Crown Thioether Chemistry

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In 1934 Meadow and Reid[1] at Johns Hopkins found that reaction of sodium ethanedithiolate with ethylene bromide gives a rubbery malodorous polymer along with a small amount of the cyclic hexamer 1,4,7,10,13,16-hexathiacyclooctadecane (18S6) (Figure 1).[2] Coming more than 30 years before the seminal work of Pedersen on crown ethers[3] and of Rosen and Busch[4] on macrocyclic thioether ligands, 18S6 and its potential ligating properties went unexplored until the work of Black and McLean in Australia in 1969.[5,6] Nevertheless, from this inauspicious beginning 50 years ago the chemistry of crown thioethers has grown into a field that is now undergoing explosive development by a number of groups around the world.

Several factors have encouraged this growth. First, the possibility (since confirmed[7,8]) of methionine coordination to Cu in the blue copper proteins fuelled speculation that the unusual optical, redox, and EPR properties of these proteins[9] originated from Cu–thioether interaction. This issue spurred the pioneering work of Rorabacher and co-workers on copper complexes of macrocyclic thioethers.[10]

Another stimulus also concerned the electronic consequences of thioether coordination. The potential analogy to phosphines suggested that thioethers might have extensive coordination chemistry of industrial utility. Moreover, this chemistry might complement that of phosphine complexes. The moderate π-acidity of thioethers[11] (intermediate between that of amines and that of phosphines) might stabilize lower oxidation states of metal ions more than amines, but less than phosphines, to yield complexes with unusual reactivity. Thus, as in the blue copper proteins, the possible development of new homogeneous catalysts hinged on one central issue: how thioethers affect the electronic structures of metal ions.

This question is best addressed in homoleptic thioether complexes (i.e., those in which only thioethers coordinate to the metal). For such complexes the absence of other ligating groups simplifies interpretation of results. Unfortunately, however, simple thioethers bind metal ions weakly. Their relatively low σ-donor and π-acceptor ability[11] (compared to that of phosphines, for example), combined with the steric encumbrance of the alkyl groups, makes homoleptic complexes of, e.g., Me₂S virtually impossible to prepare.

This synthetic challenge can be neatly met through use of crown thioethers. These ligands typically bind metal ions much more strongly than simple mono- or

bidentate thioethers; indeed, use of crown thioethers has permitted synthesis of the first homoleptic thioether complexes of a wide variety of metal ions. Crown thioethers make it synthetically feasible to impose on metal ions the often otherwise unattainable oligo(thioether) environment. By enforcing coordination of weakly binding donor groups, the crown thioether approach encourages attempts to capture metal ions in unusual oxidation states in a "molecular Dewar".

With the current renaissance of thioether coordination chemistry crown thioethers—especially 9S3—are now taking their place in the repertoire of synthetic inorganic chemistry. This Account describes recent progress on the chemistry of crown thioethers. It focusses on the work in our laboratory in the past four years on the synthesis, conformational analysis, and coordination chemistry of the crown thioethers 9S3, 12S3, 18S6, and 24S6 and concludes with a view to future advances in this field.

Synthesis of Ligands

Historically the lack of safe, general, high-yield routes to the ligands has severely impeded work on crown thioethers. Meadow and Reid[1] prepared 18S6 in 1.7% yield. In 1974 Ochrymowycz and co-workers[12] improved the yield to 32.8%, but the route requires use of mustard gas.[13]

Since then use of cesium salts in the cyclization reaction, an innovation introduced by Kellogg and co-workers,[14,15] has revolutionized synthesis of 18S6. Slow addition of a solution of 3-thiapentane-1,5-dithiol and

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(2) Abbreviations used: 9S3, 1,4,7-trithiacyclononane (trithia-9-crown-3); 12S4, 1,4,7,10-tetrathiacyclododecane (tetraathia-12-crown-4); 14S4, 1,4,8,11-tetrathiacyclotetradecane; 15S5, 1,4,7,10,13-pentathiacyclopentadecane (pentathia-15-crown-5); 18S6, 1,4,7,10,13,16-hexathiacyclooctadecane (hexathia-18-crown-6); 24S6, 1,5,9,13,17,21-hexathiacyclotetracosane (hexathia-24-crown-6).
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(13) Black and McLean[5,6] reported preparation of 18S6 in 31% yield, a surprisingly high value for the route they used. Two laboratories have independently found that this route affords 18S6 in 8% yield. Wolf, R. E., Jr.; Hartman J. R.; Cooper, S. R., unpublished work. Ochrymowycz, L. A., personal communication.
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Stephen R. Cooper was born in 1950 in Bethesda, Maryland. He graduated with a B.A. in chemistry from the University of California, San Diego, before earning the Ph.D. degree at the University of California, Berkeley (1976) with Professor M. Calvin. After postdoctoral work with Professor K. N. Raymond, he joined the faculty of Harvard as an assistant professor in 1979 and moved in 1984 to Oxford, where he is presently University Lecturer and a Fellow of St. Hugh's College. His other research interests focus on redox-active crown ethers and on the coordination chemistry of Mn(III) and Mn(IV).
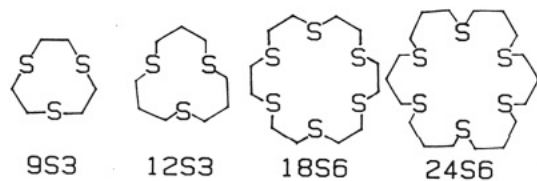
9S3   12S3   18S6   24S6

Figure 1. Crown thioethers discussed in this Account.

1,11-dichloro-3,6,9-trithiaundecane to a suspension of cesium carbonate in DMF[16] gives 18S6 on the 20-g scale in 80% yields. Accordingly, this formerly precious ligand is now readily available.

Similar improvements have taken place in the synthesis of 9S3. The very low yield (0.04%) reported by Ochrymowycz and co-workers,[17] who first synthesized this ligand in 1974,[18] effectively precluded further investigation of this promising ligand. Subsequent improvements increased the yield to 4.4%.[19] Sellman and Zapf[20] have published an ingenious template synthesis that gives 9S3 in 60% yield.

Initial attempts to apply the Cs_2CO_3/DMF cyclization method to synthesis of 9S3 gave a 20% yield,[21] which recently has been improved to 50%.[22] This method competes favorably with the template route because (1) it involves less manipulation and (2) it proceeds in one step from commercially available starting materials. Perhaps most importantly, the synthesis is general; modifications of this method provide 9-, 10-, 11-, 12-, 14-, 16-, 18-, and 24-membered crowns in high yield.[16]

The smooth cyclizations of the Cs_2CO_3/DMF route naturally focus interest on the critical role of the cesium carbonate (which clearly surpasses the other group IA carbonates[14]). At first glance the cation might be suspected of exerting a template effect. However, the high-yield cyclizations of 1,ω-dithiols with 1,ω-dihalides[14] (in which only methylene groups separate the reactive functionalities) rule out any template effect.

Cesium ion must influence the reactivity of the crucial ω-halo-α-thiolate intermediate produced by the first nucleophilic displacement, through which both cyclization and polymer formation must proceed. Cesium probably promotes this reaction by forming weak ion pairs with RS^- anions, which would make them exceptionally nucleophilic. Under high-dilution conditions this enhanced reactivity would favor intra- over intermolecular S_N2 reaction of the open-chain ω-halo-α-thiolate intermediate. Thus Cs^+ more likely promotes cyclization less by what it does than by what it does *not* do.

In summary, improvements in synthetic methodology over the past several years have made crown thioethers readily available. Far from the laboratory curiosities of a few years ago, they are now even sold commercially.[23]

[M(9S3)₂]   [M(12S3)₂]

[M(18S6)]   [M(24S6)]

Figure 2. Structures of representative crown thioether complexes. Top: $[M(9S3)_2]^{n+}$ (ref 19) (left); $[M(12S3)_2]^{n+}$ (right). Bottom: $[M(18S6)]^{n+}$ (left); $[M(24S6)]^{n+}$ (right). In all cases figures are those of Ni(II) complexes.

Conformational Analysis

Early structural work on macrocyclic thioethers revealed a curious property: the sulfur atoms tend to point out of the ring.[24-26] Because of this "exodentate" orientation[27] (which contrasts with that more commonly seen in oxa and aza macrocycles)[28] some crown thioethers tend to bridge metal ions rather than to chelate to one.[27] Not all crown thioethers, however, adopt exodentate conformations; for example, both 9S3[29] and 18S6[30] have endodentate S atoms.

What controls the conformation of these ligands? Analysis of the structures of 12S4,[31] 15S5,[31] 18S6,[30,31] and other macrocyclic thioethers[24-26] revealed a striking pattern: *in practically every crown thioether all of the C–S linkages adopt gauche placement.*[31] In oxo crowns, by contrast, the C–O bonds prefer anti placement. This difference arises largely from the different 1,4-interactions in gauche C–C–E–C and E–C–C–E units (E = O, S), which combine in oxa crowns to give anti C–O and gauche C–C bonds, but in thia crowns give the opposite: gauche C–S and anti C–C bonds.[31]

For molecules such as 14S4 and 12S4 these tendencies give a quadrangular structure with the sulfur atoms at

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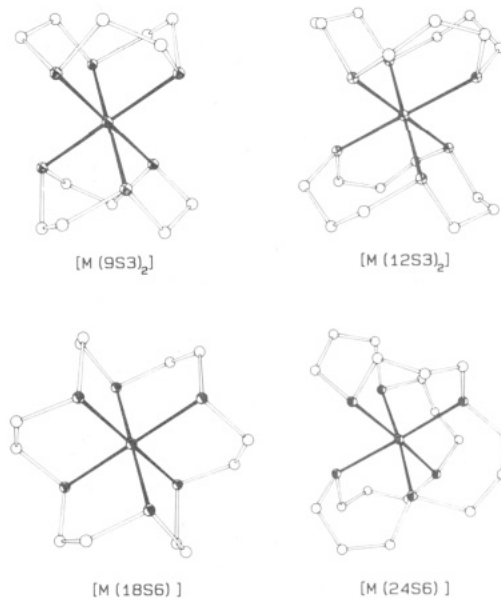(22) Blower, P. J.; Cooper, S. R. *Inorg. Chem.* **1987**, *26*, 2009.

the corners. The resulting conformations disfavor chelation, which necessitates a complete conformational rearrangement to turn the donor atoms "right side in". Conformational analysis therefore reveals why 14S4 shows little macrocyclic effect[32] (i.e., its binding affinity barely exceeds that of comparable acyclic ligands) and why Rosen and Busch[4] in their seminal work found that 12S4 more often bridges rather than chelates metal ions.[10]

Coordination Chemistry

Nickel. With a general route to the crown thioethers now in hand, the question arose, how good would crown thioethers be as ligands? In their ground-breaking work Rorabacher, Ochrymowycz, Glick, and co-workers had shown that several tetradentate macrocyclic thioethers readily form complexes with Cu(II) and Cu(I).[10] Relatively little, however, was known about other metals or about 18S6.

Following Black and McLean[5,6] we found that 18S6 reacts with nickel(II) picrate to give beautiful orange prisms. X-ray diffraction revealed an octahedral [Ni-(18S6)]$^{2+}$ cation in which the crown thioether envelopes a high-spin Ni(II) ion (Figure 2).[33,34] This structure provided the first proof that 18S6 could function as a hexadentate ligand. A curious feature of the structure was its usually short Ni–S bond lengths. In both [Ni-(18S6)]$^{2+}$ and [Ni(9S3)$_2$]$^{2+}$[19] Ni–S distances average 2.38 Å, 0.06 Å shorter than the sum of ionic radii (2.44 Å).

Subsequent work has shown that both 9S3 and 18S6 generate short Ni–S distances by constricting the metal ion (the macrocyclic constriction effect[35]). Thus the larger ring ligands 12S3 and 24S6 give [Ni(12S3)$_2$]$^{2+}$[34] and [Ni(24S6)],$^{2+}$[36] both of which have normal Ni–S bond lengths. This constriction by 9S3 and 18S6 not only shortens the Ni–S bonds, but it also increases the apparent ligand field strength of the thioethers by approximately 10%. Note that this 0.06-Å compression is equivalent to an external pressure of thousands of atmospheres!

Cobalt. The apparent compression of Ni(II) by 18S6 raised the question, what would happen with an even larger metal ion, such as Co(II)? Structural investigation of [Co(18S6)]$^{2+}$ yielded a centrosymmetric cation superficially similar to [Ni(18S6)]$^{2+}$.[37,38] Closer examination of the structure, however, revealed a marked axial elongation (0.2 Å) of the cobalt coordination sphere; in fact, in both [Co(18S6)]$^{2+}$ and [Co(9S3)$_2$]$^{2+}$[19] the CoS$_6$ coordination spheres disturbingly resembled those of Jahn–Teller-distorted Cu(II) complexes. The Jahn–Teller effect could occur in Co(II), a d^7 ion, but only if it were low spin. However, strong-field complexes of Co(II) typically lose ligands to adopt four- or five-coordination. Consequently, this explanation of the distortion seemed unlikely.

Nevertheless, magnetic measurements unambiguously established that it is correct. At room temperature [Co(18S6)]$^{2+}$ has a magnetic moment of 1.8 μ_B.[37,38] EPR spectroscopy further substantiated the low-spin formulation. In common with other T ground state ions, high-spin Co(II) complexes only show EPR spectra at very low temperatures (<20 K). The spectrum of [Co(18S6)]$^{2+}$, however, is observable even at room temperature. Furthermore, the pattern of g values ($g_\parallel \simeq 2, g_\perp > 2$) indicated a d$_{z^2}$ ground state for this low-spin d^7 ion—consistent with axial elongation. In addition, double integration established that the EPR spectrum accounted for 95 ± 10% of the spins.[37,38] Similar results were subsequently obtained for [Co(9S3)$_2$]$^{2+}$.[38,39]

This low-spin state was unexpected. Thioethers exert a ligand field roughly comparable in strength to that of ammonia,[40] and [Co(NH$_3$)$_6$]$^{2+}$ is high spin. This conflict could be resolved in one of two ways. First, the low-spin state could result from macrocyclic constriction of the metal. The resulting increase in Δ might suffice to cause spin-pairing. Alternatively, it could derive from an electronic effect of thioether coordination. To answer this question we synthesized [Co(ttn)$_2$]$^{2+}$ (where ttn is the linear trithioether 2,5,8-trithianonane) and found that this complex is also low spin.[38]

These findings showed that the unexpected electronic structures arise not from any special effect of the crown ligands, but simply from hexakis(thioether) coordination. The hexakis(thioether) environment apparently does not induce spin-pairing through imposition of a strong ligand field (a one-electron term). Rather it does so through lowering the spin-pairing energy (a two-electron term). The apparent paradox—low-spin complexes of a relatively weak-field ligand—arises from delocalization of t$_{2g}$ electron density onto the ligand (probably into S–C σ* orbitals[41]). Such delocalization reduces electron–electron repulsions, and therefore the spin-pairing energy, of the t$_{2g}$ electrons. Hence the low-spin state ultimately derives from the π-acidity of thioethers.

In fact, π-acidity causes one of the most intriguing aspects of thioether coordination: its ability to stabilize lower oxidation states. This effect appears most clearly in electrochemical behavior. In all Co(SR$_2$)$_6$ complexes the Co(III/II) couple not only approaches electrochemical reversibility—itself a rarity in cobalt chemistry—but appears at strongly oxidizing potentials. For example, [Co(18S6)]$^{2+}$ and [Co(ttn)$_2$]$^{2+}$ undergo oxidation at +844 to +864 mV, while [Co(9S3)$_2$]$^{2+}$ does so at +680 mV (all vs NHE).[38] Comparison with ammine complexes is illuminating, in view of the similar ligand field strengths of the two types of ligands. For example, [Co(9N3)$_2$]$^{2+}$ (where 9N3 is the amine analogue of 9S3) undergoes reversible oxidation at −410 mV vs NHE (in water);[42] even allowing for the difference in solvent, these two couples differ by over 1000 mV. In summary, the unusual magnetic and redox properties of these complexes reflect the ability of thioether coordination to induce unusual electronic structures in transition-metal ions.

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Copper. This ability also expresses itself clearly in their complexes with copper. Rorabacher and co-workers have investigated the copper complexes of macrocyclic tetra- and pentadentate thioethers to elucidate the origin of the unusual optical, redox, and EPR properties of the blue copper proteins (which show interaction between the copper ion and a thioether group from methionine). This impressive work, which has recently been reviewed,[10] falls outside the scope of the present Account. In summary, however, it shows that coordination to thioethers dramatically raises the Cu-(II/I) potential, increases the rate of the Cu(II/I) redox self-exchange kinetics, and generates unusually intense optical bands.[10]

Our investigation of the hexakis(thioether) complexes of Cu(II) lent further support to these general conclusions. Thus [Cu(18S6)]$^{2+}$ and [Cu(9S3)$_2$]$^{2+}$ undergo quasi-reversible one-electron reduction at +964 and +854 mV vs NHE, respectively[21] (cf. $E°$ Cu(II/I)) = +150 mV in H$_2$O). As in the Co(III/II) case, these high potentials probably result from two sources: (1) the lack of charge on the ligand, and (2) mixing of metal and ligand orbitals of π-symmetry (nephelauxetic effect). Evidence for the latter comes from EPR spectroscopy. In the Cu(II) complexes of the crown thioethers the g_{av} values deviate from g_e by less than those of "harder" donor groups (e.g., g_{av} = 2.07 and 2.22 for [Cu(18S6)]$^{2+}$ and [Cu(OH$_2$)$_6$]$^{2+}$, respectively). This diminution of Δg reflects delocalization of t$_{2g}$ electrons onto the ligands, which quenches the orbital contributions that cause deviations from g_e.

The molecular structures of these complexes also present interesting features. Like the isostructural cobalt(II) analogue, [Cu(18S6)]$^{2+}$ experiences a severe Jahn–Teller distortion (>0.2 Å).[21] Curiously, however, [Cu(9S3)$_2$]$^{2+}$ does not (<0.04 Å).[19] (Note that the lack of distortion cannot be attributed to 9S3; [Co(9S3)$_2$]$^{2+}$ is distorted by 0.12 Å.[19]) In the corresponding Cu(I) complex, [Cu(18S6)]$^+$, the Cu(I) ion has ejected two of the thioether groups to yield a four-coordinate ion.[21] The resulting cation resembles a linear two-coordinate complex to which two further thioether groups have added, with concomitant bending of the original S–Cu–S moiety (∠S1–Cu–S10 = 138°; ∠S4–Cu–S7 = 91°).

Ruthenium. We were interested in extending the above work to the second-row metal ions since the unusual electronic structures found for the first-row metals, if reproduced in second-row elements, might engender exceptional reactivity.

For a variety of reasons our attention first concentrated on ruthenium. First, Ru(II) exhibits considerable affinity for thioether coordination, as shown by the work of Chatt and co-workers.[43] Second, ruthenium complexes generally display well-behaved electrochemistry. Furthermore, as Chatt[43] and Busch[44] had pointed out previously, Ru–thioether complexes might provide catalysts rivaling those of phosphine complexes.

Extension of crown thioether chemistry to the second- and third-row metals raised the question of which ligand to use. The above results showed that the ethyl-linked macrocycles 9S3 and 18S6 compress even first-row metals. They therefore might not accommodate a

second-row metal; if so, the propyl-linked ligand 12S3 might be a better choice. To examine this issue we decided to compare the ethyl- and propyl-linked tridentate thioethers 9S3 and 12S3 in their coordination chemistry with ruthenium.

Structural investigation of [Ru(9S3)$_2$]$^{2+}$ [45-47] and [Ru(12S3)$_2$]$^{2+}$,[47] the first homoleptic thioether complexes of ruthenium, showed that both cations contain octahedral centrosymmetric RuS$_6$ coordination spheres. The change from 9S3 to 12S3 increases M–S bond lengths by 0.03 Å, as found previously for Ni(II)[34] and subsequently for Rh(III).[48] Interestingly, the two complexes show opposite patterns in their S–Ru–S bond angles; in the 9S3 complex nonchelating angles exceed chelating ones, whereas the opposite is true in the 12S3 complex. In a word, 9S3 "perches", whereas 12S3 "engulfs".

Consistent with both the strong Ru–thioether affinity and with the results on first-row metals, both crown thioethers stabilize Ru(II) very strongly. In fact, [Ru-(9S3)$_2$]$^{2+}$ only undergoes oxidation at +1.99 V,[45-47] while [Ru(12S3)$_2$]$^{2+}$ does so at 1.66 V,[47] both vs NHE and in CH$_3$CN (cf. [Ru(amine)$_6$]$^{3+/2+}$, $E_f \simeq 0$ V).

Thus, despite apparently being too small, ethyl-linked crown thioethers nevertheless can coordinate to second- and third-row metal ions. For example, others showed that 9S3 and 18S6 wrap up Pd(II)[49,50] and Pt(II)[49,51] to yield fascinating structures in which two trans S atoms "semicoordinate" in a fashion reminiscent of the axially elongated Co(II) and Cu(II) complexes.

The potential analogy between phosphines and thioethers adds interest not only to the thioether chemistry of Ru, but even more to that of Rh. For example, previous results established the exceptionally high reactivity of Rh(I)–thioether complexes toward oxidative addition.[11,52] They also demonstrated the ability of RhL$_3$X$_3$ complexes (where L = SR$_2$) to catalyze the hydrogenation of olefins.[11,52]

Rhodium. The strong stabilization of lower oxidation states by thioethers, coupled with the geometrical constraints imposed by the crown ligands, opened an exciting possibility for Rh. Thioethers interact strongly with both Rh(III) and Rh(I), the common oxidation states of this element. Electronically, they should preferentially stabilize Rh(I). On the other hand, the square-planar geometry of Rh(I) complexes conflicts with the tendency of 18S6 and (9S3)$_2$ to enforce octahedral coordination. Hence stereochemical considerations would presumably favor Rh(III).

Could the interplay between these cross-cutting effects result in stability for the intermediate Rh(II) complex? Few monomeric Rh(II) complexes are known; they usually decompose rapidly through dispropor-

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tionation or metal–metal bond formation. We reasoned that the crown ligands could inhibit both of these reactions by wrapping up the individual metal ions.

These hopeful arguments were certainly plausible, but in truth they were not very convincing in light of the synthetic challenge posed by the target molecule. Reaction of $RhCl_3$ hydrate with silver triflate followed by addition of 9S3 readily afforded pale yellow crystals of $[Rh(9S3)_2](CF_3SO_3)_3$. X-ray diffraction revealed an octahedral RhS_6 coordination sphere in a structure much like that of the Ru analogue.[53] The electrochemical behavior, however, provided a gratifying surprise.

Cyclic voltammetry of $[Rh(9S3)_2]^{3+}$ showed *two* nearly reversible one-electron waves centered at –65 and –477 mV vs NHE. Coulometry confirmed that each of these reductions consumes a single electron per Rh ion. Moreover, electrochemical reduction of the Rh(III) complex by one electron yields a straw-colored solution that at 77 K gives a rhombic EPR spectrum with $g_1 = 2.085$, $g_2 = 2.042$, and $g_3 = 2.009$. In addition, the first of these transitions displays ^{103}Rh hyperfine (^{103}Rh, $I = 1/2$, 100%) splitting of 12×10^{-4} cm^{-1}.[53] As in the isoelectronic Co(II) complex, this g-value pattern (g_1, $g_2 > 2$; $g_3 \simeq 2$) is consistent with a d_{z^2} ground state, and hence with axial elongation of this Jahn–Teller active low-spin d^7 ion. The data therefore unequivocally pointed to one conclusion: that coordination to this crown thioether somehow stabilizes Rh(II) as a monomeric species.

This result immediately raised a number of questions. First, does $[Rh(9S3)_2]^{2+}$ owe its existence to kinetic or thermodynamic factors? The electrochemical reduction potentials show unequivocally that the Rh(II) complex is thermodynamically stable with respect to disproportionation. In fact, the difference in the Rh(III)/(II) and Rh(II)/(I) potentials implies that the equilibrium constant for the comproportionation reaction

$$Rh(III) + Rh(I) = 2Rh(II)$$
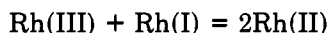
approaches 10^7 (antilog $(\Delta E/59)$). On the other hand, EPR and cyclic voltammetric studies show that $[Rh(9S3)_2]^{2+}$ decays over approximately 30 min, presumably due to slow dimerization. If so, 9S3 probably stabilizes the monomeric Rh(II) complex kinetically by slowing the dimerization. Second, is this stabilization peculiar to 9S3? Preliminary experiments indicate that it is not: as discussed below, 12S3 gives qualitatively similar results. Third, does this stabilization of Rh(II) result from crown effects (e.g., constriction of the RhS_6 coordination sphere, or steric crowding of the metal ion), or, as in the case of the low-spin Co(II) complexes, simply from hexakis(thioether) coordination? Work now under way addresses this question.

Recent results show how crown thioethers can be used to "tune" the electrochemical behavior of the rhodium complexes.[54] Among Rh(III/II/I) complexes of constant coordination number, an increase in ligand ring size should favor Rh(I): longer M–L distances will better match the increased radius of a lower oxidation state ion (at constant coordination number). Consistent with this simple argument, substitution of 9S3 with 12S3 in $[Rh(L)_2]^{3+}$ increases the Rh–S bond lengths by
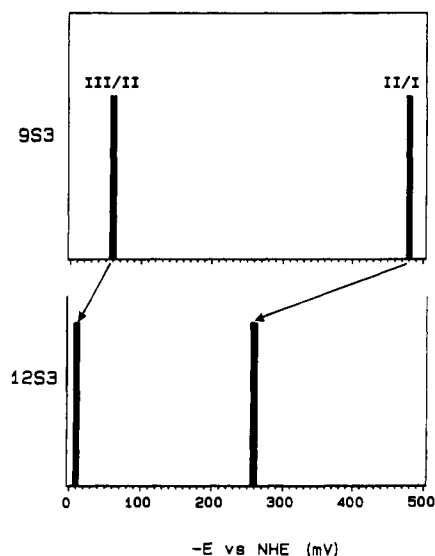
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Figure 3. Reduction potentials in the $[Rh(9S3)_2]^{n+}$ (top) and $[Rh(12S3)_2]^{n+}$ (bottom) ($n = 3, 2, 1$) systems, showing how change in ring size affects the stability of the Rh(II) complex with respect to disproportionation.

approximately 0.03 Å;[54] it also shifts the Rh(III)/(II) and especially the Rh(II/I) potential to more positive values (Figure 3).[54]

These data show that, of the two ligands, 12S3 favors Rh(I) over Rh(II) much more than does 9S3. A change from 9S3 to 12S3 decreases ΔE from 412 to 250 mV—a difference that implies that K_{comp} decreases from 10^7 to $10^{4.2}$. Thus this simple change of ligand increases the propensity of Rh(II) to disproportionate by almost 3 orders of magnitude.

Of course, the relative preference of 9S3 or 12S3 for a given oxidation state depends critically on the geometry of the ion involved. Both Rh(III) complexes are octahedral; we presume (largely from the EPR data) that the Rh(II) complexes are also at least quasi-octahedral. This leaves one other question: what is the geometry of the Rh(I) complex? Rhodium(I) most commonly adopts square-planar coordination; on the other hand, the ability of 9S3 in particular to enforce octahedral coordination must not be underestimated. For example, although low-spin Co(II) complexes are also often square planar, and Ag(I)–thioether complexes are usually tetrahedral, with 9S3 both yield octahedral complexes. Thus octahedral geometry cannot be excluded, although square-planar coordination remains more likely.

Silver. Silver(I) complexes of crown thioethers presented another question of coordination geometry. Most Ag–thioether complexes exhibit idealized tetrahedral geometry. On the other hand, 9S3 clearly tends to enforce three- or sixfold coordination (in its mono and bis complexes, respectively). Which tendency would prevail? Initial synthetic work gave $[Ag(9S3)_2]^+$, for which we expected a tetrahedral structure in which the two 9S3 rings "slipped" with respect to each other. An S atom from one of the ligands could cap an AgS_3 unit formed by the other to give a tetrahedral structure with [3 + 1] coordination. Alternatively, both 9S3 molecules could slip to give [2 + 2] tetrahedral coordination. X-ray structural analysis of this compound exposed our failure to appreciate the remarkable li-

(54) Rawle, S. C.; Yagbasan, R.; Cooper, S. R., in preparation.

gating properties of 9S3. [Ag(9S3)$_2$](triflate) comprises a six-coordinate cation that in broad respects resembles those of the other bis(9S3) complexes.[55] Closer examination reveals some notable differences, however. For example, the average M–S distance exceeds those in other (9S3)$_2$ complexes by approximately 0.2 Å.

The redox chemistry of this complex yielded another surprise. As discussed above, crown thioethers generally stabilize lower oxidation states. In light of this emerging pattern, therefore, the facile *oxidation* of [Ag(9S3)$_2$]$^+$ at +1.31 V vs NHE was, to say the least, unexpected. Oxidation of [Ag(9S3)$_2$]$^+$ in MeOH by Ce(IV) gives a deep blue solution (with g_{iso} = 2.03) that decolorizes on standing.[55]

This oxidation may occur largely either on the ligand or on the metal. The former, however, is inconsistent with the redox chemistry of free 9S3 (which undergoes oxidation only at a much higher potential). If the latter is correct, chemical intuition—which suggests that oxidation of Ag(I) should be difficult—is misleading. Such intuition derives primarily from two-coordinate (and to a lesser extent, four coordinate) complexes of Ag(I). Imposition of six-coordination, however, could increase the effective electron density at the metal; the unusually low Ag(II/I) potential could then arise from the anomalous coordination number of the Ag(I) ion.

Complexes of 9S3 exhibit not only remarkable electronic structures but also noteworthy stability. These two phenomena are, of course, closely related. Reduction (or oxidation) of a particularly stable complex might decrease the metal–ligand affinity but still yield an isolable complex. Hence the crux of this chemistry is, what accounts for the particular stability of 9S3 complexes?

The answer appears to lie in conformational factors. Comparison of 9S3 with 12S3 sets in opposition the size and conformation of the macrocyclic rings. While 9S3 is conformationally well-suited for complexation (since no conformational change is needed), its cavity is apparently too small for some metal ions. On the other hand, while 12S3 can provide a larger cavity, its exodentate conformation in the free form[56] necessitates substantial rearrangement to permit ligation as a tridentate ligand (Figure 4).

This large conformational change diminishes the stability of 12S3 complexes with respect to those of 9S3. For example, [M(12S3)$_2$]$^{n+}$ complexes (M = Fe(II), Co(II), Ni(II)) decompose instantly on contact with water; those of 9S3 can be recrystallized from this solvent.[57] The contrast underscores how profoundly the conformational preferences of ligands can influence their coordination chemistry.

It also points up the clear need for stability constant determinations, the importance of which transcends crown thioether chemistry. Owing to their weak solvation and their lack of protic equilibria, crown thio-
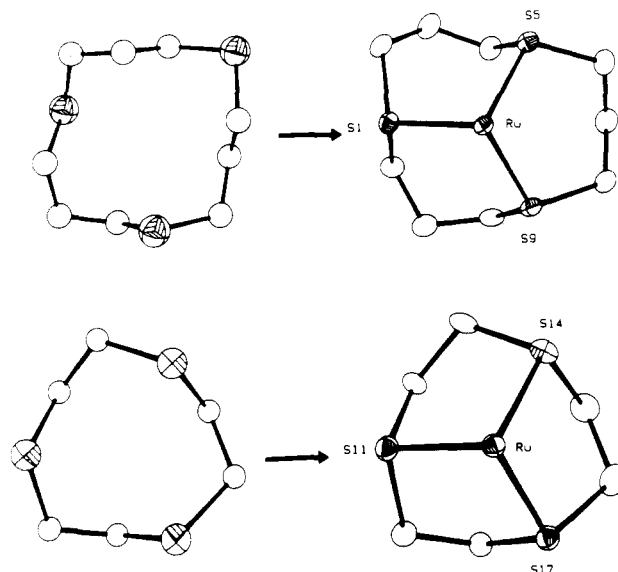

Figure 4. Typical ligand conformational changes on formation of [M(12S3)$_2$]$^{2+}$ (top) and [M(9S3)$_2$]$^{2+}$ (bottom). (Here M = Ru; for the structure of free 9S3, see ref 29.) Note the minimal perturbation of 9S3 compared to that suffered by 12S3, consistent with the much greater stability of 9S3 complexes.

ethers are an ideal system in which to test the growing perception that conformational enthalpy plays a pivotal role in complexation. Ultimately, understanding *why* some crown thioethers bind so much better than others will provide information vital to rational design of future ligands of all types.

Prospects for Future Work

To date most research on crown thioethers has focussed on exploratory synthetic work to determine the scope of their coordination chemistry. In the future the emphasis will shift to reactivity. Complexes such as [Rh(9S3)$_2$]$^{2+}$ and [Rh(9S3)$_2$]$^+$ invite speculation regarding their reaction chemistry. While homoleptic hexakis(thioether) complexes are ideal for study of how thioethers affect electronic structure, the absence of vacant coordination sites may suppress their reactivity. Consequently, future attention will be directed toward, for example, 15S5, which offers access to a coordination site on the metal.

This is not to say that the exploratory synthetic phase of crown thioether chemistry is yet complete. For example, early transition metals pose a remaining synthetic challenge, as do the lanthanides and actinides. The strong tendency of thioethers to stabilize low oxidation states suggests that crown thioethers may yield Ln(II) complexes. In a similar vein, the crown thioether chemistry of, e.g., uranium can now be only the subject of wistful speculation.

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