Facile Two-Step Construction of a Novel Tetrathiamacrotricycle

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Summary: The reactions of [Os(CO)(CA)(PPh$_3$)$_3$] (A = O, S) with 4,7,10-trithiatrideca-2,11-diyne provide cyclopentadienone and cyclopentadienethione complexes, the latter affording a novel polythioether macrotricyclic ligand on subsequent treatment with dimethylacetylenedicarboxylate.

We have recently been concerned with the metal-mediated reactions of 4,7,10-trithiatrideca-2,11-diyne (**1**),[1,2] motivated by the simple concept that the many and various metal-mediated alkyne coupling protocols currently available might be applied to polythioether α,ω-diynes to provide access to a variety of functionalized polythiamacrocycles. Initial studies based on [RhCl(PPh$_3$)$_3$] were discouraging in that they demonstrated a remarkable lability of the S−C(sp) bonds.[1] However, studies based on the complex [Ru(CO)$_2$(PPh$_3$)$_3$] proved more fruitful, providing the novel macrocyclic cyclopentadienone complex [Ru(CO)(PPh$_3$){η^4-κ-*S*-O=C(CMe=CSC$_2$H$_4$)$_2$S}] (**2a**).[2] The facility (ambient conditions) of this [1+2+2] CO/alkyne co-cyclization reaction contrasts markedly with the behavior of [Ru(CO)$_2$(PPh$_3$)$_3$] toward diphenylacetylene, which only provides coupled products under prolonged forcing conditions.[3] The ease of formation of **2a** also precluded the observation of any intermediates; however, our suggested mechanism drew upon precedent from the reactions of [Os(CO)(CS)(PPh$_3$)$_3$] with ethyne[4] and diphenylacetylene[5] for which metallacyclohexadienethione ("osmabenzene") and metallacyclobutenethione products were isolated. We have therefore investigated the reactions of **1** with the complexes [Os(CO)(CA)(PPh$_3$)$_3$] (A = O **3**,[6] S, **4**[7]). The products of these reactions not only reinforce our proposal but provide access to a complex of an unprecedented tricyclic tetrathioether macrocyclic ligand.

Reassuringly, the reaction of [Os(CO)$_2$(PPh$_3$)$_3$][6] with **1** was found to proceed in an identical manner to the ruthenium analogue, albeit under more forcing conditions (refluxing benzene). Data for the product [Os(CO)(PPh$_3$){η^4-κ-*S*-O=C(CMe=CSC$_2$H$_4$)$_2$S}] (**2b**)[8] were comparable to those for **2a**. As in the formation of **2a**, no intermediates were observed, suggesting that the rate-limiting step occurs early in the mechanism. The reaction of **1** with **4** was next investigated. Although no reaction ensues at room temperature, heating the reagents in benzene under reflux results in the formation of a new complex, which we suggest is **2c**, the thiocarbonyl analogue of **2b**, albeit on the basis of somewhat limited spectroscopic and microanalytical data.[8] The complex is essentially insoluble in all the common organic solvents with which it does not react with (vide infra), a property that compromised the acquisition of spectroscopic data. Most notable among the spectroscopic data obtained were (i) the loss of infrared activity attributable to a terminal thiocarbonyl ligand and (ii) a ^{1}H NMR spectrum that is reminiscent of those for **2a**[2] and **2b**. Attempts to obtain ^{13}C{^{1}H} NMR data from solutions of **2c** in CD$_2$Cl$_2$ were thwarted by a slow reaction with the solvent to provide the salt [Os(CO)(PPh$_3$){ClCD$_2$SC(CMe=CSC$_2$H$_4$)$_2$S}]Cl (d_2-**5**·Cl), which was characterized as both the d_2 and fully protio derivative.[8] The complex **5**$^+$ features a cyclopentadienyl ligand that is part of a macrobicyclic ligand with a pendant thioether coordinated to osmium(II). Cyclopentadienethione complexes remain a rare class of compound,[9] and both reports point toward the sulfur atoms being strongly nucleophilic; the oxidative cleavage of ruthenocenyl disulfide provides the binuclear complex [Ru(μ-S=C$_5$H$_4$)(η-C$_5$H$_5$)]$_2^{2+}$, in which the thiones act as donors to adjacent ruthenium centers,[9a] while the cobalt complex [Co(η^4-S=C$_5$Ph$_4$)(η-C$_5$H$_5$)] is readily alkylated at sulfur.[9b]

The reactions of **2c** with a range of electrophilic alkylating agents will be discussed elsewhere;[10] however these and the formation of **5**·Cl suggest that the thione group in **2c** is particularly nucleophilic. The reaction of **2c** with the electrophilic alkyne dimethylacetylenedicarboxylate (DMAD) was therefore investigated. There is limited precedent for the reaction of ene-thiones with activated alkynes; however in general these proceed via [4+2] cycloaddition.[11] This route is prevented for **2c**, which is unable to achieve the requisite *S*-cis ene-thione geometry. The product of the reaction of **2c** with DMAD was identifed as the complex **6** of a novel macrotricyclic ligand arising from the [2+3] coupling of the alkyne with the thione and carbon center α to the thione. The reaction proceeds under mild conditions and provides only one regioisomer, which was unambiguously identified by crystallographic analysis (Figure 1).[8] Two mechanistic routes appear plausible (Scheme 2); either (a) a

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(1) Caldwell, L. M.; Edwards, A. J.; Hill, A. F.; Neumann, H.; Schultz, M. *Organometallics* **2003**, *22*, 2531.
(2) Hill, A. F.; Rae, A. D.; Schultz, M.; Willis, A. C. *Organometallics* **2004**, *23*, 81.
(3) Hill, A. F.; Schultz, M.; Willis, A. C. *Organometallics* **2004**, *23*, 5729.
(4) Elliott, G. P.; Roper, W. R.; Waters, J. M. *J. Chem. Soc., Chem. Commun.* **1982**, 811.
(5) Elliot, G. P.; Roper, W. R. *J. Organomet. Chem.* **1983**, *250*, C5.
(6) Cavit, W. R.; Grundy, K. R.; Roper, W. R. *J. Chem. Soc., Chem. Commun.* **1972**, 60.
(7) Collins, T. J.; Grundy, K. R.; Roper, W. R. *J. Organomet. Chem.* **1982**, *231*, 161.

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concerted [2+3] cycloaddition or alternatively (b) a two-step sequence involving initial nucleophilic attack by the thione at the alkyne to provide a zwitterionic intermediate that collapses via C−C bond formation. At present we have no evidence to differentiate between the two mechanisms, but note that the thermal [4+2] cycloaddition reaction of DMAD with thiobenzophenone is purported to proceed via a zwitterionic intermediate.[11b] Of interest is the regiospecificity displayed in the exclusive formation of **6**, in that C−C bond formation occurs pseudo-trans to the phosphine ligand. The displacement of the pendant thioether in **2a** requires forcing conditions (110 °C), and so we are disinclined to invoke direct participation of the osmium center via coordinatively unsaturated intermediates. Since the phosphine, carbonyl, and thioether ligands are distal to the sites for ring formation, it would appear that the regioselectivity arises entirely from frontier orbital controlled electronic effects.

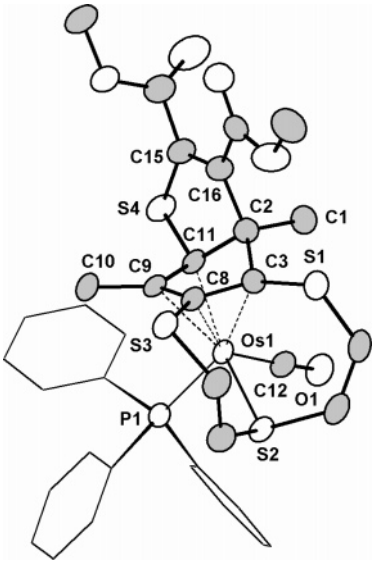


Figure 1. Molecular geometry of **6** in the crystal of **6**·C_6H_{12} (50% probability ellipsoids, hydrogen atoms omitted and phenyl groups simplified). Selected bond lengths (Å) and angles (deg): Os1−S2 2.3685(8), Os1−P1 2.3335(9), Os1−C3 2.202(3), Os1−C8 2.236(3), Os1−C9 2.236(3), Os1−C11 2.158(3), Os1−C12 1.874(4), S1−C3 1.770(3), S1−C4 1.818-(4), S3−C7 1.820(4), S3−C8 1.765(3), S4−C11 1.794(3), C2−C3 1.544(5), C2−C11 1.530(5), C3−C8 1.462(5), C8−C9 1.409(5), C9−C11 1.479(5), S2−Os1−P1 94.27(3), S2−Os1−C12 92.06(11).

The molecular geometry of **6** in a crystal of the cyclohexane monosolvate is depicted in Figure 1. The osmium center has a pseudo-piano-stool geometry with unremarkable Os, P1, C12, and S2 interligand angles and bond lengths. Interest focuses on the macrocycle which is best described as a cyclopentadiene coordinated tetrahapto to zerovalent osmium. Coordination of a 1,3-butadiene fragment to a metal center typically results in an increase in electron delocalization and reduction in the degree of 1,3-diene bond length alternation. This is particularly evident in **6**, to the extent that it is the

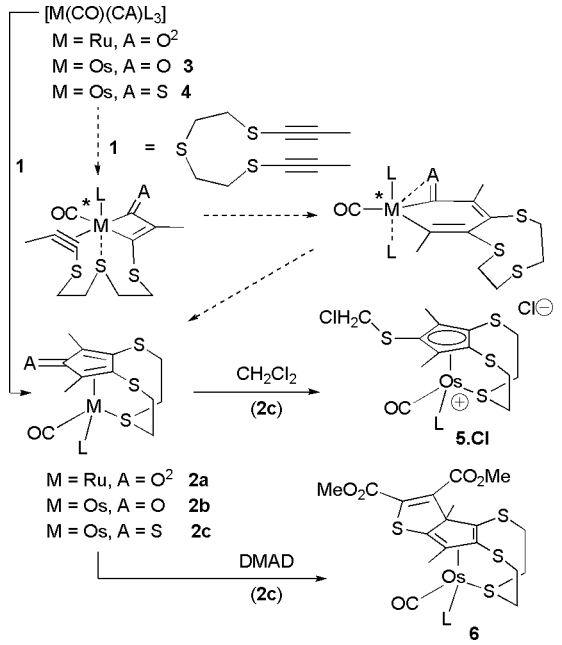
(8) Characterizational data ('@δ_X=' indicates 2-D correlations to nucleus X; ^{1}H (300), ^{13}C (75), and ^{31}P (121 MHz) NMR: CD_2Cl_2, 298 K): (a) **2b**: A mixture of **1** (60 mg, 0.30 mmol) and **3** (230 mg, 0.30 mmol) in benzene (5 mL) was heated under reflux for 30 min and then left to cool slowly. The resulting yellow precipitate was isolated by filtration, washed with ethanol and hexane, and dried in vacuo. Yield: 60 mg (28%). Mp: 220 °C. IR Nujol: 1908 ν(OsCO), 1577 ν(C=O) cm^{-1}. CH_2Cl_2: 1918 ν(OsCO), 1558 ν(C=O) cm^{-1}. ^{1}H NMR: 7.6, 7.43 (m × 2, 15 H, C_6H_5), 4.03 (ddd, 1 H, J_{HH} = 15, 12, 2.4, @δ_C = 29.0, @δ_H = 2.68, 1.78, 1.20), 2.92 (ddd, 1 H, J_{HH} = 12, 3, 3, @δ_C = 43.2, @δ_H = 2.45, 2.16, 1.98), 2.68 (ddd, 1 H, J_{HH} = 15, 3, 4, @δ_C = 29.0), 2.45 (ddd, 1 H, J_{HH} = 13, 3, 3, @δ_C = 26.9), 2.16 (ddd, 1 H, J_{HH} = 15, 15, 3, @δ_C = 26.9), 1.98 (ddd, 1 H, J_{HH} = 3, remaining component of resonance obscured by CH_3 resonance, @δ_C = 43.2), 1.78 (ddd, 1 H, J_{HH} = 15, 5, 2, @δ_C = 19.0), 1.20 (ddd, 1 H, J_{HH} = 12, 3, 3, @δ_C = 19.0). ^{13}C{^{1}H} NMR: δ 189.5 (RuCO), 135.1 (d, J_{PC} = 54.1, C^1(C_6H_5), 133.9 (d, J_{PC} = 11.2, C^{2,6}(C_6H_5), 133.9 (d, J_{PC} = 2, C^4(C_6H_5), 128.6 (d, J_{PC} = 10.5, C^{3,5}(C_6H_5), 93.12, 85.0, 76.8, 73.7 (C_4C=O), 43.2, 29.0, 26.9, 18.9 (SCH_2), 9.92, 8.62 (CH_3), quarternary ketonic carbon resonance not unequivocally identified. ^{31}P{^{1}H}: δ 11.94 (C_6D_6), 11.89 (CD_2Cl_2). FAB-MS (nba): *m/z* = 741 [HM]$^+$, 712 [M − CO]$^+$. Anal. Found: C, 48.54; H, 4.00; N, 0.00; S, 12.67; P, 3.80. Calcd for $C_{30}H_{29}O_2OsPS_3$: C, 48.76; H, 3.96; N, 0.00; S, 13.02; P, 4.19. (b) **2c**: A mixture of **4** (600 mg, 0.57 mmol) and **1** (138 mg, 0.60 mmol) in benzene (10 mL) was heated under reflux for 30 min and then left to cool. The brown solid that precipitated was isolated by filtration, washed with thf and hexane, and dried in vacuo. Yield: 225 mg (52%). ^{1}H NMR: δ 7.6−7.2 (m, 15 H, C_6H_5), 4.15 (ddd, 1 H, J_{HH} = 15, 13, 1.8 @δ_C = 27.5), 3.01 (ddd, 1 H, J_{HH} = 14, 2.3, 2.3, @δ_C = 42.2), 2.79 (ddd, 1 H, J_{HH} = 15, 4.4, 3.3, @δ_C = 27.5), 2.43 (ddd, 1 H, J_{HH} = 14, 2.7, 2.7, @δ_C = 26.0), 2.29 (d, 3 H, J_{HP} = 1.8, CH_3 @δ_C = 12.4, pseudo-trans to CO), 2.16 (ddd, 1H, J_{HH} = 13, 13, 2.7, @δ_C = 26.0), 2.05 (ddd, 1 H, J_{HH} = 15, 15, 3.6 @δ_C = 42.2), 1.94 (ddd, 1 H, J_{HH} = 16, 3.9, 2.4 @δ_C = 19.0), 1.14 (ddd, 1 H, J_{HH} = 12, 12, 2.7 @δ_C = 19.0), 1.12 (d, 3 H, J_{HP} = 2.4 Hz, CH_3 @δ_C = 11.4, pseudo-trans to PPh_3). ^{13}C{^{1}H} NMR: δ 130.0 (C_2C=S), 133−128 (m, PPh_3), 111, 102 (*C*Me × 2), 83, 77 (C_2*C*−S × 2), 42.2 (CH_2 α to δ_C = 26.0), 27.5 (CH_2 α to δ_C =19.0), 26.0 (CH_2 α to δ_C = 42.2), 19.0 (CH_2 α to δ_C = 27.5), 12.4 (CH_3 pseudo-trans to CO), 11.4 (CH_3 pseudo-trans to P) (OsCO not observed). ^{31}P{^{1}H} NMR: δ 6.25. IR Nujol: 1930 (ν_{CO}) cm^{-1}. FAB-MS (nba): *m/z* = 756 [M]$^+$. NB ^{13}C-{^{1}H} NMR data inferred from two-dimensional spectra due to reaction with CD_2Cl_2. (c) **5**·Cl: Yield: 80% (spectr. quant.). Mp: 170−175 °C. ^{1}H NMR: δ 7.53−7.25 (m, 15 H, C_6H_5), 4.69 4.59 (AB, 1H × 2, $^2J_{HH}$ = 12, CH_2Cl), 4.37 (ddd, 1 H, J_{HH} = 13, 12, 2.2 @δ_C = 28.3), 3.37 (m, 1 H, @δ_C = 25.6), 3.32 (m, 1 H, @δ_C = 42.8), 3.18 (ddd, 1H, J_{HH} = 16, 3.6, 2.7, @δ_C = 28.3), 3.07 (ddd, 1H, J_{HH} = 15, 2.0, 1.9, @δ_C = 16.9), 2.67 (ddd, 1 H, J_{HH} = 14, 3.6, 2.3, @δ_C = 25.6), 2.50 (d, 3 H, J_{HP} = 1.6, CH_3 @δ_C = 11.8), 2.01 (ddd, 1 H, 15, 13, 3.3, @δ_C = 42.8), 1.67 (d, 3H, J_{HP} = 2.3 Hz, CH_3 @δ_C = 11.2), 0.96 (m, 1 H, @δ_C = 16.9). ^{13}C{^{1}H} NMR: δ 179.6 (d, $^2J_{CP}$ = 9.5, OsCO), 133.5 [d, $^2J_{CP}$ = 11, C$^{2,\ 6}$(C_6H_5)], 131.9 [s, C^4(C_6H_5)], 130.8 [d, $^1J_{CP}$ = 59, C^1(C_6H_5)], 129.1 [d, J_{CP} = 11, C^{3,5}(C_6H_5)], 118.1, 109.2 (*C*CH_3 × 2), 88.5, 86.5 (=*C*SCH_2CH_2 × 2), 82.5 (*C*SCH_2Cl), 42.8 (CH_2, α to δ_C = 25.6), 28.3 (CH_2, α to δ_C = 16.9), 25.6 (CH_2, α to δ_C = 42.8), 16.9 (CH_2, α to δ_C = 28.3), 11.8 (s, CH_3), 11.2 (s, CH_3). ^{31}P{^{1}H} NMR: δ 0.91 (s). IR Nujol: 1951; CH_2Cl_2: 1968 cm^{-1}. APCI-MS: *m/z* = 805 [**5**]$^+$. **6**: A mixture of **2c** (100 mg, 0.13 mmol) and DMAD (25 μL, 0.20 mmol) in dichloromethane (5 mL) was stirred for 15 min and then diluted with ethanol to precipitate a tan solid, which was isolated by filtration and dried in vacuo. Yield: 70 mg (59%). Mp: 150−155 °C (dec). IR CH_2Cl_2: 1912s (OsCO), 1724br (C=O); Nujol: 1918s (OsCO), 1719m (C=O) cm^{-1}. ^{1}H NMR (CD_2Cl_2, 298 K) (300 MHz): δ 7.43−7.19 (m, 15 H, C_6H_5), 4.31 (ddd, 1 H, J_{HH} = 13, 13, 2.1, @δ_C = 27.6), 3.69 (s, 3 H, OCH_3), 3.68 (s, 3 H, OCH_3), 2.78 (m, 3 H, @δ_C = 44.9, 32.3, 27.6), 2.20 (m, 2 H, @δ_C = 44.9, 32.3), 1.64 (ddd, 1 H, J_{HH} = 14, 13, 3.6, @δ_C = 17.9), 1.58 (d, 3 H, J_{HP} = 3.0, CCH_3, @δ_C = 12.4), 1.43 (d, 3 H, J_{HP} = 0.9, CCH_3, @δ_C = 20.4), 1.26 (ddd, 1 H, J_{HH} = 14, 12, 3.3 Hz, @δ_C = 17.9). ^{13}C{^{1}H} NMR (121 MHz, see Figure 1 for designations): δ 164.8, 163.9 (CO_2 × 2), 150.2 (CCO_2), 135.8 [d, $^1J_{CP}$ = 76, C^1(C_6H_5)], 134.0 [d, $^2J_{CP}$ = 18, $C^{2,6}$(C_6H_5)] 130.2 [d, $^4J_{CP}$ = 3, C^4(C_6H_5)], 128.6 [d, J_{CP} = 16 Hz, C^{3,5}(C_6H_5)], 103.3 (C^9), 85.74, 85.18 (C^{3,8}), 59.8 (C^2), 52.73, 52.02 (OCH_3 × 2), 52.2 (C^{11}), 44.9, 32.3, 27.6 (CH_2), 20.4 (CH_3), 17.9 (CH_2), 12.4 (CH_3). ^{31}P{^{1}H} NMR (121 MHz): δ 8.5. ESI-MS: 899 [M]$^+$, 757 [M − DMAD]$^+$. Crystal data for **2**. C_6H_{12}: $C_{42}H_{47}O_5OsPS_4$, M_w = 981.27, monoclinic, $P2_1/n$ (#14), a = 12.6976(2) Å, b = 9.8747(1) Å, c = 33.4827(4) Å, β = 98.5399(5)°, V = 4151.68(9) Å^3, Z = 4, ρ_{calc} = 1.570 g cm^{-3}, T = 200 K, colorless needle, 9591 independent measured reflections [$2\theta \leq 55°$], R_1 = 0.0235, wR_2 = 0.0261, 6524 absorption-corrected reflections [$I > 3\sigma(I)$], 467 parameters, CCDC 247964.

(9) Sato, M.; Sensui, M.-A. *Chem. Lett.* **1996**, 991. (b) Lee, J.-C.; Tomita, I.; Endo, T. *Chem. Lett*. **1998**, 121. (c) For a general review of the organometallic chemistry of thiones and thioaldehydes see: Fischer, H.; Stumpf, R.; Roth, G. *Adv. Organomet. Chem.***1998**, *43*, 125.

(10) Hill, A. F.; Rae, A. D.; Schultz, M.; Willis, A. C. Manuscript in preparation.

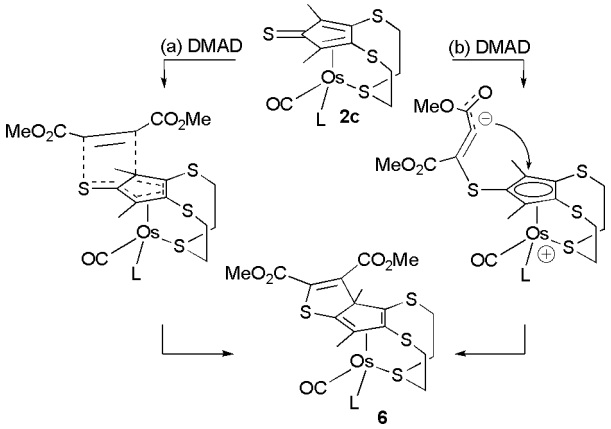
(11) (a) Tominaga, Y.; Morita, Y.; Matsuda, Y.; Kobayashi, G. *Chem. Pharm. Bull.* **1975**, *23*, 2390. (b) Gotthardt, H.; Nieberl, S. *Liebigs Ann. Chem*. **1980**, 867. (c) Gotthardt, H.; Nieberl, S.; Dönecke, J. *Liebigs Ann. Chem*. **1980**, 873. (d) Okuma, K.; Shiki, K.; Sonoda, S.; Koga, Y.; Shioji, K.; Kitamura, T.; Fujiwara, Y.; Yokomori, Y. *Bull. Chem. Soc. Jpn*. **2000**, *73*, 155. (e) Ohmura, H.; Motoki, S. *Bull. Chem. Soc. Jpn*. **1984**, *57*, 1131. (f) Jutzi, P.; Schwartzen, K.-H.; Mix, A.; Stammler, H.-G.; Neumann, B. *Chem. Ber*. **1993**, *126*, 415.

Scheme 1[a]



[a] L = PPh_3, DMAD = dimethylacetylenedicarboxylate, * = proposed intermediate.

Scheme 2. (a) Concerted vs (b) Zwitterionic Routes for the Cycloaddition of DMAD to 2c



C8−C9 bond length of 1.409(5) Å that is by far the shortest in the ring. While ring strain and substituent bulk may well be factors, the contribution of a σ,σ',π-but-2-ene-1,4-diyl osmium(II) canonical form to the overall bonding description should be considered. Consistent with this perspective, we note that the bonds from osmium to C3 and C11 are significantly shorter than those to C8 and C9 (8σ and 18σ, respectively). Tethering of the pendant thioether (S2) does not appear to induce any strain on the cyclopentadiene coordination, given that Os−C8 and Os−C9 are not significantly different in length.

In conclusion, a complex tricyclic polythioether macrocycle has been constructed in two steps. The question of generality arises, with respect to both the potential range of dipolarophiles and the range of α,ω diynes that might be similarly co-cyclized. While we have not yet investigated the latter, preliminary studies of the former have been somewhat disappointing. This is not through any flaw in the basic principle, but rather through the practical caveat that we have not yet identified a nonreactive solvent in which **2c** is sufficiently soluble for study. For the strongly electrophilic dipolarophile DMAD, the reaction with **2c** is sufficiently rapid in CH_2Cl_2 that no **5**·Cl is observed. With the, albeit limited, range of alternative dipolarophiles investigated in dichloromethane[12] either mixtures of compounds were obtained or, more commonly, formation of **5**·Cl predominated. Nevertheless, variation in the co-ligands and alkyne substitution should be possible to enhance the solubility of analogues of **2c**. Thus, the synthesis of **6** at least indicates a conceptual approach to macrocycle synthesis that offers much potential for development.

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Supporting Information Available: Full details of the crystal structure analysis of **6**·C_6H_{12} (CCDC247964). This material is available free of charge via the Internet at http://pubs.acs.org.

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(12) Preliminary studies (^{31}P NMR, CD_2Cl_2) indicate that tetracyanoethylene leads to a mixture of at least four as yet unidentified species; methylbutynoate provides predominately d_2-**5**·Cl with a small amount of an adduct presumed to be an analogue of **6** but with undefined regiochemistry; maleic anhydride, dimethylmaleate, and dimethylfumarate failed to compete with the solvent, resulting in exclusive formation of d_2-**5**·Cl, a disappointing result given the possibility of these educts forming two further stereogenic centers in the hypothetical adducts.