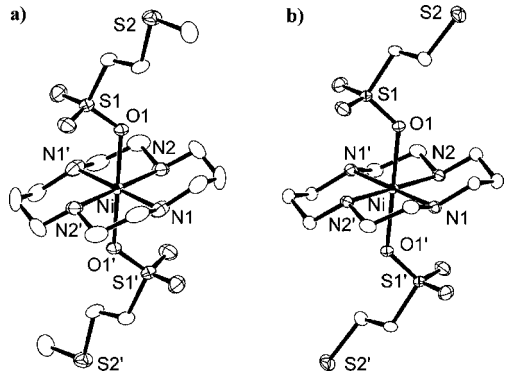


Figure 4. Molecular structures of (a) **3** and (b) **4** with 50% probability ellipsoids.

Table 1. Selected Bond Lengths (Angstroms) and Angles (degrees) of 3 and 4

	3	4
Ni1−O1	2.145(6)	2.1301(11)
Ni1−N1	2.065(5)	2.0705(19)
Ni1−N2	2.066(5)	2.0758(19)
O1−Ni1−N1	89.0(2)	88.82(5)
O1−Ni1−N2	87.6(2)	88.28(5)
N1−Ni1−N2	94.8(2)	94.38(7)

lengths and angles are summarized in Table 1.[13] In these complexes, the four nitrogen atoms of the tetraazacycle are crystallographically coplanar.[14] Two molecules of $MeSCoM^-$ (or $HSCoM^-$) are bound to Ni from above and below the N_4 equatorial plane, completing an octahedral coordination geometry at Ni. Each coordination occurs in an η^1 manner through interaction with a sulfonate oxygen. The bond distances around the nickel atoms are similar to those of known N_4-coordinated octahedral Ni(II) sulfonate complexes.[16] While one oxygen of each sulfonate is bound to Ni, the other two oxygens form intramolecular hydrogen bonds with the NH protons of cyclam, where the N−O distances range from 2.97 to 3.10 Å. In **4**, the sulfonate oxygen interacts

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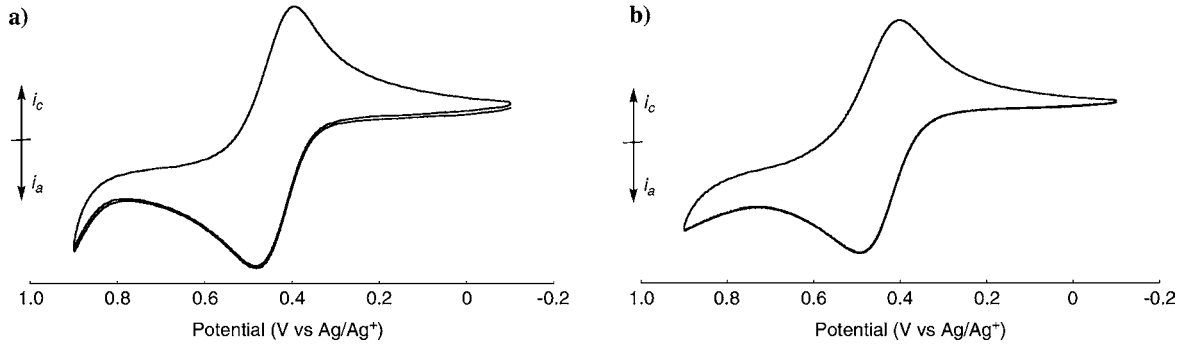


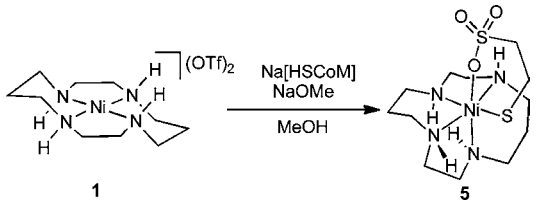
Figure 5. Cyclic voltammograms of 0.5 mM of (a) **3** and (b) **4** recorded at a rate of 50 mV/s in CH_3CN with 0.1 M ($^nBu_4N$)[PF_6] as the supporting electrolyte. Potentials are referenced to Ag/Ag^+.

with the intermolecular thiol proton with an S−O distance of 3.482(4) Å, forming a 1D chain.[17]

Redox Properties of 3 and 4. We investigated the cyclic voltammetry (CV) of **3** and **4** in acetonitrile at room temperature. As shown in Figure 5a, complex **3** exhibits a reversible couple at $E_{1/2}$ = 0.44 V (vs Ag/Ag^+) corresponding to the Ni^{II}/Ni^{III} redox,[18] which suggests good stability of the Ni(III) state. This potential is negatively shifted by 0.23 V from that of [Ni(cyclam)]$(OTf)_2$ (**1**)[18,19] and the perchlorate salt,[20] probably because coordination of the two sulfonates stabilizes the Ni(III) state. Complex **4** also exhibits a similar reversible Ni^{II}/Ni^{III} redox event at $E_{1/2}$ = 0.45 V.[18]

Synthesis of [Ni^{II}(cyclam)(SCoM)] (5). Reaction of **1** with the sodium salt of coenzyme M, Na_2[SCoM], afforded Ni(cyclam)(SCoM) (**5**) in 40% yield as blue-violet crystals (Scheme 2). The molecular structure of **5** as determined by X-ray analysis is shown in Figure 6. In contrast to the coordination mode of $HSCoM^-$ in **4**, the $SCoM^{2-}$ ligand was found to chelate the nickel via the thiolate sulfur S1 and a sulfonate oxygen O1. The unit cell contains two independent molecules **5a** and **5b**, whose structures are alike except for the chelate-ring conformations, twist boat and chair conformations for **5a** and **5b**, respectively. While the Ni assumes a distorted octahedral geometry, the N4 macrocycles are not coplanar due to the cisoidal SCoM chelate coordination. The stereoconfiguration of the nitrogen atoms of the N4 ligands were partially inverted upon coordination of the $SCoM^{2-}$ chelate.[21] The Ni−S bond lengths [2.4395(13) (**5a**) and 2.4040(14) Å (**5b**)] are similar to that found for the $MCR_{ox1\text{-}silent}$ state (2.41 Å) in the protein, which indicates that the coenzyme M in the $MCR_{ox1\text{-}silent}$ state coordinates as a thiolate rather than as a thiol (Table 2).

Scheme 2



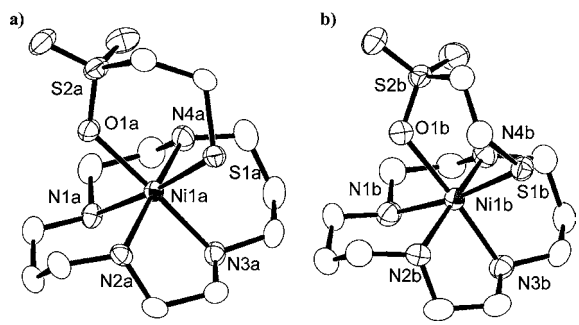


Figure 6. Molecular structures of **5** with thermal ellipsoids drawn at the 50% level.

Table 2. Selected Bond Lengths (Angstroms) and Angles (degrees) of 5a and 5b

	5a	5b
Ni1−S1	2.4395(13)	2.4040(14)
Ni1−O1	2.162(3)	2.198(3)
Ni1−N1	2.151(3)	2.134(4)
Ni1−N2	2.112(3)	2.141(4)
Ni1−N3	2.111(4)	2.101(4)
Ni1−N4	2.109(3)	2.096(4)
S1−Ni1−O1	88.93(9)	88.45(10)
S1−Ni1−N1	172.74(11)	171.49(13)
S1−Ni1−N2	89.59(10)	93.26(12)
S1−Ni1−N3	91.00(10)	91.76(12)
S1−Ni1−N4	99.60(11)	96.28(13)
O1−Ni1−N1	83.95(13)	83.31(16)
O1−Ni1−N2	92.85(14)	91.24(15)
O1−Ni1−N3	176.72(14)	173.99(16)
N1−Ni1−N4	92.56(15)	94.59(16)

Synthesis of [Ni^{III}(cyclam)$(MeSCoM)_2$](OTf) (8). We targeted the synthesis of a Ni(III) cyclam complex carrying the $MeSCoM^-$ ligand. We first tried the reactions with the reported Ni(III) complex [Ni^{III}(cyclam)Cl_2]Cl (**6**),[9] but this was not successful due to the strong coordination of the chloride ligands. Thus, complex **6** was treated with 3 equiv of AgOTf in acetonitrile and converted into a new Ni(III) complex [Ni^{III}(cyclam)$(NCCH_3)_2$]$(OTf)_3$ (**7**) in 72% yield as determined by X-ray analysis (see Supporting Information). Reaction of **7** with 2 equiv of ($^nBu_4N$)[MeSCoM] proceeded smoothly in contrast to the case of **6**, and [Ni^{III}(cyclam)-$(MeSCoM)_2$](OTf) (**8**) was obtained in 62% yield as dark brown crystals (Scheme 3).

The molecular structure of **8** was elucidated by X-ray analysis. Although the asymmetric unit contains one and two half molecules, one of them is depicted in Figure 7, because these structures are very much alike. The basic structural motif

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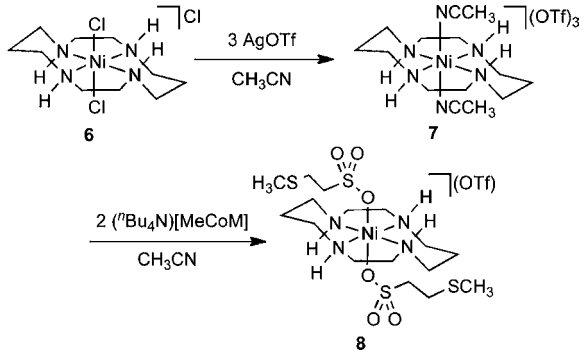
Scheme 3



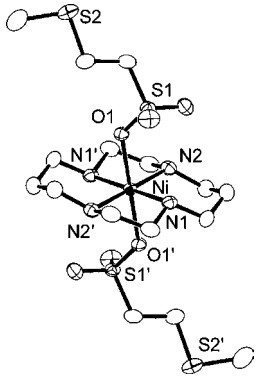


Figure 7. Molecular structure of **8** with thermal ellipsoids drawn at the 50% level.

of **8** resembles that of the related Ni(II) complex **3** in Figure 4a. However, the Ni−O and Ni−N bond distances are reasonably shorter by 0.07−0.09 Å than those of **3**, which is consistent with the higher Ni(III) state (Table 3). The sulfonate oxygens

Table 3. Selected Bond Lengths (Angstroms) and Angles (degrees) of 8

	8
Ni1−O1	2.077(3)
Ni1−N1	1.980(2)
Ni1−N2	1.986(2)
O1−Ni1−N1	89.22(13)
O1−Ni1−N2	85.63(13)
N1−Ni1−N2	93.12(12)

are forming hydrogen bonds with intramolecular NH protons of cyclam with O−N distances of 2.89−3.36 Å.

The solid state EPR spectrum of **8** at 8 K exhibited an axial signal as shown in Figure 8, which is typical of $S = 1/2$ octahedral d^7 metal complexes with spin density residing predominantly in the d_{z^2} orbital of the nickel. Although the $g_{\|}$ value of **8** is shifted from related Ni(III) cyclams listed in Table 4,[22−24] this is similar to the value of the Ni(III) 2,3-dimethylcyclam complex $[Ni^{III}(Me_2[14]aneN_4)(NO_3)_2]^+$ ($g_{\|}$ = 2.103, $g_{\perp}$ = 2.221, 2.182).[25] The $g_{\|}$ value of **8** is also shifted from Ni(III)F430M, the pentamethyl ester of the isolated cofactor F430 in the Ni(III) state.[24] It is worth mentioning that the spectrum of **8** is quite different from that of MCR_{ox1}, showing approximately axial spectra with g values with $g_{\perp}$ = 2.1527, 2.1678 and $g_{\|}$ = 2.2312.[4a] A similar discordance was reported between the enzyme and the isolated cofactor

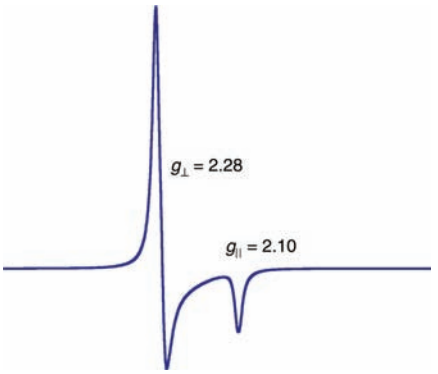


Figure 8. X-band EPR spectrum of **8** in solid state at 8 K.

Table 4. EPR Parameters for the $[Ni^{III}(cyclam)X_2]^{n+}$ Complexes

X	$g_{\perp}$	$g_{\|}$	conditions
$MeCoM^-$ (**8**)	2.28	2.10	solid
MeCN	2.2148	2.0250	1 M $HClO_4$ in H_2O at 77 K
OH_2	2.2193	2.0332	1 M $HClO_4$ in H_2O at 77 K
NO_3^-	2.2402	2.0334	solid
Ni(III)F430M	2.211	2.020	0.1 M Bu_4NBF_4 in MeCN at 98 K

Ni(III)F430 M by Harmer et al.[6a] They suggested that CoM thiolate and Gln ligands in the axial positions might coordinate more strongly in the protein arrangement around the active site, because the g-value ordering for MCR_{ox1} is characteristic for those with the spin density in the $d_{x^2-y^2}$ orbital instead of d_{z^2} assuming the nickel in the MCR_{ox1} has a trivalent d^7 state.[26] The sulfonates in the axial positions of **8** may not coordinate strongly compared to the amide oxygen and thiolate of the MCR_{ox1}, so that their EPR are not similar.

Reaction of 7 with (^{n}Bu$_4$N)[HSCoM]. Because the Ni^{II}/Ni^{III} redox event of **4** was observed as a reversible process in the CV scan as shown in Figure 5b, we attempted the synthesis of a $HSCoM^-$-coordinated Ni(III) cyclam as a MCR_{ox1} model. When complex **7** was allowed to react with 2 equiv of (^{n}Bu$_4$N)[HSCoM], the intense dark green color of **7** gradually diminished and eventually turned to light purple within an hour. This color change suggested that the complex was reduced to a Ni(II) species, which contrasted to the result of the reaction with $MeSCoM^-$ that gave the Ni(III) adduct **8**. Upon standing at room temperature, the resulting solution deposited light purple crystals, and the X-ray crystallographic analysis revealed that the product is the 1-D coordination polymer $[-Ni^{II}(cyclam)(CoMSSCoM)-]_n$ (**9**) composed of $[Ni^{II}(cyclam)]^{2+}$ and the disulfide $CoMSSCoM^{2-}$ that binds nickels of $[Ni^{II}(cyclam)]^{2+}$ at both terminal sulfonates. Apparently, $HSCoM^-$ was oxidized by the Ni(III) center and converted to the disulfide with reduction of the Ni(III) to Ni(II). The yield of **9** was 42% on the basis of nickel, which is quite good since a one-half of **7** should have been consumed as an oxidant (Scheme 4).

Complex **9** was also obtained by oxidation of **5**. The CV spectrum of **5** exhibits an irreversible oxidation event at E_{pa} = −0.06 V (vs Ag/Ag^+),[18] which indicated that oxidation of the $[SCoM]^{2-}$ of **5** would occur more facilely than that of **4**. Indeed, treatment of **5** with 1 equiv of $[Cp_2Fe][PF_6]$ in methanol led to immediate formation of **9** as a light purple crystalline powder in 33% yield.

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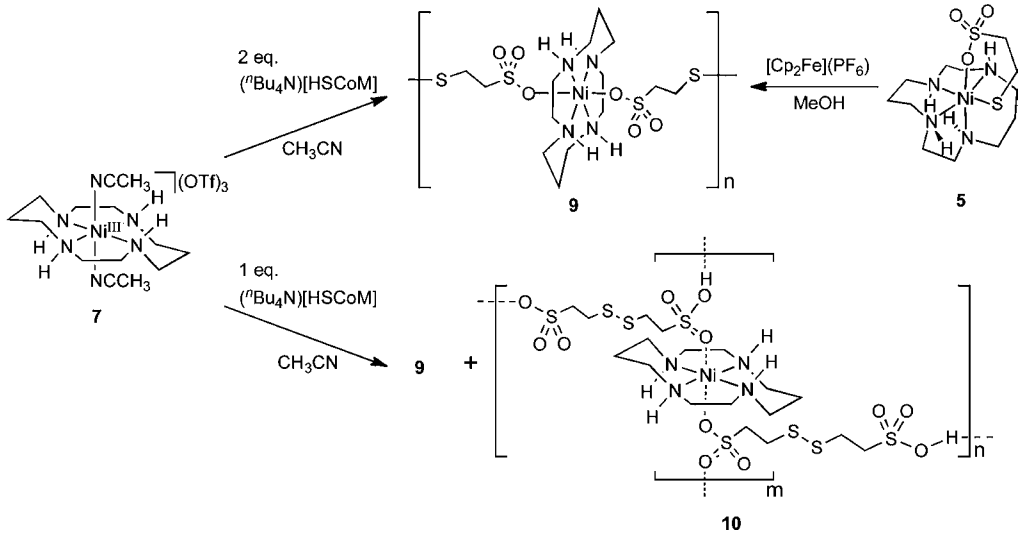
Scheme 4



A similar reaction of **7** by reducing the $HSCoM^-$ amount to 1 equiv also gave **9**, but in addition, a small amount of $[Ni(cyclam)(HCoMSSCoM)_2]_n$ (**10**) was obtained as orange crystals. The structure of **10** was also confirmed by X-ray analysis.

Molecular Structures of 9 and 10. The molecular structures of **9** and **10** are shown in Figures 9 and 10, respectively, and selected bond lengths and angles are given in Table 5. The geometry around the nickel of **9** is octahedral, and

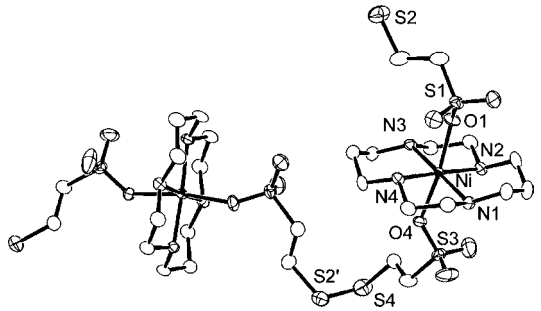


Figure 9. Molecular structure of **9** with thermal ellipsoids drawn at the 50% level.

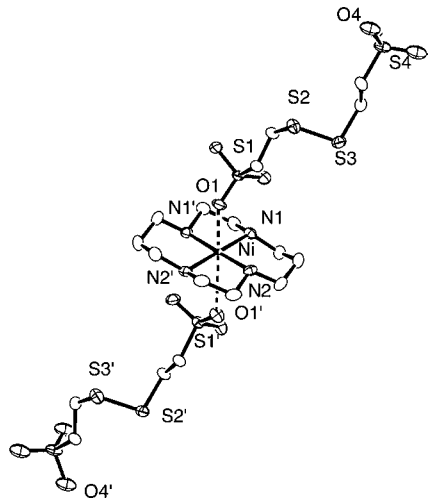


Figure 10. Molecular structure of **10** with thermal ellipsoids drawn at the 50% level.

Table 5. Selected Bond Lengths (Angstroms) and Angles (degrees) of 9 and 10

	9	10
Ni–O1	2.170(2)	2.804(2)
Ni–O2	2.185(2)	
Ni–N1	2.078(3)	1.941(2)
Ni–N2	2.068(3)	1.951(2)
Ni–N3	2.062(2)	–
Ni–N4	2.055(3)	–
O1–Ni–O4(O1′)	170.35(10)	155.69(6)

the metric parameters are similar to those observed for the sulfonate complexes **3** and **4**. It also resembles the MCR_{silent} state structure shown in Figure 1a. Complex **10** also appears to assume a similar structure around the nickel, but the axial Ni–O lengths (2.805(2) Å) are obviously elongated, and the Ni–N bonds become shorter. Although the Ni–O distance is within the sum of their van der Waals radii, the geometry can be better described as square planar rather than octahedral, and O1 and O1* are weakly interacting with the nickel. The light orange color of **10** also conforms to the square planar nickel. The weakened Ni–O interaction is attributable to the hydrogen bond formed via the proton that bridges the two sulfonates bonded to the nickels intermolecularly.

■ DISCUSSION

As shown in Figure 3, the MCR_{ox1} state is postulated to contain an F430 Ni(III) center, axially coordinated by Gln and coenzyme M as either a thiolate or a thiol, assuming that the MCR_{ox1} is an oxidized state relative to the Ni(II) state.[6b] Harmer et al. recently reported that this state would be described as a Ni(III) (d^7) thiolate in resonance with a thiyl radical/high-spin Ni(II) state on the basis of EPR studies.[6a] When we added $HSCoM^-$ to the Ni(III) complex **7**, the corresponding Ni(III) thiolate adduct was not observed but the reaction went further to give the homodisulfide $(CoMSS\text{-}CoM)^{2-}$ with concomitant reduction of Ni(III) to Ni(II) states. Thus, in this study, we could not disclose the properties of the

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Table 6. Crystal Data for 3−5 and 7−10

complex	3	4	5	7·CH_3CN	8·0.5CH_3CN	9	10
formula	$C_{16}H_{38}N_4NiO_6S_4$	$C_{14}H_{34}N_4NiO_6S_4$	$C_{12}H_{28}N_4NiO_3S_2$	$C_{19}H_{33}N_7F_9NiO_9S_3$	$C_{18}H_{39.5}N_{4.5}F_3NiO_9S_5$	$C_{14}H_{32}N_4NiO_6S_4$	$C_{18}H_{42}N_4NiO_{12}S_8$
fw	569.44	541.39	399.20	829.38	739.03	539.37	821.73
cryst syst	triclinic	triclinic	orthorhombic	triclinic	triclinic	monoclinic	monoclinic
space group	*P*-1 (No. 2)	*P*-1 (No. 2)	*Pbca* (No. 61)	*P*-1 (No. 2)	*P*-1 (No. 2)	$P2_1/n$ (No. 2)	*C*2/*c* (No. 15)
a, Å	9.129(3)	8.668(4)	17.379(5)	9.375(2)	13.5572(15)	9.373(2)	22.920(5)
b, Å	12.182(4)	8.680(5)	14.775(4)	12.653(3)	14.2342(15)	18.151(4)	9.2546(13)
c, Å	13.140(4)	8.810(5)	27.878(8)	15.550(3)	18.346(2)	13.176(6)	18.029(3)
α, deg	73.219(20)	119.359(7)	90	72.872(9)	71.475(7)	90	90
β, deg	70.579(17)	96.713(4)	90	74.341(9)	72.896(8)	90.765(3)	120.645(6)
γ, deg	68.152(16)	90.824(3)	90	76.744(9)	68.011(7)	90	90
V, Å^3	1256.2(7)	571.8(5)	7158(3)	1674.7(6)	3050.3(6)	2241.5(8)	3290.1(10)
Z	2	1	16	2	4	4	4
ρ_{calcd}, g cm^{-1}	1.505	1.572	1.482	1.645	1.609	1.598	1.659
μ, cm^{-1}	11.429	12.510	13.335	8.715	10.485	12.763	11.581
F_{000}	604	286	3392	850	1544	1136	1720
$2\theta_{max}$, deg	55.0	55.0	55.0	55.0	55.0	55.0	55.1
no. of reflns collected	9853	4486	53 089	19 878	24 896	26 808	19 366
no. of indep reflns (R_{int})	5486 (0.032)	2493 (0.017)	8185 (0.070)	7631 (0.019)	13 389 (0.028)	5131 (0.095)	3762(0.244)
no. of params	284	139	398	437	706	263	201
*R*1[a]	0.0835	0.0330	0.0709	0.0562	0.0614	0.0615	0.0601
*wR*2[b]	0.2461	0.0688	0.1887	0.1518	0.1816	0.1636	0.1514
GOF on F^2[c]	1.120	1.068	1.108	1.058	1.105	1.058	1.015
CCDC	857822	857823	857824	857825	857826	857827	857828

[a] $R1 = \Sigma||F_o| - |F_c||/\Sigma|F_o|$ ($I > 2\sigma(I)$). [b] $wR2 = [(\Sigma w(|F_o| - |F_c|)^2/\Sigma wF_o^2)]^{1/2}$ (all data). [c] $GOF = [\Sigma w(|F_o| - |F_c|)^2/(N_o - N_v)]^{1/2}$ (N_o = number of observations, N_v = number of variables).

Ni(III) cyclam thiolate complex. To achieve this, the intermolecular reaction should be avoided as is the case of the MCR_{ox1} state, in which the protein residues around the MCR active site including the arginine residue that coordinates to the terminal sulfonate of the coenzyme M play the roles.

SUMMARY

Several divalent and trivalent nickel cyclam complexes having coenzyme M derivatives have been synthesized. In the structures of the Ni(II) complexes **3** and **4**, $MeSCoM^-$ and $HSCoM^-$ both bind through the harder, charged sulfonate oxygen rather than the softer, less polar thioether or thiol, as is also the case for MCR_{silent} state. Deprotonation of $HSCoM^-$ to produce $SCoM^{2-}$ unmasks the sulfur to produce a strong, charged thiolato donor, which binds to the Ni(II) ion of **5**. The Ni−S distance found for **5** suggests that the Ni-bound sulfur of $MCR_{ox1\text{-}silent}$ is a deprotonated thiolate rather than its conjugate acid thiol. The structure of Ni(III) MeSCoM complex **8** was also analyzed, in which the MeSCoM are bound through the sulfonate oxygens. The HSCoM analogue of the Ni(III) cyclam was not obtained due to the disulfide formation via self-coupling of the oxidized coenzyme M thiolate, which gave the Ni(II) cyclam coordinated by the homodisulfide sulfonates **9** and **10**.

EXPERIMENTAL SECTION

General Procedures. All reactions and manipulations of moisture-sensitive compounds were conducted under an inert atmosphere of dry nitrogen by employing standard Schlenk techniques or a glovebox under nitrogen atmosphere. Hexane, ether, THF, and acetonitrile were degassed and purified by the method of Grubbs, where the solvents were passed over columns of activated alumina and supported copper catalyst supplied by Hansen & Co. Ltd. MeOH was distilled from Mg in a nitrogen atmosphere. CH_3NO_2 and water were bubbled with nitrogen prior to use. For UV−vis spectra, a JASCO V560 spectrometer was used. ESI-TOF-MS spectra were obtained from a Micromass LCT TOF-MS spectrometer. Elemental analyses for C, H, N, and S were performed on a LECO CHNS-932 elemental analyzer where the crystalline samples were sealed in silver capsules. The EPR spectrum was recorded on a Bruker EMX-plus spectrometer at X-band frequencies with a liquid helium cryostat. Cyclic voltammograms were recorded using a carbon working electrode with 0.1 M (^{n}Bu$_4$N)[PF_6] as the supporting electrolyte. The potential is reported with respect to a Ag/$AgNO_3$ nonaqueous reference electrode filled with acetonitrile and (^{n}Bu$_4$N)[PF_6].[18] X-ray diffraction data were collected on a Rigaku AFC8 or a Rigaku RA-Micro7 equipped with a CCD area detector using graphite-monochromated Mo K*α* radiation. Nickel halides and other reagents were purchased and used without further purification. The following compounds were prepared according to literature procedures: Ni(cyclam)Cl_2,[27] [Ni(cyclam)](OTf)$_2$ (**1**),[12] [Ni(cyclam)(Cl)$_2$](Cl) (**6**),[9] Na[MeSCoM],[28] (^{n}Bu$_4$N)[MeSCoM],[29] and (^{n}Bu$_4$N)[HSCoM].[30]

Preparation of [Ni(cyclam)](BAr$^F_4$)$_2$ (2). [Ni(cyclam)](OTf)$_2$ (**1**) (220 mg, 0.4 mmol) was treated with $NaBAr^F_4$ (714 mg, 0.8 mmol) in 10 mL of THF, and the resulting solution was evaporated in vacuo. The residue was washed with water and dried to give **2** in 78% yield. ESI-TOF-MS (THF), *m*/*z* (%): 1120.5 ([M + BAr^F_4])$^+$). UV−vis (MeCN, rt; λ_{max}, nm) (ε, cm^{-1} M^{-1}): 443 (73). Anal. Calcd for $C_{74}H_{48}B_2N_4Ni$: C, 44.77; H, 2.44; N, 2.82. Found: C, 44.91; H, 2.45; N, 2.57.

Synthesis of Ni(cyclam)(MeSCoM)$_2$ (3). To a THF solution (10 mL) of **2** (200 mg, 0.10 mmol) was added a THF solution (5 mL) of (^{n}Bu$_4$N)[MeSCoM] (80 mg, 0.20 mmol), and this was stirred at room temperature for 30 min. The light purple solution was evaporated in vacuo, and the residue was washed with Et_2O. The crude product was recrystallized from THF/Et_2O to give **3** as light purple crystals in 68% yield. ESI-TOF-MS (MeCN), *m*/*z* (%): 412.9 ([M − (MeSCoM)]$^+$) (100%). UV−vis (THF, rt; λ_{max}, nm) (ε, cm^{-1} M^{-1}): 337 (10), 511 (7), 664 (5). Anal. Calcd for $C_{16}H_{38}N_4S_4NiO_6$: C, 33.75; H, 6.73; N, 9.84; S, 22.52. Found: C, 34.04; H, 6.27; N, 9.98; S, 22.29.

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Synthesis of Ni^{II}(cyclam)(HSCoM)$_2$ (4). Complex **4** was obtained as described for **3** but using **2** (200 mg, 0.10 mmol) and (^{n}Bu$_4$N)[HSCoM] (77 mg, 0.20 mmol) in 57% yield as light purple crystals. ESI-TOF-MS (MeCN), m/z (%): 398.9 ([M − (HSCoM)]$^+$) (100%). UV−vis (MeCN, rt; λ_{max}, nm) (ε, cm^{-1} M^{-1}): 338 (16), 520 (10), 654 (7). Anal. Calcd for $C_{14}H_{34}N_4S_4NiO_6$: C, 31.06; H, 6.33; N, 10.35; S, 23.69. Found: C, 31.20; H, 5.86; N, 10.13; S, 23.62.

Synthesis of Ni(cyclam)(SCoM) (5). To a methanol solution (10 mL) of [Ni(cyclam)](OTf)$_2$ (**1**) (119 mg, 0.28 mmol) was added a methanol solution (5 mL) of Na[HSCoM] (48 mg, 0.28 mmol) and sodium methoxide (15 mg, 0.28 mmol). The resulting blue solution was stirred at room temperature for 1 h and evaporated to dryness. The residue was extracted with acetonitrile and allowed to stand for 48 h to give **5** as blue crystals in 40% yield. UV−vis (MeCN, rt; λ_{max}, nm) (ε, cm^{-1} M^{-1}): 371(17), 576(10). Anal. Calcd for $C_{12}H_{28}N_4S_2NiO_3$: C, 36.10; H, 7.07; N, 14.03; S, 16.06. Found: C, 35.62; H, 6.93; N, 13.75; S, 15.25.

Preparation of [Ni^{III}(cyclam)(NCCH$_3$)$_2$](OTf)$_3$ (7). To an acetonitrile suspension (10 mL) of [Ni(cyclam)(Cl)$_2$](Cl) (**6**) (108 mg, 0.30 mmol) was added an acetonitrile solution of AgOTf (231 mg, 0.90 mmol) with vigorous stirring. The deep greenish brown solution was filtered off, and the filtrate was evaporated to dryness. The residue was dissolved in acetonitrile, and layering of Et$_2$O onto the greenish brown solution gave brown crystals of **7**·CH$_3$CN in 72% yield. ESI-TOF-MS (MeCN), m/z (%): 556.0 ([M − 2(CH$_3$CN) + 2(OTf)]$^+$) (100%), ([M − 2(CH$_3$CN) + (OTf)]$^+$, one electron reduced) (35%). UV−vis (MeCN, rt; λ_{max}, nm) (ε, cm^{-1} M^{-1}): 306(10 300), 365(sh.) Anal. Calcd for $C_{17}H_{30}N_6S_3F_9NiO_9$: C, 25.90; H, 3.84; N, 10.66; S, 12.20. Found: C, 25.92; H, 3.61; N, 11.10; S, 12.08.

Synthesis of [Ni^{III}(cyclam)(MeSCoM)$_2$](OTf)·0.5CH$_3$CN (8). To an acetonitrile solution of **7** (157 mg, 0.20 mmol) was added (^{n}Bu$_4$N)[MeSCoM] (180 mg, 0.45 mmol), and this was stirred at room temperature for 3 h. Et$_2$O was slowly layered onto the resulting brown solution to give **8**·0.5CH$_3$CN as brown crystals in 62% yield. Anal. Calcd for $C_{18}H_{38}N_4S_5NiO_9F_3$·0.5($C_2H_3N$): C, 29.25; H, 5.39; N, 8.53; S, 21.69. Found: C, 29.14; H, 5.30; N, 8.37; S, 21.11.

Reaction of [Ni^{III}(cyclam)(NCCH$_3$)$_2$](OTf)$_3$ (7) with 2 Equiv of (^{n}Bu$_4$N)[HSCoM]. To an acetonitrile solution (5 mL) of **7** (52 mg, 0.066 mmol) was added (^{n}Bu$_4$N)[HSCoM] (54 mg, 0.14 mmol) with stirring. The color changed to light purple. The resulting solution stood for 5 h, and light purple crystals of [−Ni(cyclam)(CoMSSCoM)−]$_n$ (**9**) precipitated in 42% yield. Anal. Calcd for $C_{14}H_{32}N_4S_4NiO_6$: C, 31.17; H, 5.98; N, 10.39; S, 23.78. Found: C, 31.25; H, 6.03; N, 10.27; S, 22.97.

Reaction of [Ni^{III}(cyclam)(NCCH$_3$)$_2$](OTf)$_3$ (7) with 1 Equiv of (^{n}Bu$_4$N)[HSCoM]. To an acetonitrile solution (5 mL) of **7** (79 mg, 0.10 mmol) was added (^{n}Bu$_4$N)[HSCoM] (38 mg, 0.10 mmol) with stirring. The color changed to light yellow. The resulting solution was concentrated to give a mixture of light purple crystals of **9** and yellow crystals of Ni(cyclam)(HCoMSSCoM)$_2$ (**10**). Anal. Calcd for $C_{18}H_{42}N_4S_8NiO_{12}$ (**10**): C, 26.31; H, 5.15; N, 6.82; S, 31.22. Found: C, 26.12; H, 5.06; N, 5.89; S, 31.01.

Oxidation of Ni(cyclam)(SCoM) (5). To a methanol solution (5 mL) of **5** (119 mg, 0.28 mmol) was added a methanol solution (5 mL) of [Cp$_2$Fe](PF$_6$) (48 mg, 0.28 mmol). After stirring the resulting solution for 3 h a light purple crystalline powder was precipitated. The residue was washed with MeOH and Et$_2$O to give crude **9** in 33% yield.

Crystal-Structure Determination. Crystallographic data and refinement parameters for **3**−**5** and **7**−**10** are summarized in Table 6. Single crystals were mounted on a loop using oil (CryoLoop, Immersion Oil, Type B or Paraton, Hampton Research Corp.) and set on a Rigaku AFC-8 (for **3**−**5** and **7**) or Rigaku AFC-10 (for **8**−**10**) instrument equipped with a mercury CCD detector (for **3**−**5** and **7**) or with a Saturn CCD detector (for **8**−**10**). Measurements were made using graphite-monochromated Mo Kα radiation (λ = 0.71070 Å) under a cold nitrogen stream. The frame data were integrated and corrected for absorption with the Rigaku/MSC CrystalClear program package. The structures were solved with the use of direct methods (SIR-92 or SIR-97) and standard difference map techniques and refined by full-matrix least-squares procedures on F^2 by the Rigaku/MSC CrystalStructure package. Anisotropic refinement was applied to all non-hydrogen atoms, but the disordered crystalline solvent molecules for **9** were refined isotropically (see Table 6). The methyl group of MeSCoM$^-$, the counteranion $CF_3SO_3^-$ in **8**, and the sulfonic acid SO_3−H in **10** were disordered over several positions, in which respective ratios were freely refined while the total occupancy of the components was constrained to unity. The ratio of disordered SO_3−H atoms in **10** was simply set at 1:1. The hydrogen atom of SH in **4** and **10** were assigned from the Fourier map and refined isotropically. All other hydrogen atoms were put at calculated positions. Supplementary crystallographic data for this paper can be obtained free of charge from the Cambridge Crystallographic Data Centre at www.ccdc.cam.ac.uk/data_request/cif.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Crystallographic data in CIF format for **3**−**5** and **7**−**10**, additional structural details of **4** and **7**, CV data for **1** and **5**. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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