

Immobilized Boron-Centered Heteroscorpionates: Heterocycle Metathesis and Coordination Chemistry

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The preparation of a resin-supported boron-scorpionate ligand and its nickel(II) coordination complexes are reported. The supported ligand is prepared as its potassium salt, making it a general reagent suitable for chelation of any transition metal ion. Resin-immobilized benzotriazole (Bead-btz) reacted cleanly with KTp^* (Tp^* = hydrotris(3,5-dimethylpyrazolyl)borate) by heterocycle metathesis in warm dimethylformamide (DMF) to yield bead- Tp^*K , {resin-btz(H)B(pz^{*})₂}K. Significantly, bead- Tp^*K readily bound nickel(II) from simple salts with minimal leaching of the nickel ion. Bead- Tp^*NiNO_3 reacts further with cysteine thiolate (ethyl ester), imparting the deep green color to the beads characteristic of a $\text{Tp}^*\text{NiCysEt}$ coordination sphere. Bead- $\text{Tp}^*\text{NiCysEt}$ exhibited an oxygen sensitivity similar to $\text{Tp}^*\text{NiCysEt}$ in solution (*Inorg. Chem.* **1999**, p 5690) and also independently verified for a selenocystamine analogue, $\text{Tp}^*\text{NiSeCysAm}$. Addition of fresh cysteine thiolate ethyl ester to oxidized bead- $\text{Tp}^*\text{NiCysEt}$ reproduced the original green color. Heterocycle metathesis was also used to prepare KTp' as a white solid. Reaction with nickel(II) gave $(\text{Tp}')_2\text{Ni}$, separable into two different isomers. The air-sensitive molybdenum(0) complex, $[\text{PPh}_4][\text{Tp}'\text{Mo}(\text{CO})_3]$, was also prepared and the C_s complex symmetry demonstrated by infrared and ¹³C NMR spectroscopies. Immobilized $\text{TpmMo}(\text{CO})_3$ was prepared from the previously reported resin-supported tris(pyrazolyl)methane. In contrast to its weak coordination of nickel(II) (*Inorg. Chem.* **2009**, p 3535), bead- Tpm proved a strong chelate toward this second row metal. The supported scorpionates described here should find use in studies of selective metal-protein binding, metalloprotein modeling, and heterogeneous catalysis, and render such scorpionate applications amenable to combinatorial methods.

Introduction

Scorpionate ligands, first developed by Trofimenko in the late 1960s, are well established and highly versatile ligands in inorganic chemistry.^{1,2} Their metal-complex applications range from enzyme mimics³ to catalysts in a variety of reactions.⁴ The benefits of these ligands would be expanded tremendously by immobilization onto a solid support, allowing them to be incorporated into automated synthesis protocols and combinatorial methods. One reason these ligands have

not found more widespread use in heterogeneous methods is the synthetic challenge presented when trying to covalently attach a traditional boron-based scorpionate to a solid support. We report here a facile method of anchoring a boron-centered heteroscorpionate to a solid support by way of a heterocycle metathesis process and subsequent binding of nickel(II), unprecedented for any first row transition metal ion. This resin-supported nickel(II) scorpionate offers a promising step in our efforts to develop heterogeneous nickel-centers for selective amino acid binding.⁵

Scorpionate chelates commonly possess the architecture of two or more heterocyclic rings (typically pyrazole or similar nitrogen donors) attached to a central “hinge” atom that is most often boron or carbon. In a traditional scorpionate, the boron or carbon hinge has three such heterocycles attached, and the fourth atom is either hydrogen or a carbon fragment like phenyl or alkyl groups (Figure 1). This assembly presents two logical points for scorpionate covalent attachment: through the fourth substituent on boron or carbon

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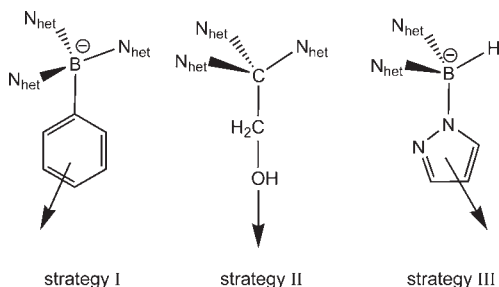


Figure 1. Three point-of-attachment strategies for scorpionates. Arrows refer to points at which functional groups can be added to provide synthetic handles for attachment to heterogeneous supports. N_{het} refers to N-donor heterocycles, often pyrazoles, triazoles, or imidazoles.

(Figure 1, Strategies I and II) or through one of the heterocyclic rings that also serves as a coordinating ligand for metals (Figure 1, Strategy III). Metzler-Nolte et al.⁶ made bioconjugates by attaching the simplest scorpionate, Tp,⁷ to an immobilized oligopeptide chain through a carboxylic acid-phenyl substituent on boron (HOC(O)-Ph-B-) (Strategy I), a first for boron-scorpionates. In their work, the ligand was coordinated to substitutionally robust platinum(IV), rhenium(I), and ruthenium(II) in the early stages of the synthesis as HOC(O)PhTpPt(CH₃)₃, HOC(O)PhTp^{M_c}Re(CO)₃, and HOC(O)PhTp^{M_c}RuCp. This was necessary to improve stability of the complexes during subsequent steps leading to the bioconjugate targets. Jäkle and co-workers reported a method for converting a trimethylsilyl-functional group, attached to the phenyl rings of linear polystyrene (PS), to NaPhTp, which was subsequently coordinated to a CpRu⁺ moiety.⁸ Although this method offers the advantage of a transition metal-free scorpionate, the flexibility of the PS chain would give bis(scorpionate) sandwich products with small first-row divalent metals ions. Alternatively, Reger et al.⁹ demonstrated that Tpm⁷ could be functionalized to give an alcohol at the hinge carbon, allowing Tpm to be coupled to alkyl halides via Williamson ether synthesis (Strategy II). We demonstrated recently that this method could be employed to attach Tpm to PS synthesis beads, which subsequently bound nickel(II) ions from solution.¹⁰

Unfortunately, none of these routes are suitable for preparing functional heterogeneous analogues of the Tp^{*}Ni⁺ Lewis acid center that demonstrates selective cysteine coordination.^{5,11} The process of coupling preformed half-sandwich scorpionates, like Tp^RNiX, to solid supports would suffer from formation of non-functional coordinatively saturated bis(ligand) products, (Tp^R)₂Ni, or interference of labile nickel(II) ions with the coupling reactions. While Strategy II is a straightforward, high-yield route to a supported scorpionate that readily bound

nickel(II) ions, this particular supported-Tpm was prone to leaching of nickel ions¹² under the conditions required for amino acid selectivity studies.

The limitations presented to our own work by Strategy I and II prompted investigation of a new strategy (III of Figure 1). It became clear that strong nickel(II) binding required the negative charge of a tetrasubstituted boron atom, in the form of supported Tp-type ligand, as opposed to the neutral carbon hinge of the supported Tpm. The preparation of a supported monoanionic scorpionate as its potassium salt would give a ligand suitable for subsequent nickel(II) coordination in the manner that is commonly used for KTp^R ligands and transition metal ions in homogeneous methods.

A feature of boron-scorpionates with important consequences here is the relative lability of B–N bonds in these systems. Bp⁷ and Tp derivatives will exchange attached pyrazole rings for free pyrazole rings in molten pyrazole reaction media. When the structure of the molten pyrazole is different from the original ones in Bp and Tp, this tends to give mixed products.¹³ This B–N weakness limits the usefulness of scorpionates in certain catalytic applications.¹⁴ When the pyrazole rings on Tp derivatives are unsymmetrical, they undergo 1,2-sigmatropic (“borotropic”) shifts,^{15–17} which leads to ligand isomerization in metal complexes of unsymmetrical hydrotris(3,5-disubstitutedpyrazolyl)borates.¹⁸ Vahrenkamp et al.¹⁹ exploited this feature of the B–N bond to replace one of the pyrazole rings of Tp with a thioimidazole (Tim), giving HB(pz)₂(Tim)[−]. The reaction was carried out in the molten state and led to mixed products with low yields of the target compound.

We reasoned that Vahrenkamp et al.’s method might be used to generate a supported boron-scorpionate. Benzotriazole (btz) is a common nitrogen-containing heterocycle that has been attached to a variety of polystyrene resins,^{20,21} making it the likely candidate for Strategy III. Homoscorpionates based on 1,2,4-triazoles²² and 1,2,3-benzotriazoles²³

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and their transition metal complexes are known, and traditionally synthesized via standard high temperature reactions with sodium or potassium borohydride in excess molten heterocycle,²⁴ as was first established by Trofimenko more than 40 years ago.²⁵ For the purpose of Strategy III, the ability of benzotriazole to mimic the behavior of pyrazole when bound to boron was key. Here we demonstrate that benzotriazole, when immobilized on Novasyn TG amino resin HL, will replace one of the 3,5-dimethylpyrazole rings from Tp* via a methathesis process, resulting in a fully functional resin-supported heteroscorpionate ligand as its potassium salt, bead-Tp*K. Once formed, this heteroscorpionate shows excellent coordinating ability for nickel(II), and allows for functional binding activity of this immobilized nickel toward cysteine in solution.

Our interest in supported scorpionates focuses on the way that scorpionate-nickel complexes selectively bind with the amino acid cysteine, when it is at the N-terminus of an oligopeptide, in the presence of other amino acids and even in the presence of cysteine in other positions in the oligopeptide.⁵ This could form the basis of a selective sensor for cysteine in situ. Another feature of Tp*Ni-cysteine coordination is oxygen sensitivity which leads to cysteine-sulfenates,¹¹ a quality here shown for supported-Tp*NiCys complexes and for a new Tp*Ni(seleno-cysteine) analogue. In addition, the current results demonstrate general coordination chemistry of the free Tp' ligand toward nickel(II) and molybdenum(0) in homogeneous applications. This is extended to the characterization of supported-TpM Mo(CO)₃ demonstrating the robust coordination of this heterogeneous ligand system toward this more inert second row metal.

Experimental Methods

Novasyn TG amine resin HL was obtained from Nova-Biochem and had a functional group density of 0.46 mmol/g of bead. The presence of PEG chain linkers between the core of the PS bead and functional groups on these resins allows for characterization of the solid supported products by standard ¹³C and ¹¹B NMR methods. KTP* was prepared via literature methods,²⁵ and its purity confirmed by thin layer chromatography, ¹H, ¹³C, and ¹¹B NMR. DMF was stored over 4 Å molecular sieve prior to use. [PPh₄][Tp*Mo(CO)₃] was prepared following the procedure described for the tetraethylammonium salt.²⁶ Unlike the latter salt, this PPh₄⁺ salt is insoluble in methanol. In protio-DMF this compound gave the following ¹³C {¹H} NMR features: 15.4, 12.7 ppm (pyrazole-CH₃); 105.3 ppm (4-C-pz ring); 118.9, 131.2, 135.6, 136.1 (all doublets with various J_{P-C}, PPh₄⁺); 143.0, 150.6 ppm (3,5-C-pz ring); 231.1 ppm (C=O). IR (KBr) 2520 cm⁻¹ ν(B-H), str. 1884, 1754, 1737 cm⁻¹ ν(C=O). The preparation of Tpm supported on polystyrene synthesis beads via a polyethyleneglycol tether through an ether linkage (bead-OCH₂Tpm) has been previously reported.¹⁰

Boron-free NMR tubes were purchased from Norell. NMR were recorded on a JEOL ECX 300 MHz spectrometer. Infrared measurements on samples as KBr pellets or using a diamond anvil ATR attachment were recorded using a Thermo

Nicolet FT IR 100 spectrometer. Electronic spectra were recorded using Varian Cary 50 instruments with 1 cm quartz cells, for solution phase measurements, and a video Barreline diffuse reflection probe (Harrick Scientific) interfaced to the spectrometer via a fiber optic coupler for solid phase samples. Solid samples for UV-visible spectroscopy were sandwiched between microscope slides. Magnesium oxide powder suspended in like manner was used for a background blank for bulk powders.

Synthesis of KTP' (Potassium Hydrobis(3,5-dimethylpyrazolyl)benzotriazo-1-lylborate). Solid KTP* (1.00 g, 2.99 mmol) and solid benzotriazole (0.389 g, 3.27 mmol) were added to a Schlenk tube and placed under a dry nitrogen atmosphere. To this mixture was added 10 mL of degassed DMF via cannula needle, effecting complete dissolution of all solids. This solution was heated at 70 °C for 2 h. Progress in the reaction was readily monitored using ¹¹B NMR of the mixture gradient shimmed on the protio-DMF signal. KTP* starting material shows a doublet (J_{BH} = 90 Hz) centered at -7.6 ppm. Over time this resonance decreased while the corresponding new doublet (J_{BH} = 85 Hz) at -4.6 ppm emerged and is indicative of KTP'. The presence of newly formed free 3,5-dimethylpyrazole was also evident in thin layer chromatography (TLC) analyses of the reaction mixture (silica gel plates, 70:30 ethylacetate:hexanes). The crude solid was isolated by stripping the DMF from the mixture using a liquid nitrogen/vacuum trap. This white residue was washed three times on a sintered glass frit with diethyl ether (removing pyrazole product and unreacted benzotriazole) and dried under a stream of air. Yield 0.77 g (71%) NMR (DMSO d₆) ¹H (δ_{DMSO} = 2.47 ppm): two singlets at 1.94, 1.99 ppm (12 H, pz ring-CH₃); singlet at 5.60 ppm (2 H, pz ring 4-H); multiplet centered at 7.11 (3 H, btz ring H's); multiplet centered at 7.81 ppm (1 H, btz ring H closest to boron-N). ¹¹B NMR: -4.6 ppm (br. singlet). ¹³C NMR (δ_{DMSO} = 40.0 ppm): 12.7, 14.3 ppm (pz ring-CH₃); 104.6 ppm (pz ring 4-C); 114.2, 118.0 ppm (4-C, 7-C btz ring); 122.2, 124.8 ppm (5-C, 6-C btz ring); 138.1, 145.9 ppm (8-C, 9-C btz ring); 143.1, 145.7 ppm (3-C, 5-C pz ring). This ligand was used without further purification.

Synthesis of (Tp')₂Ni (cis and trans Isomers). The (Tp')₂Ni complex was synthesized by adding methanol (25 mL) to a mixture of solid KTP' (108 mg, 0.30 mmol) and solid NiSO₄·6H₂O (42 mg, 0.16 mmol). Dissolution of the solids produced a gradual color change from the green of nickel sulfate to the pale lavender of the product mixture. As the product formed, it precipitated from the reaction mixture as a lavender solid. This slurry was stirred for 30 min to ensure complete formation of the (Tp')₂Ni. The precipitate was then filtered and washed with water, methanol, and diethyl ether then dried with a nitrogen stream. Yield 64 mg (61%). Anal. Expt (Theory): C, 54.91 (54.98); H, 5.55 (5.48); N, 28.04 (28.05). TLC (chloroform, silica gel) revealed two compounds present in the analytically pure sample. These were separated by column chromatography (chloroform mobile phase, 3 cm × 8 cm column made from 70 to 230 mesh 60 Å silica gel stationary phase). The two isomers eluted at different rates as the sample moved through the column, producing two lavender bands that were collected separately. After the first band (less polar isomer) had eluted from the column, the mobile phase was switched to 10:90 methanol/chloroform, leading to the complete elution of the second (more polar) isomer. Each product was isolated as a pale lavender solid following evaporation of the elution solvent. Yield: 22 mg of the less polar isomer (35% of total) and 41 mg of the more polar isomer (65%). Each of the isomers is distinguished by unique ν(B-H) stretch in the IR (Figure 11) as well as a specific ¹¹B NMR chemical shift, reflecting the different chemical environments around boron in each isomer. More Polar Isomer: IR: ν(B-H) = 2509 cm⁻¹. ¹¹B NMR (CDCl₃): -36 ppm. Less Polar Isomer: IR: ν(B-H) = 2501 cm⁻¹. ¹¹B NMR (CDCl₃): -38 ppm.

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Synthesis of [PPh₄][Tp*Mo(CO)₃]. The method described by the Enemark group²⁷ for formation of TpmMo(CO)₃ was modified for this reaction. Thus, solid Mo(CO)₆ (75 mg, 0.28 mmol) and solid KTp' (102 mg, 0.28 mmol) were placed under a nitrogen atmosphere in a 25 mL Schlenk flask. Degassed DMF was added to this solid mixture via cannula, and the reaction mixture was stirred at 100 °C for 60 min while being vented to an oil bubbler. Gas evolution was readily apparent within the first 15 min of reaction time, and the solution developed a deep red-orange color. The mixture was heated until this gas evolution ceased, and the mixture was cooled under nitrogen. To this red-orange solution was added via cannula an air-free aqueous solution of PPh₄Cl (1 g in 2 mL H₂O). After stirring for several minutes the product began to precipitate as a bright orange solid. The addition of 2 mL more of degassed water to this mixture induced considerably more solid precipitation. The solid was then filtered under nitrogen, washed three times with water, and dried on the Schlenk frit in vacuo through a liquid nitrogen trap. The product is extremely soluble in THF, DMF and methanol, in contrast to its closely related analogue [PPh₄][Tp*Mo(CO)₃] that may be readily washed with methanol. Yield 145 mg (62%). Anal. Expt (Theory, for [PPh₄][Tp*Mo(CO)₃]-0.3DMF): C, 61.13 (61.20); H 4.86 (4.82); N 12.16 (11.87). All spectroscopic samples were subsequently prepared in an inert atmosphere glovebox. Infrared (KBr): $\nu(\text{B-H})$ 2511 cm⁻¹, $\nu(\text{C=O})$ 1888, 1764, 1736 cm⁻¹. NMR (acetone-d₆) ¹³C (acetone -CD₃ δ = 29.1 ppm): 230.7 ppm (C=O *trans* to btz ring), 229.8 ppm (C=O *trans* to pz* rings), 151.2 (-C-N btz ring), 137.6 (-C-N btz ring), 125.9, 123.1, 117.8, 111.1 ppm (-C-C-C btz ring), 105.1 ppm (4-C pz* ring), 14.8, 12.1 ppm (-CH₃ of pz*), 135.5 ppm (d, $J_{\text{P-C}}$ = 2.8 Hz, C of Ph *para* to ³¹P), 134.8 ppm (d, $J_{\text{P-C}}$ = 10.4 Hz, C of Ph *ortho* to ³¹P), 130.6 ppm (d, $J_{\text{P-C}}$ = 13.0 Hz, C of Ph *meta* to ³¹P), 118.1 ppm (d, $J_{\text{P-C}}$ = 89.7 Hz, C-P); ¹¹B: -9.8 ppm (d, $J_{\text{B-H}}$ = 78 Hz). ¹H (acetone residual H at 2.03 ppm) 2.38, 2.49 ppm (6H, s, -CH₃), 5.67 ppm (2H, s, 4-H, pz* ring), 7.17 ppm (1H btz ring, m) 7.35 ppm (1H btz ring, m), 7.72-7.98 ppm (22H, complex mult., Ph and btz).

Preparation of Bead-TpmMo(CO)₃. Solid Mo(CO)₆ (Sigma Aldrich, 122 mg, 0.46 mmol) and bead-Tpm (303 mg, 0.078 mmol based on a functional group density of 0.26 mmol/g of dry beads) were placed in a Schlenk tube under a dry nitrogen atmosphere. Nitrogen degassed DMF (5 mL) was added to this mixture of solids via cannula, and the entire mixture was allowed to sit for 3 h to ensure swelling of the bead matrix with the reaction mixture. This mixture of beads and solution was then heated to 60 °C and gently stirred for 14 h. During the first several hours of heating evolution of gas (presumably CO) was observed and the beads changed color noticeably from their original pale tan color to a deep orange-brown. At the end of this heating process the bead-mixture was cooled under nitrogen and transferred under nitrogen to a fritted peptide vessel where they were washed with DMF six times (~ 4 mL each, added via cannula needle and always under nitrogen) to remove remaining Mo(CO)₆. This was then dried in vacuo through a liquid N₂ trap. Residual DMF did not obscure the transitions assigned to C=O in either the IR or the ¹³C NMR spectra. IR (ATR) 1905, 1780 cm⁻¹ $\nu(\text{C=O})$. ¹³C NMR prepared in an inert atmosphere glovebox (acetone-d₆) 228.9 ppm (C=O), 151.8 ppm (-NH-C(O)- linker), 145.1 ppm (3-C, pz ring), 133.5 ppm (3-C, pz ring), 127.9 ppm (broad, PS matrix), 70 ppm (very intense, -CH₂-PEG chain), 106.7 ppm (4-C, pz ring).

Coupling of Heterocycles to PS-Synthesis Beads. Novasyn TG amino resin HL (bead-NH₂) was used for this work. Benzotriazole-5-carboxylic acid was coupled to the resin by standard DCC-mediated coupling, as adapted by Katritzky et al.^{20b} A 5-fold molar excess of light brown HOC(O)-btz reacted with

bead-NH₂ with gentle stirring in DMF in the presence of DCC at 40 °C over 24 h.²⁸ The beads were washed subsequently with DMF 5 \times , THF 4 \times , THF:H₂O (50/50) 4 \times , H₂O 5 \times , THF:H₂O (50/50) 4 \times , MeOH 4 \times , and CH₂Cl₂ 4 \times (~ 4 mL each time). The beads were then dried under vacuum. FTIR (ATR) 1652 cm⁻¹, amide $\nu(\text{C=O})$. These bead-btz have a light brown color (similar to the light brown of the free carboxylic acid) and gave a negative Kaiser test when tested for the presence of free -NH₂ groups. Coupling was also confirmed by ¹³C NMR (DMSO-d₆). Spectrum and peak assignments are given in Supporting Information, Figure S1.

Formation of Bead-Tp/K Using Supported Benzotriazole-5-carboxylic Acid. A 5-fold molar excess of KTp* (285 mg) and 306 mg of bead-btz were placed together under a dry nitrogen atmosphere into a septum-fitted Schlenk tube. Five milliliters of degassed DMF was added via cannula. This mixture was allowed to stand for 1 h to swell the beads, and then the mixture was gently stirred with heating (70 °C) for 24 h. The mixture was cooled under nitrogen, and the bead-product was subsequently worked up in air. These were washed with DMF 1 \times , H₂O 3 \times , H₂O:DMF (50/50) 3 \times , DMF 3 \times , DMF:CH₂Cl₂ (50/50) 3 \times , and CH₂Cl₂ 3 \times (4 mL each) The beads were then dried under vacuum. ¹³C NMR (DMSO-d₆): structures and assignments are included in Figures 3 and 4. ¹¹B NMR (DMSO-d₆): δ = -6 ppm.

Addition of Nickel(II) to Bead-Tp/K. A 200 mg sample of bead-Tp/K was initially swollen in methanol for 20 min while suspended in a fritted peptide vessel. The methanol was drained from the swollen beads, and a green solution of Ni(NO₃)₂·6H₂O in methanol (0.1 M) was added to the beads. This mixture was gently rotated overnight, after which the remaining nickel nitrate solution (noticeably reduced in color) was drained from the beads. These treated beads were washed thoroughly using the following protocol: MeOH 3 \times , H₂O 2 \times , MeOH 3 \times , CH₂Cl₂ (4 mL each), then dried under vacuum and a nitrogen stream. The washed beads had a discernible blue-green color (Figure 7), indicating bound nickel, and distinct from the original light amber color of the un-nickelated beads. An electronic spectrum was recorded for these colored beads using diffuse reflectance and with the un-nickelated beads used for background subtraction.

Cysteine Binding by Bead-Tp/NiNO₃. This reaction is patterned after the method previously described for the formation of Tp*NiCysEt;¹¹ all steps were performed with solvents and reagents thoroughly degassed with nitrogen. CysEt represents *l*-cysteine ethyl ester purchased from Sigma-Aldrich as its amine hydrochloride salt. A 40 mg sample of blue-green bead-Tp/NiNO₃ was swollen in methanol on a sintered peptide vessel that was fitted top and bottom with septa. This methanol was drained from the beads using a positive nitrogen stream. A solution of HCysEt·HCl (150 mg, 0.81 mmol) in 10 mL of methanol was prepared in a 25 mL septum fitted Schlenk tube. To this solution was added 0.25 mL of triethylamine (1.8 mmol) via syringe, and this solution was stirred 5 min. A 2.5 mL aliquot of this CysEt solution was then added to the bead-Tp/NiNO₃ causing the beads to become deep green in color, visibly reminiscent of the emerald green color of Tp^RNiCysEt reported previously (Figure 7).¹¹ The mixture in the peptide vessel was gently rotated for 30 min while maintaining an air-free environment. Following this period, the excess supernatant was pushed off the beads using a positive nitrogen stream. The beads were repeatedly washed through the septum fittings, always pushing the solvent off with positive nitrogen pressure. An electronic spectrum was recorded for these colored beads using diffuse

(28) We note problems encountered when the alternative HOBt/DIC peptide coupling method was employed. While this method did produce Btz coupled to the PS-resin (confirmed by ¹³C NMR), subsequent reactions with KTp* failed to yield bead-Tp/K. The N-H group of the imidazole ring is known to react with peptide coupling reagents: Benoiton, N. L. *Chemistry of Peptide Synthesis*; Taylor and Francis Group: Boca Raton, FL, 2006; pp 169-170.

(27) Dhawan, I. K.; Bruck, M. A.; Schilling, B.; Grittini, C.; Enemark, J. H. *Inorg. Chem.* **1995**, *34*, 3801-3808.

reflectance and with the un-nickelated bead-Tp'K used for background subtraction. Exposure of these green Tp'NiCysEt beads to atmospheric oxygen bleached their green color over the span of 1 h, and the electronic spectrum of the beads was again recorded using DR. Reintroduction of fresh methanolic CysEt to the beads again placed under nitrogen caused the reemergence of the same green color and DR electronic spectrum.

Synthesis of Tp*NiSeCysAm. Solid Tp*NiNO₃ (132 mg, 0.32 mmol)¹¹ was placed under a nitrogen atmosphere and dissolved in 30 mL of degassed methanol, giving a light blue solution. The selenate used in this reaction was prepared *in situ* by reducing the diselenide amine hydrochloride with sodium borohydride. The yellow diselenide, as its amine hydrochloride (selenocystamine dihydrochloride, from ICN Biomedicals; 50 mg, 0.16 mmol of Se–Se), was placed under a nitrogen atmosphere and dissolved in 20 mL of degassed methanol. Excess solid sodium borohydride (20 mg) was added to this solution, causing effervescence and a disappearance of the yellow color, indicating reduction of the diselenide to the corresponding selenate.²⁹ This colorless solution was added via cannula to the blue Tp*NiNO₃ solution, causing an immediate color change to deep lime green. This mixture was stirred for an additional 15 min, during which the product began to precipitate as a deep lime green solid. Additional precipitate formed when the mixture was cooled on an ice bath. The product was filtered under nitrogen on a sintered glass Schlenk frit, washed two times with cold methanol, and then dried under a positive nitrogen stream. Yield 106 mg (70%). Anal. Expt (theory): C, 42.91 (42.63); H, 5.95 (5.89); N, 20.68 (20.47). IR (KBr): 3348, 3290 cm⁻¹, sharp ν (N–H) primary amine; 3123 cm⁻¹ ν (C–H) pz* ring; 2950, 2923, 2862 cm⁻¹, aliphatic ν (C–H); 2510 cm⁻¹, ν (B–H).

Reversible Alkylation of Tp*NiCysEt. Solid Tp*NiCysEt (10.7 mg, 0.021 mmol)¹¹ in a septum-fitted Schlenk tube was dissolved in a minimum of nitrogen-degassed acetonitrile (ca. 4.5 mL). A second solution of methyl *p*-toluenesulfonate (Aldrich, 15.8 mg, 0.084 mmol) in 1 mL of acetonitrile was prepared in like manner. The colorless methyl *p*-toluenesulfonate solution was added to the Tp*NiCysEt solution using a gastight syringe, causing an immediate change from deep green to pale blue. These changes are summarized in Figure 10. The reversibility of this process was demonstrated by the addition of excess degassed triethylamine (22 mg), causing the immediate re-emergence of the deep green color and characteristic sulfur-to-nickel charge transfer band.

Reaction of Bead-Tp'K with Mo(CO)₆. Solid bead-Tp'K (62 mg, 0.025 mmol available Tp'K) was placed under a dry nitrogen atmosphere in a septum fitted Schlenk tube. The beads were swollen overnight in 5 mL of degassed DMF. This DMF was decanted from the beads using a syringe. A mixture of Mo(CO)₆ (35 mg, 0.13 mmol) in 5 mL of DMF was prepared in a second air-free Schlenk tube. This mixture was added to the swollen beads via cannula, and the bead-Tp'K/Mo(CO)₆ mixture was heated at 60 °C for 15 min. Over this period the beads darkened considerably (to a deep red color). The reaction mixture was cooled under nitrogen, and the dark brown supernatant was removed. The dark brown-red product beads were washed several times with 5 mL portions of degassed DMF. An infrared spectrum of the beads was recorded using ATR (Supporting Information, Figure S4).

Results and Discussion

The goals of this work were to develop a facile route to a resin-supported boron-scorpionate, demonstrate the coordinating ability of this scorpionate toward nickel(II) ions, and then demonstrate functional binding activity of these immobilized

nickel ions for cysteine. It was also important that the coordination behavior of new heteroscorpionates and polymer supported variants be described for other metals, providing a broader impact for the inorganic discipline. For this reason, new homo- and heterogeneous scorpionate molybdenum(0) tricarbonyl complexes were also prepared; piano-stool group 6 and 7 metal Tp^RM(CO)₃ complexes are firmly established precedents affording useful comparative spectroscopic signatures.³⁰ The present work represents a significant milestone in coordination chemistry because the few reported covalently immobilized boron-centered scorpionate complexes were limited to substitutionally inert second- (Mo, Ru)^{6a,31} and third-row (Re, Pt)⁶ metal ions. The success here for Tp' with nickel(II) establishes a workable strategy for the supported-scorpionate chemistry of the majority of first-row transition metals. Resin-supported metal ion chemistry, ranging from small molecule sensors, to bioinorganic modeling, and heterogeneous catalysis, will now benefit from the versatility of the scorpionate class of ligands.

Preparation of a Supported Boron-Scorpionate. By covalently immobilizing a ligand on resin, advantages like ease of product workup and isolation are introduced, and leaching of metal complexes from the support, which can occur when the ligands are only adsorbed onto surfaces, is avoided.³² With PEG spacers between the ligand and the core of the resin, routine ¹³C and ¹¹B NMR spectroscopy can be used to augment ATR-IR and DR-UV-vis spectroscopy techniques. The primary challenge in preparing supported boron-centered scorpionates is controlling the reactivity introduced by the Lewis acidity of boron and polar boron–nitrogen bonds.

There are two ways that a boron-centered heteroscorpionate can be covalently linked to a resin: through a substituent on one of the boron-coordinated heterocycles, or through a fourth substituent, such as a benzene ring, that bears a synthetic handle in one location and is connected to the boron through a C–B bond. The latter approach was elegantly demonstrated by the group of Metzler-Nolte.⁶ They immobilized fully prepared metal scorpionate complexes, HOC(O)PhTp^RML_n (M = Pt, Re, Ru; L_n = 3CH₃, 3CO, and Cp) through a peptide link, using the carboxylic acid substituent on the metal-complexes and an amine-functionalized synthesis bead. The approach of Jäkle and co-workers took this further,⁸ but the flexibility of their linear PS support would not prevent coordinatively saturated bis(scorpionate) complexes from forming with first row metal ions. The desirability of a transition-metal-free supported-scorpionate that would only allow unsaturated mono(scorpionate) metal complexes prompted us to instead construct a supported boron-scorpionate as its potassium salt on cross-linked-PS-resin synthesis beads, and here the polarity and Lewis

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acid/base properties of the boron–nitrogen bond proved an asset.

The preparation of bead-Tp'K began by first demonstrating that one of the 3,5-dimethylpyrazole rings of Tp**K* could exchange with a free N-heterocycle, benzotriazole, in solution. Exchange of N-heterocycles at boron has been documented as an isomeric complication in scorpionates possessing unsymmetrical 3,5-disubstituted pyrazoles.¹⁸ Vahrenkamp's group utilized heterocycle exchange at KTp under neat molten conditions to prepare the boron-centered heteroscorpionate {HB(pz)₂(tim)}*K* (pz = pyrazole, tim = 2-thioimidazole).¹⁹ Mixed products were obtained, and yields were low. In the present work, the metathesis reaction of KTp* with 1 equiv of btz was monitored by ¹¹B NMR in solution and shown to cleanly produce KTp'. The resonance assignable to the new btz-containing heteroscorpionate grew in 3–4 ppm downfield of the original homoscorpionate resonance. This reaction was originally demonstrated over several days in anisole at 170 °C, under the assumption that elevated temperatures were required, similar to conditions necessary for molten-pyrazole preparations of other scorpionates.^{19,33} Switching the solvent to DMF noticeably improved the solubility of all reagents and allowed Tp'K to be prepared at lower temperatures (70 °C) and in a matter of hours (Figure 2).

The boron atom of the new heteroscorpionate, Tp', binds to the N-1 nitrogen of benzotriazole as opposed to the less sterically encumbered N-2 ring position as demonstrated by the lack of symmetry in the ¹³C NMR spectrum of the ligand. This has been noted as a general feature of benzotriazole homoscorpionates and attributed to the retention of aromaticity when bound through the N-1 position.³⁴

This heterocycle metathesis was next applied to resin-supported benzotriazole, resulting in the preparation of covalently supported KTp'. Resin-supported benzotriazole was first prepared by coupling 1,2,3-benzotriazole-5-carboxylic acid to the amino group of Novasyn TG amine HL resin using DCC giving amber-colored bead-btz, as has been previously reported.²¹ When the reaction was done using DIPCDI/HOBt coupling conditions, as reported by Paio et al.,²¹ subsequent reaction to make supported bead-Tp'K was unsuccessful. Importantly, we made no effort to protect the N–H group of benzotriazole, so competing reaction of btz with the coupling agents may have occurred.²⁸ Our samples of Novasyn-resin-btz reproduced the infrared (ATR) spectrum,²¹ and for the first time we report its characterization by ¹³C NMR (Supporting Information, Figure S1). The reaction of bead-btz with a 5-fold molar excess (typically employed for resin work) of KTp* in DMF yielded the intact supported heteroscorpionate, KTp'. Best results were observed when bead-btz was swollen in a DMF solution of KTp* for several hours before heating the mixture for 24 h at 70 °C. The proposed structure of bead-KTp' is shown in Figure 3. Its ¹³C NMR spectrum, including peak assignments, is shown in Figure 4.

Resin-Supported Scorpionate Complexes of Nickel(II). Bead-Tp'NiX systems show none of the tendency toward

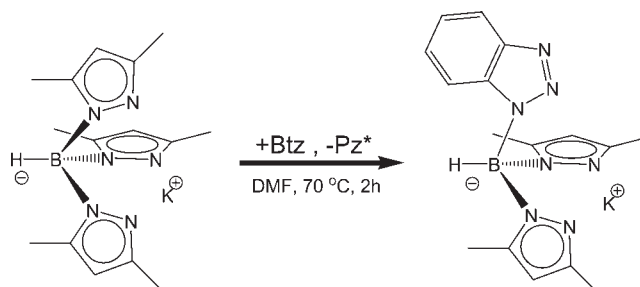


Figure 2. Reaction scheme for the preparation of KTp' by the metathesis reaction of KTp* with free Btz in DMF.

nickel leaching that limited the utility of our previously reported immobilized carbon-based scorpionate system, bead-TpmNiCl₂.¹⁰ Bead-Tp'NiX can be repeatedly and effectively washed with a range of solvents (H₂O, MeOH, CH₂Cl₂, DMF, Et₂O) with little to no effect on the appearance and apparent nickel content of the beads (as judged by DMG tests of the washings).³⁵ Resin supported bead-Tp'NiNO₃ has the same electronic spectral features as homogeneous Tp**NiNO*₃ (Figure 5). On this basis, a similar structure is proposed for the supported nickel complex (Figure 6).

Bead-supported scorpionates demonstrate a decided synthetic advantage in their behavior toward nickel(II) compared to their unsupported analogues. Importantly for supported nickel in all cases (bead-Tpm and bead-Tp') no evidence of bis(ligand) sandwich complexes was observed. It has been well-established that the formation and isolation of single-ligand half-sandwich scorpionate nickel complexes (Tp^RNiX) requires steric control (typically substituents like *t*-butyl, phenyl, isopropyl, and even methyl at the pyrazole ring 3-position) on the ligands to retard the coordination of two opposing ligands on the small nickel(II) ion. The dispersed nature of the present supported functional groups discourages the association of two ligands at a single nickel(II) site. As a result, bead-Tp'K readily binds nickel(II) from simple methanolic nickel(II) salt solutions (Figure 7). In contrast, these same simple reaction conditions, free of the solid support, rapidly produce only bis(ligand) sandwich products for KTp', Tpm, and KTp*. The ease of preparation of single-Tp^R products of first row metals on the solid support compensates the effort required to produce the supported scorpionate in the first place. Such a result is desirable to ease the preparation of supported nickel(II) complexes, and it may prove useful where steric encumbrance is a hindrance. It has been shown by Łukasiewicz and co-workers that extreme steric bulk on the pyrazole rings of Tp derivatives can render the scorpionate-coordinated metal inaccessible.³⁶

Bead-Tp'NiNO₃ reacts readily with cysteine thiolate ethyl ester (CysEt, Figure 7), giving evidence to open coordination sites suggested by Figure 6 for this heterogeneous nickel-scorpionate. This cannot occur for coordinatively saturated bis(ligand) complexes like (Tp*)₂Ni.¹¹ We propose that bead-Tp'NiCysEt adopts the same trigonal

(35) DMG represents dimethylglyoxime, a highly nickel-specific chelate used in gravimetric nickel analyses. Skoog, D. A.; West, D. M. *Fundamentals of Analytical Chemistry*, 4th. ed.; Saunders College Publishing: Chicago, IL, 1982; pp 147 and 736.

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(33) Anisole was also used as a high boiling solvent for such reactions. Eichhorn, D. M.; Armstrong, W. H. *Inorg. Chem.* **1990**, *29*, 3607–3612.

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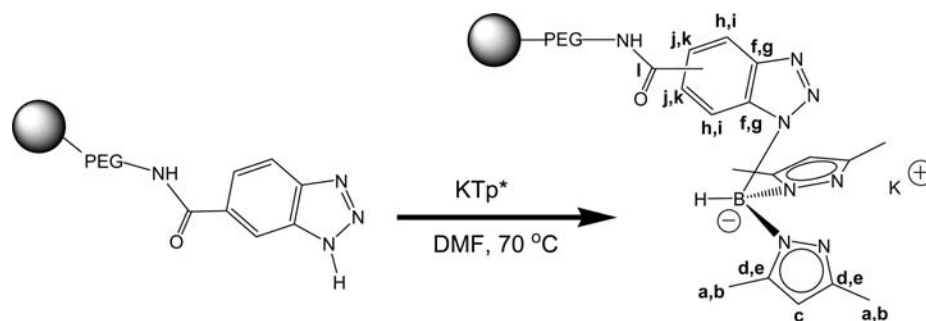


Figure 3. Bead-supported KTp' (bead- $\text{Tp}'\text{K}$) is prepared by the same metathesis reaction of KTp^* with bead-Btz as was developed for the unsupported reagents. The product bead- $\text{Tp}'\text{K}$ is likely a mixture of two different isomers resulting from the amide linkage connecting at either the 5 or the 6 position on the benzotriazole ring. Carbon assignment labels in boldface refer to ^{13}C NMR peak assignments in the spectrum shown in Figure 4 below.

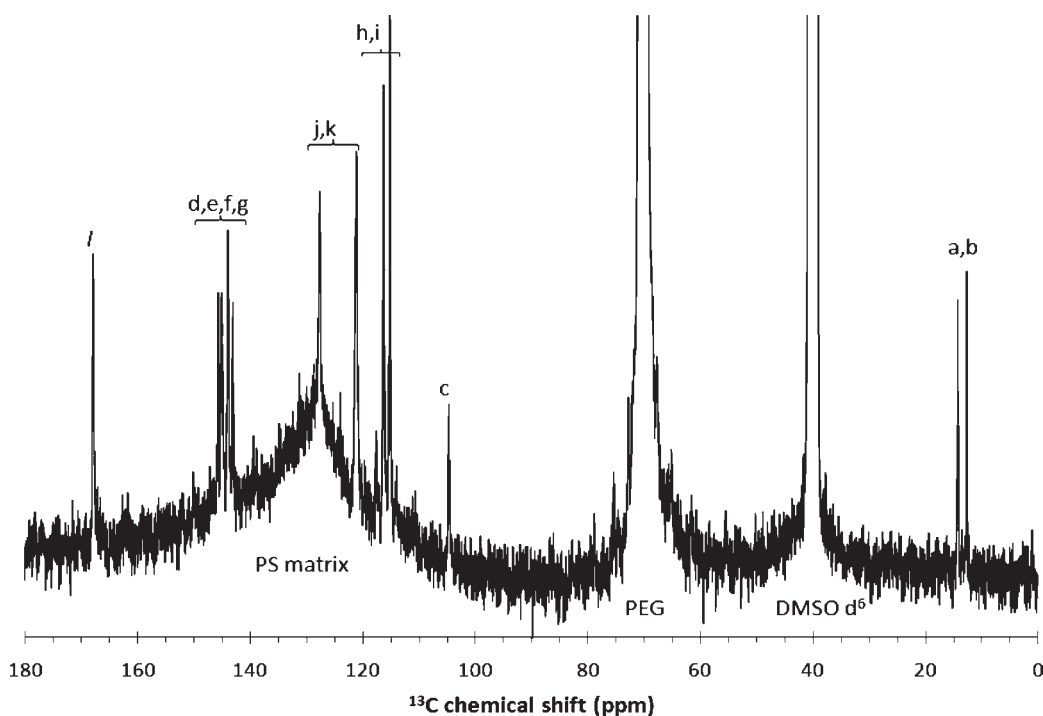


Figure 4. Carbon-13 NMR spectrum of bead- $\text{Tp}'\text{K}$ ($\text{DMSO}-d_6$). Peak assignments are made in the spectrum. These assignments correspond to the labels included in the molecular structure shown in Figure 3 above.

bipyramidal (TBP) nickel(II) coordination geometry as was experimentally confirmed for $\text{Tp}^*\text{NiCysEt}$ by single crystal X-ray diffraction (XRD).¹¹ Btz-nitrogen and the cysteine amine-nitrogen would occupy axial coordination sites around nickel with the two pyrazole-nitrogen atoms and sulfur of cysteine defining the equatorial plane. This supposition is based on the fact that bead- $\text{Tp}'\text{NiCysEt}$ exhibits the majority of characteristics previously observed for solution phase $\text{Tp}^*\text{NiCysEt}$. Both systems are deep green in color, a property shown to result from an intense S to Ni CT band in the range 400–450 nm for $\text{Tp}^*\text{NiCysEt}$ and observed here for bead- $\text{Tp}'\text{NiCysEt}$ (Figure 8). Both systems see their green color very effectively bleached (resulting in a loss and not a shift in this CT band, Figures 7 and 8) with exposure to atmospheric oxygen, behavior that was also exhibited by the selenocystamine analogue in solution (*vide infra*). Similar reactions, conducted in solution with $\text{Tp}^*\text{NiCysEt}$, failed to yield lavender bis(scorpionate) thermodynamic products after the color was

bleached. If a coordinatively unsaturated Tp^*Ni^+ species was formed during oxidation, such sandwich products should result.¹¹ Moreover, the electronic spectra of oxidized (ligand) NiCysEt complexes are distinct from the (ligand) NiNO_3 precursors from which they are originally formed. It is likely that, in the case of immobilized $\text{Tp}'\text{NiCysEt}$, oxidation does not completely dislodge the cysteine from the nickel ion. However, the characteristic features of unoxidized (ligand) NiCysEt (deep green color, Figure 7, and S to Ni CT band) immediately return when fresh CysEt is added, implying that the oxidized cysteine is dislodged from the nickel by the unoxidized ligand. This catalytic cycle was previously demonstrated for solution phase $\text{Tp}^*\text{NiCysEt}$ ¹¹ and is considerably simplified for the present bead- $\text{Tp}'\text{NiCysEt}$ heterogeneous system, representing a promising first report of catalytically active covalently anchored metal-scorpionates. The repeated binding of cysteine thiolate to bead- $\text{Tp}'\text{NiX}$ is clear chemical evidence for the existence of numerous coordinatively unsaturated

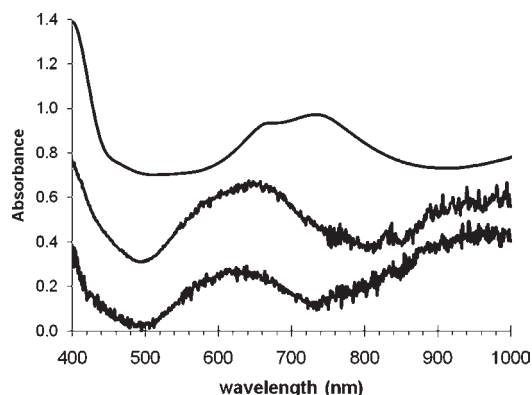


Figure 5. Electronic spectra of solid bead-Tp^{*}NiNO₃ (bottom, by DR), solid Tp^{*}NiNO₃(OH₂) (middle, by DR), and Ni(NO₃)₂ in methanol (top, 0.1 M solution). All show the characteristic pattern of three broad transitions assignable to the three spin allowed transitions typical of pseudo-octahedral nickel(II) coordination spheres. Notably, the bottom two spectra are nearly identical as would be expected of their common *fac*-NiN₃O₃ coordination spheres. The top spectrum displays the pattern typical of weak field NiO₆ geometries.

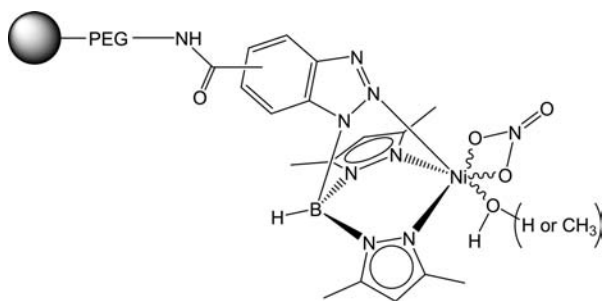


Figure 6. Proposed structure of bead-Tp^{*}NiNO₃. While the coordination geometry of nickel in this system deduced from electronic spectra (Figure 5) is consistent with a *fac*-NiN₃O₃ coordination sphere, it is uncertain whether water or methanol occupies the final coordination site.

bead-Tp^{*}NiX groups on the synthesis beads. Additional tests of bead-Tp^{*}NiX with reversible binding of other amino acids are ongoing.

Nickel-Chalcogen π Bonding in Tp^{*}NiCysEt and Its Seleno-Cysteine Analogue. The characteristic intense band near 400 nm observed for green bead-Tp^{*}NiCysEt and all members of the Tp^XNi(ECysR) class of compounds (Tp^X = Tp^{*} and Tp^{PhMe} and E = S or Se) implies that all likely adopt the trigonal bipyramidal (TBP) geometry experimentally confirmed for Tp^{*}NiCysEt by single crystal XRD.¹¹ The TBP equatorial plane is defined by the sulfur of CysEt and two of the Tp^{*} nitrogen atoms. Axial positions are occupied by the third Tp^{*} nitrogen and the amine nitrogen of chelating CysEt. Here the preparation of Tp^{*}NiSeCysAm is reported, and its electronic spectrum (Figure 9) is similar to that recorded for the sulfur analogues (CysEt, Cys, and CysAm). Importantly, Tp^{*}NiSeCysAm demonstrates an even more acute sensitivity to oxygen ($t_{1/2}$ Se \sim 20% of $t_{1/2}$ S), but also characterized by the same loss of the CT band as seen in the cases where the ligand contains sulfur (Figure 9). The Se to Ni CT band of unoxidized Tp^{*}NiSeCysAm is lower in energy than the sulfur form. This result, coupled with the greater sensitivity to oxygen, is consistent with higher energy atomic orbitals of selenium over sulfur. Oxidation likely disrupts in-plane chalcogen-nickel π bonding in TBP Tp^{*}NiECysR, leading

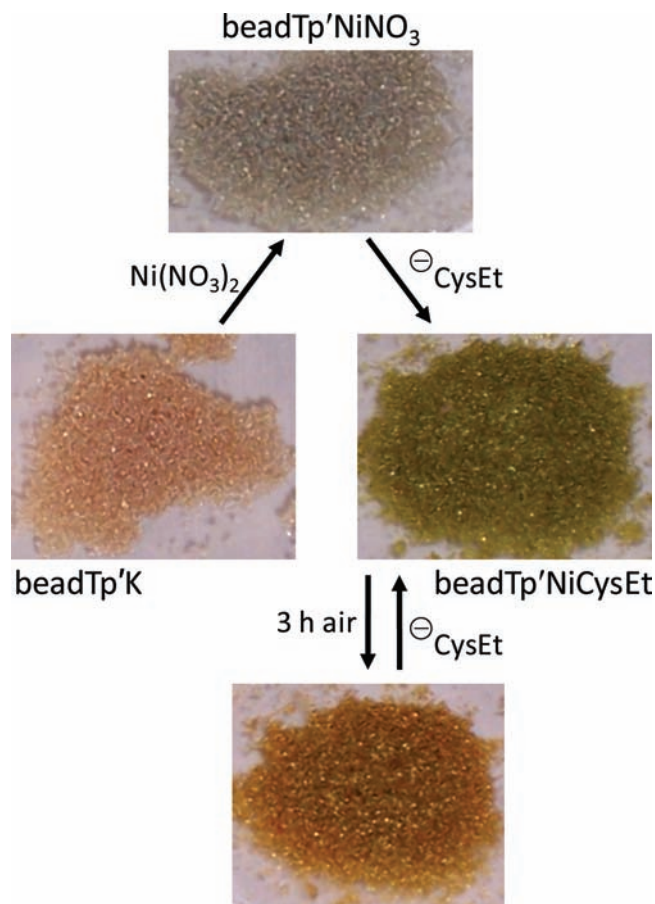


Figure 7. Photographs of bead-Tp^{*}K (left), bead-Tp^{*}NiNO₃ (top), and bead-Tp^{*}NiCysEt (right, green under N₂). The light amber color of bead-Tp^{*}K is a feature assigned to the aromatic carboxyl-Btz heterocycle, and this persists into the final ligand preparation. The effect of aerial oxidation on bead-Tp^{*}NiCysEt is seen as a bleaching of the original green color. The green color may be repeatedly regenerated with the addition of fresh methanolic cysteine thiolate (under N₂).

to weakening/breaking of this bond, and loss of their characteristic deep green color. This appears to be the origin of green color appearance/disappearance in the present bead-Tp^{*}NiCysEt system.

This π -bonding hypothesis was further tested by alkylation experiments involving Tp^{*}NiCysEt in donor solvents (Figure 10 and Supporting Information, Figure S2). The addition of a methyl cation source (methyl *p*-toluenesulfonate or trimethyloxonium tetrafluoroborate) causes efficient bleaching of the S-to-Ni CT band, and the original spectrum of deep green Tp^{*}NiCysEt is replaced by one typical of six-coordinate nickel(II) (Figure 10 and Supporting Information, Figure S2), giving a light blue solution. The solvent dependence of this spectrum of methylated-Tp^{*}NiCysEt (λ_{max} are shorter in CH₃CN compared to DMF)³⁷ confirms the coordination of one to three solvent molecules at nickel caused by a weakening/rupture of the nickel-sulfur bond because of conversion of the original anionic thiolate to a neutral methyl-thioether donor. Nickel-chalcogen π bonding must, therefore, be an integral feature of the selectivity of nickel for cysteine and seleno-cysteine and

(37) For comparison 10 Dq is 10,700 cm⁻¹ for Ni(NCCH₃)₆²⁺ and is only 8,500 cm⁻¹ for Ni(DMF)₆²⁺; Lever, A. B. P. *Inorganic Electronic Spectroscopy*; Elsevier: New York, 1968; p 336.

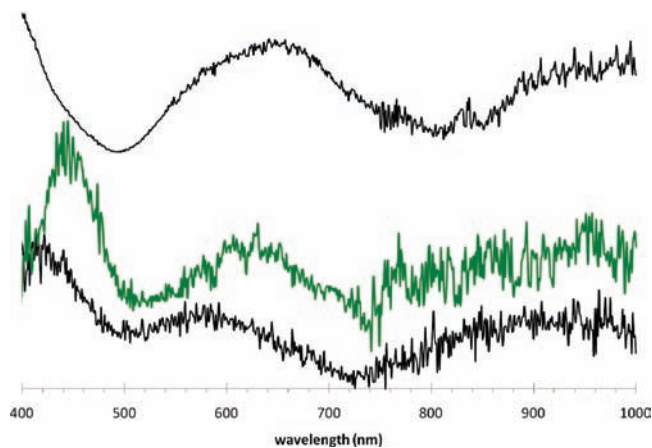


Figure 8. Electronic spectra by diffuse reflectance of bead-Tp'NiNO₃ (top, black), unoxidized bead-Tp'NiCysEt (green), and oxidized bead-Tp'NiCysEt (bottom, black). Transitions for the cysteine derivatives are shifted to higher energy relative to the nitrate precursor and reflect the stronger donor character of cysteine thiolate chelate over nitrate. The initial bead-Tp'NiCysEt spectrum shows an intense transition near 440 nm (assigned as S to Ni CT), and this band decreases in intensity with oxidation analogous to what was seen for Tp^RNiCysEt.

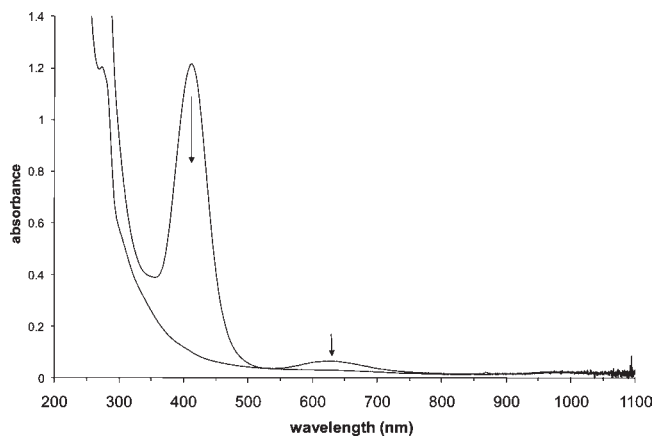


Figure 9. Electronic spectrum of a methanolic solution of Tp*NiSeCy-sAm (ca. 0.3 mM). The intense band at 410 nm is assigned as a selenium to nickel charge transfer. This band is rapidly lost upon exposure of this solution to air; the second nearly featureless spectrum was taken less than 5 min after opening the cuvette solution to air.

is again consistent with the behavior of the green color seen for bead-Tp'NiCysEt.

General Coordination Behavior of Tp' toward Nickel(II). The replacement of a single dimethylpyrazole ring of Tp* with a single btz ring does not significantly alter the coordination mode of Tp' from the parent homoscorpionate. All results indicate that Tp' acts like an archetypical scorpionate. Specifically, it is a facially chelating monoanion toward nickel(II) and molybdenum(0). Those complexes are much more soluble than their Tp* counterparts, especially in polar media (alcohols and DMF, but not water).^{22a} Transition metal complexes of benzotriazole-containing homoscorpionates (like hydrotris(benzotriazolyl)borate) show generally poor solubilities in organic solvents.^{24,38} Similarly poor solubility is seen with (Tp*)₂Ni in most organic solvents.

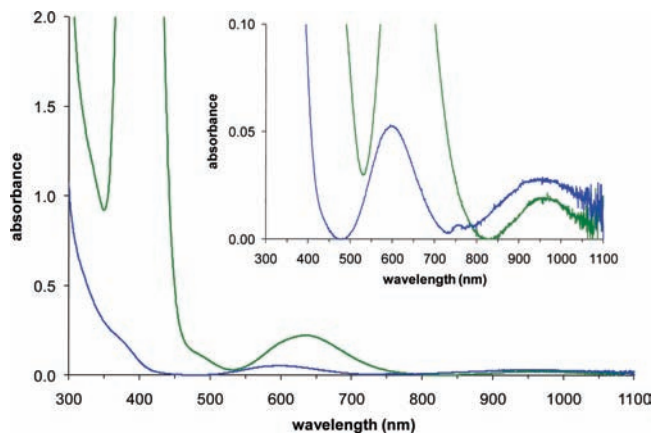


Figure 10. Electronic spectrum of Tp*NiCysEt in acetonitrile (5 mM, green spectrum) in which the sulfur-to-nickel charge transfer (CT) band near 400 nm predominates. This band is off-scale because of the high initial concentration. The blue spectrum results from the addition of excess methyl *p*-toluene sulfonate and is typical of a six-coordinate nickel(II) (three spin-allowed transitions), and is highly solvent dependent. In DMF the same blue color and qualitatively similar spectrum results but all bands are shifted to lower energies.

KTp' reacts efficiently with nickel(II) to form (Tp')₂Ni sandwich complexes (Figures 11 and 12). The majority of structurally characterized six-coordinate nickel(II) heteroscorpionates have been shown to adopt a *trans* configuration of donor atoms about the metal center. This is seen, for example, in several different structurally characterized nickel(II) N,N',O-donating heteroscorpionates, where the two oxygen atoms of opposing ligands coordinate to nickel(II) *trans* to one another.³⁹ We did not investigate the influence, if any, that the reaction solvent or other conditions might have on the formation of varying amounts of the two isomers. The more polar isomer (presumably *cis*) of (Tp')₂Ni was formed in greater abundance using the conditions described above.

Iron(II) heteroscorpionates have been prepared by Buchen and Gütllich, where ligands of the form HB(pz)_{3-n}(pz*)_n⁻ (*n* = 1 or 2) were used.⁴⁰ Similar to what is seen here for Ni(Tp')₂, analytically pure iron(II) heteroscorpionates were reported from these syntheses. Buchen and Gütllich acknowledged the likelihood of *cis* and *trans* isomerism in the FeN₆ core of their synthesized complexes (resulting from two possible pz/pz* arrangements); however, these were never separated, and their iron(II) products were treated as pure materials in the variable temperature magnetic work of their report.

All attempts to grow single crystals of either isomer of (Tp')₂Ni have proven unsuccessful. Clusters of very thin needle were obtained during crystallization of these compounds from chloroform or 20:80 methanol/chloroform mixtures, but these were too fragile to isolate. Therefore, the powder X-ray diffraction pattern for each was collected to confirm their different crystalline habits and, by inference, different molecular structures anticipated by the proposed isomeric structures shown in Figure 12. These powder XRD patterns are shown in Figure 13, and the pattern for (Tp*)₂Ni is included for comparison. These data show there is little similarity in the unit cell configurations

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(40) Buchen, T.; Gütllich, P. *Inorg. Chim. Acta* **1995**, *231*, 221–223.

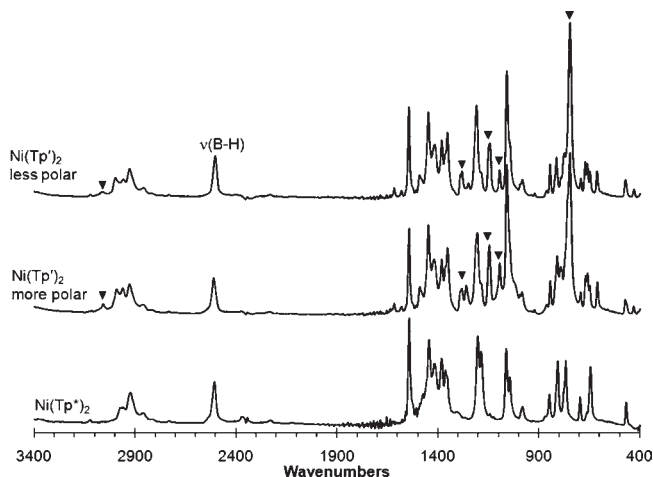


Figure 11. Infrared spectra of the two different isomers of $(\text{Tp}')_2\text{Ni}$ compared to $(\text{Tp}^*)_2\text{Ni}$ (all as KBr pellets). The $\nu(\text{B-H})$ band typical of scorpionates is labeled; less polar isomer $\nu(\text{B-H}) = 2501 \text{ cm}^{-1}$, more polar isomer $\nu(\text{B-H}) = 2509 \text{ cm}^{-1}$. Vibrations indicative of benzotriazole are labeled with black triangles. These nearly coincident top two spectra emphasize the similar ligand covalent bonding in these two isomers. This supports assigning these isomers as *cis* and *trans* forms of $(\text{Tp}')_2\text{Ni}$.

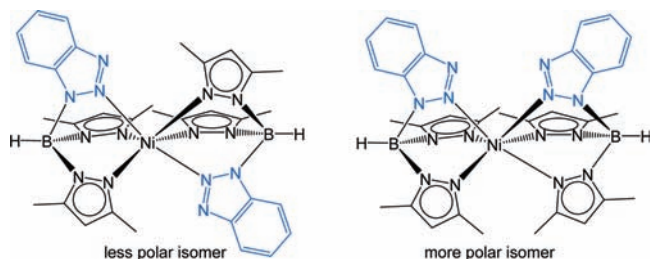


Figure 12. Proposed structures of two different isomers resulting from the coordination of the heteroscorpionate (Tp') with nickel(II). The polarity of the isomers derives from their mobility during chromatographic separation with the more polar, likely *cis*, isomer showing less mobility and the less polar (likely *trans*) isomer showing more mobility on silica gel. The *cis* isomer is a potential chelate for other metals.

for the two isomers of $(\text{Tp}')_2\text{Ni}$, implying different packing arrangements in the solid state that would most likely result from different isomeric (*cis* and *trans*) structures.

Molybdenum(0) Complexes of Tp' and Supported- Tpm . The ligand systems Tp' and bead- Tpm were used to prepare piano-stool molybdenum(0) tricarbonyl complexes for spectroscopic validation of these systems against established literature precedents.³⁰ Dendrimer-supported $\text{TpmMo}(\text{CO})_3$ has also been reported.³¹ Importantly for the present work, this class of compounds shows unequivocal spectroscopic signatures of *fac*- $\text{N}_3\text{Mo}(\text{CO})_3$ molybdenum(0) coordination spheres: strong $\nu(\text{C}\equiv\text{O})$ in the infrared and distinctive ^{13}C NMR resonances near 230 ppm due to coordinated CO.

Replacement of a single dimethylpyrazole ring with benzotriazole (changing Tp^* to Tp') gave the anticipated spectroscopic changes in these complexes as well as some differences in reactivity and solubility. The former ligand complex, $\text{Tp}^*\text{Mo}(\text{CO})_3^-$, as its PPh_4^+ salt, proved to be air stable both in the solid state and in solution. In contrast to the 3-fold symmetric $\text{Tp}^*\text{Mo}(\text{CO})_3^-$ anion, the new asymmetric anion, $\text{Tp}'\text{Mo}(\text{CO})_3^-$ (maximum C_s symmetry), shows two inequivalent CO ligands in its ^{13}C NMR spectrum (Figure 14), and distinct splitting of the

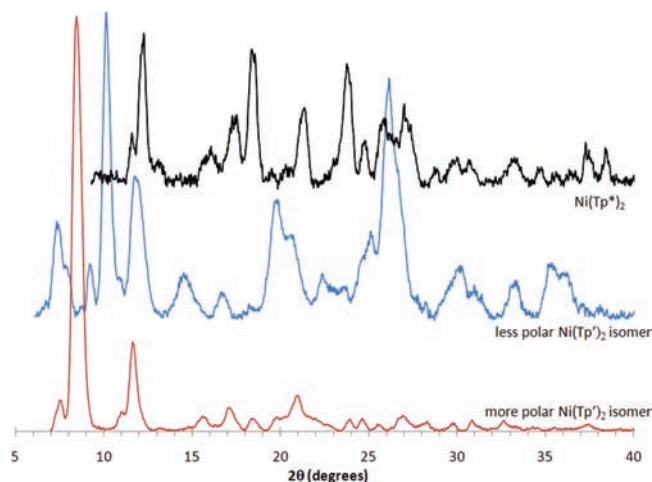


Figure 13. Powder XRD patterns for $\text{Ni}(\text{Tp}^*)_2$ (top), less polar isomer of $\text{Ni}(\text{Tp}')_2$ (middle), and the more polar isomer of $\text{Ni}(\text{Tp}')_2$. $\lambda = 1.542 \text{ \AA}$ ($\text{Cu K}\alpha$). All three solids show distinctly different patterns indicating their different crystalline habits, consistent with different molecular structures for all three.

E (in C_3) symmetry $\nu(\text{C}\equiv\text{O})$ band in the infrared (see Table 1). The $\text{Tp}'\text{Mo}(\text{CO})_3^-$ anion, while stabilized somewhat by the PPh_4^+ cation in the solid state, is much more oxygen sensitive in solution than its Tp^* analogue. The donor strength of Tp' appears intermediate between the two parent scorpionates, Tp^* and Ttz ,⁴¹ with molybdenum in these systems (compare $\nu(\text{C}\equiv\text{O})$ in Table 1); however, all three of these anionic scorpionates are stronger donors than the carbon-based scorpionates Tpm or Tpm^* , as evidenced by the higher $\nu(\text{C}\equiv\text{O})$ frequencies seen in bead- $\text{TpmMo}(\text{CO})_3$ and $\text{Tpm}^*\text{Mo}(\text{CO})_3$ (Table 1). The slight asymmetry (split *E* band) evident in the infrared $\nu(\text{C}\equiv\text{O})$ pattern for $[\text{PPh}_4][\text{Tp}^*\text{Mo}(\text{CO})_3]$ is attributed to packing forces in the solid state; this asymmetry was not evident in solution by ^{13}C NMR. The absence of similar *E* band splitting (Supporting Information, Figure S3) for bead- $\text{TpmMo}(\text{CO})_3$ results from the solution-like atmosphere of the bead-PEG matrix and/or the lack of packing influence from the counterion required in the anionic boron-based analogues.

Supported Tpm and Tp' both demonstrated ready binding of molybdenum(0) from $\text{Mo}(\text{CO})_6$. Importantly, the preparation and characterization of bead- $\text{TpmMo}(\text{CO})_3$ demonstrates that resin-supported Tpm is a stable anchorage for this metal. Even though supported- Tpm only weakly binds nickel(II),¹⁰ coordinated molybdenum of bead- $\text{TpmMo}(\text{CO})_3$ is not washed free of the beads, allowing ^{13}C NMR to be recorded for the supported molybdenum complex. In the case of bead- $\text{Tp}'\text{K}$, the same reaction conditions with $\text{Mo}(\text{CO})_6$ presumably produced bead- $\text{Tp}'\text{Mo}(\text{CO})_3\text{K}$ as a supported potassium salt (Supporting Information, Figure S4). However, it was not possible to prevent bead- $\text{Tp}'\text{Mo}(\text{CO})_3\text{K}$ from darkening, a change resulting in eventual loss of all CO ligands (by IR-ATR). Similar degradation was reported under homogeneous conditions for the anion $\text{Tp}^{\text{iPr}}\text{Mo}(\text{CO})_3^-$.^{16,42} The inertness

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(42) It is possible that the degradation is caused by the difference in cation. The potassium counterion used in the formation of the immobilized $\text{Tp}'\text{Mo}(\text{CO})_3$ complex, may not stabilize the anion as well as PPh_4^+ , the cation used for the solution-phase complex.

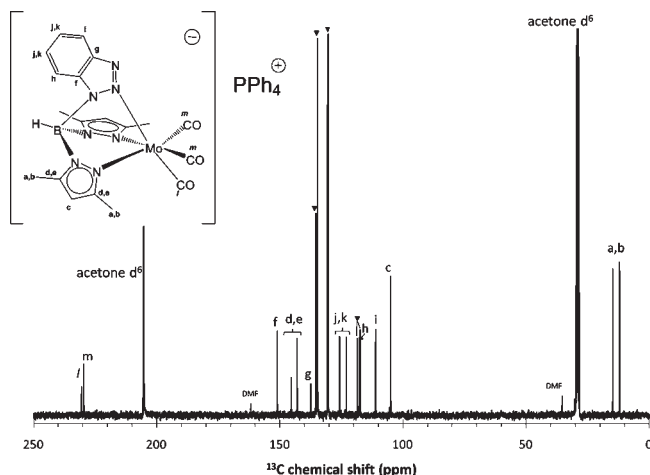


Figure 14. ^{13}C $\{^1\text{H}\}$ NMR spectrum of $[\text{PPh}_4][\text{Tp}'\text{Mo}(\text{CO})_3]$ in acetone- d_6 . Assignments are made in the figure. A trace of DMF from the original reaction mixture is labeled. Assignments for carbon atoms f, g, h, and i are based on a comparison with free benzotriazole and allowance for the differences introduced by coordination of N-1 to boron. The four carbon resonances (black triangles) of the tetraphenylphosphonium cation are all split into doublets with $J_{\text{P-C}}$ ranging from 2 to 89 Hz because of coupling with and proximity to the phosphorus atom of the cation.

Table 1. Carbonyl Stretching Frequencies (cm^{-1}) for Several $\text{Tp}^{\text{R}}\text{Mo}^0(\text{CO})_3$ Systems

| $\text{Tp}^{\text{R}}\text{Mo}^0(\text{CO})_3$ (KBr) | A_1 | E |
|--|-------|---------------|
| $[\text{PPh}_4][\text{Tp}^*\text{Mo}(\text{CO})_3]$ | 1884 | 1754, 1737 sh |
| $[\text{PPh}_4][\text{Tp}'\text{Mo}(\text{CO})_3]$ | 1888 | 1764, 1736 |
| $[\text{NEt}_4][\text{TtzMo}(\text{CO})_3]^a$ | 1906 | 1775 |
| bead- $\text{TpmMo}(\text{CO})_3^b$ | 1905 | 1780 |
| $\text{Tpm}^*\text{Mo}(\text{CO})_3^c$ | 1900 | 1763 |

^a Ref 41; Ttz = hydrotris(benzotriazole-1-yl)borate. ^b By ATR. ^c Ref 27; Tpm^* = tris(3,5-dimethylpyrazolyl)methane.

of the supported molybdenum centers to displacement was further accentuated when the original bead- $\text{TpmMo}(\text{CO})_3$ complex was oxidized to the point of losing all CO ligands (by IR). The color of the beads darkened, but did not revert to that of the free ligand, indicating persistent molybdenum content even when washed with polar solvents.

Conclusions

Scorpionates have been used as ligands with the majority of transition metals and p-block metal ions, but they have not been exploited extensively in heterogeneous applications. Despite the obvious advantages of using ligands that have been immobilized—accessibility to combinatorial methods, recyclability of metal ions, and separation of metal complexes from reaction mixtures—reports of immobilized boron-centered scorpionates are scarce. The present work represents the first report of a cross-link PS resin-supported boron-scorpionate as its free potassium salt. The strong chelating ability of bead- Tp' toward nickel(II) and molybdenum(0) was demonstrated. These examples represent notable first

reports of resin-supported boron-heteroscorpionate complexes of these metal ions and demonstrate the utility of preparing the supported ligand as its potassium salt, which can easily be replaced by more desirable transition metal ions for subsequent reactivity studies.

Importantly, bead- $\text{Tp}'\text{NiX}$ complexes are here shown to possess functional reactivity toward cysteine thiolate without metal leaching. The resulting bright green colored bead- $\text{Tp}'\text{NiCysEt}$ further showed reactivity characteristics similar to solution phase analogues ($\text{Tp}^*\text{NiCysEt}$) and to new comparative selenium analogues ($\text{Tp}^*\text{NiSeCysAm}$). All of these nickel-chalcogen complexes showed a clear susceptibility to aerial oxidation, causing a bleaching of their characteristic green color, but not the removal of nickel(II) from its scorpionate chelate, indicating this change was directed at the cysteinyl-chalcogen functional group. The reappearance of the green color with the addition of fresh unoxidized cysteine and reversible alkylation of $\text{Tp}^*\text{NiCysEt}$ all support this conclusion. The recyclability of bead- $\text{Tp}'\text{Ni}$ in the present work is particularly desirable, because it portends potential heterogeneous catalysis at nickel, a result that would not have been possible in previous work with bead- TpmNiCl_n .

Resin-supported scorpionates show none of the tendencies to form bis(scorpionate) sandwich compounds with nickel under any conditions, amplifying the synthetic utility of these chelates with first row transition metals. They should allow access to previously unobserved half-sandwich scorpionate complexes with minimal steric interference that could not be made in homogeneous systems. The generality of the metathesis approach for the synthesis of heteroscorpionates, both immobilized and free of the support, is currently being investigated. Immobilized heteroscorpionates prepared in this manner are expected to find far-reaching applications in metal coordination chemistry, including catalysis, enzyme mimetics, and bioconjugate design. Supported scorpionates should help make such studies amenable to combinatorial methods, allowing for easy parallel synthesis and purification.

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Supporting Information Available: ^{13}C NMR of bead-btz, alkylation of $\text{Tp}^*\text{NiCysEt}$ followed by electronic spectroscopy, FT-IR (using ATR) of bead- $\text{TpmMo}(\text{CO})_3$ and of bead- $\text{Tp}'\text{Mo}(\text{CO})_3\text{K}$. This material is available free of charge via the Internet at <http://pubs.acs.org>.