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# Stereospecific Oxidative Demetallation of Highly Functionalized CpCo(1,3-Diene) Complexes: An Experimental and Computational Study

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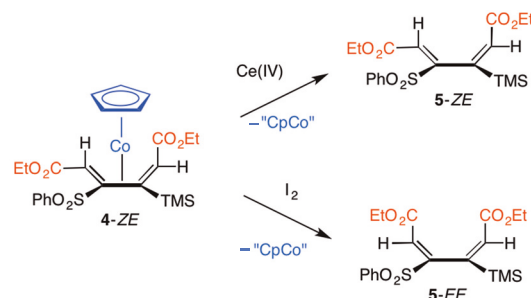
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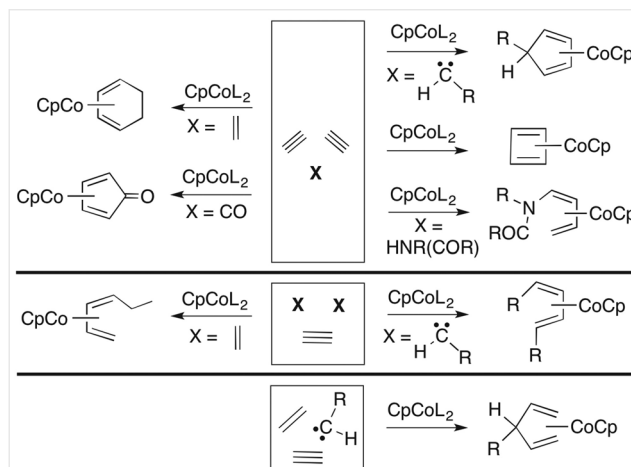
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**Abstract** Three diastereomers of a highly functionalized tetrasubstituted cyclopentadienylcobalt–diene complex,  $(\text{Cp})\text{Co}[\eta^4\text{-CH}(\text{CO}_2\text{Et})=\text{C}(\text{SO}_2\text{Ph})\text{C}(\text{SiMe}_3)=\text{CH}(\text{CO}_2\text{Et})]$  (**4-ZE**, **4-EZ**, **4-ZZ**; Cp = C<sub>5</sub>H<sub>5</sub>), undergo oxidative demetallation by ceric ammonium nitrate (CAN) to give the corresponding metal-free dienes,  $\text{CH}(\text{CO}_2\text{Et})=\text{C}(\text{SO}_2\text{Ph})\text{C}(\text{SiMe}_3)=\text{CH}(\text{CO}_2\text{Et})$  (**5-ZE**, **5-EZ**, **5-ZZ**), with retention of configuration. The oxidation of **4-ZE** by iodine occurs with a different stereoselectivity than that observed with CAN, to provide the fourth diastereomer **5-EE** in high yield. B97D/Def2-TZVPP(CH<sub>2</sub>Cl<sub>2</sub>) calculations predict the diene free-energy ordering as: **5-EE** < **5-ZE** < **5-EZ** < **5-ZZ**.

**Key words** cobalt, diene, oxidation, computation, demetallation

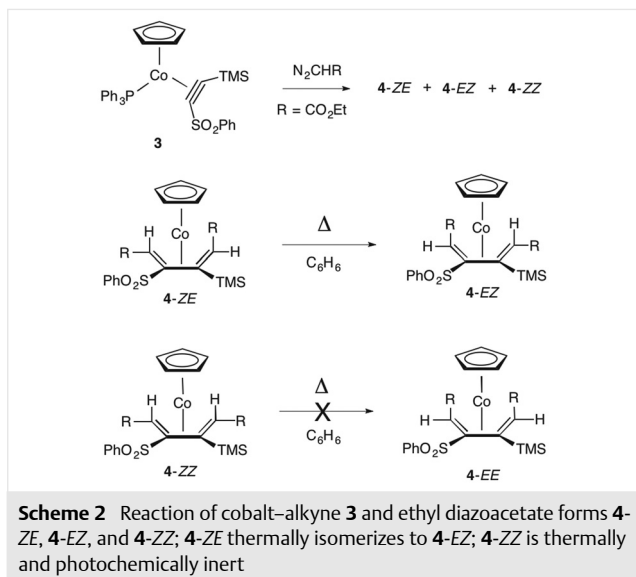
Cyclopentadienylcobalt-mediated conversions of alkynes to diene complexes occupy a privileged position in the development of metal–diene chemistry. First reported in 1970 by Yamazaki,<sup>2</sup> and ingeniously developed for the synthesis of complex molecules by Vollhardt and others,<sup>3–15</sup> CpCo–alkyne complexes play a central role in an impressive array of alkyne to cobalt- $\eta^4$ -diene conversions (Scheme 1).

Ideally, oxidative diene demetallation, for example by cerium(IV), copper(II), or iron(III),<sup>11–14</sup> cleanly separates the CpCo from the diene fragment and yields useful products for organic synthesis. Such is the typical case for CpCo–cyclohexadiene<sup>11</sup> and CpCo–cyclopentadiene<sup>12</sup> complexes, although overoxidation to form aromatic products may occur.<sup>8,12</sup> Oxidative demetallation of acyclic diene complexes<sup>8,9a,d,12</sup> may result in *cis-trans* isomerization.<sup>8</sup>



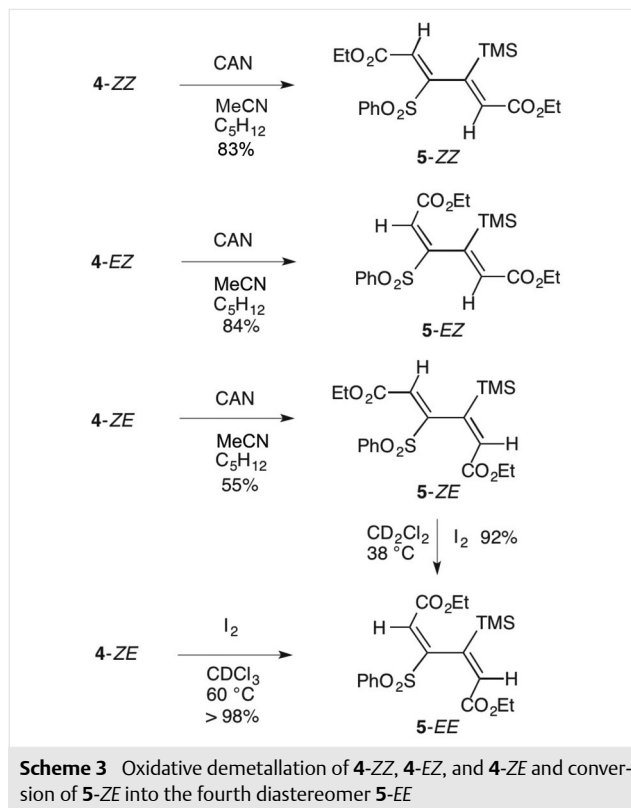
**Scheme 1** Representative alkyne routes toward CpCo- $\eta^4$ -diene complexes (Cp = C<sub>5</sub>H<sub>5</sub>; L = CO, Ph<sub>3</sub>P, cyclooctadiene, ethylene)

Cp(PPh<sub>3</sub>)Co(TMSC≡CSO<sub>2</sub>Ph) (**3**; Cp = C<sub>5</sub>H<sub>5</sub>) reacts with ethyl diazoacetate to form the highly functionalized tetrasubstituted diene complexes **4-ZE**, **4-EZ**, and **4-ZZ** in a 3:1:6 ratio, with no evidence for formation of **4-EE** (Scheme 2).<sup>9d,14</sup> Heating a benzene solution of **4-ZE** at 70 °C results in an ca. 30:1 equilibrium mixture of **4-EZ**/**4-ZE** without formation of **4-ZZ**; **4-ZZ** is thermally and photochemically inert. This stereoselective isomerization at the diene termini of **4-ZE** is presumably coupled mechanistically to a switch of the metal from one face of the diene to the other.<sup>15</sup>



Access to **4-ZE**, **4-EZ**, and **4-ZZ** presented an opportunity to explore stereochemical control in the oxidative demetallation of highly functionalized acyclic diene complexes. Oxidation of **4-ZZ** (0.022 mmol) was carried out using ceric ammonium nitrate (CAN; 0.673 mmol) in 1:1 acetonitrile-pentane solution at  $-78^{\circ}\text{C}$ .<sup>16</sup> Removal of the volatiles after 18 hours at  $4^{\circ}\text{C}$  followed by chromatographic purification led to the isolation of **5-ZZ** in 83% yield (Scheme 3).<sup>17</sup> In a similar fashion, **4-EZ** and **4-ZE** were subjected to oxidative demetallation with CAN to give **5-EZ** (84% yield) and **5-ZE** (55% yield), respectively. The assigned configuration of the liberated dienes is consistent with a series of NOE studies ( $\text{CDCl}_3$ ).<sup>17-19</sup> The vinyl hydrogen resonances in the  $^1\text{H}$  NMR spectrum of **5-ZZ** are observed at  $\delta = 5.80$  and  $5.98$ . Irradiation of the TMS hydrogen resonance enhanced the  $\delta = 5.98$  but not the  $5.80$  resonance. A similar experiment for **5-EZ** gave a large NOE at the  $\delta = 6.77$  resonance (H2), with no NOE at the  $\delta = 5.49$  resonance (H5); whereas for **5-ZE**, large NOE were observed at both the  $\delta = 6.21$  and  $6.02$  resonances. Thus, oxidative demetallation of all three complexes of **4** liberates the diene ligand with retention of configuration.

In an effort to prepare **5-EE** – the diene diastereomer not accessible directly from cobalt-alkyne complex **3** and ethyl diazoacetate – iodine-catalyzed isomerization of **5-ZE** was examined by monitoring a  $\text{CD}_2\text{Cl}_2$  solution of **5-ZE**, iodine, and ethyl acetate as an internal standard at  $38^{\circ}\text{C}$  by  $^1\text{H}$  NMR spectroscopy. After 336 hours, the resonances for **5-ZE** were absent and a new set of resonances indicated clean conversion into **5-EE** in 92% yield. Access to **5-EE** is facilitated by utilizing iodine as oxidant and isomerization catalyst in a one-pot oxidation-isomerization process. Thus, oxidation of **4-ZE** with iodine in chloroform at  $60^{\circ}\text{C}$  led to the clean formation of **5-EE** in quantitative yield. Un-

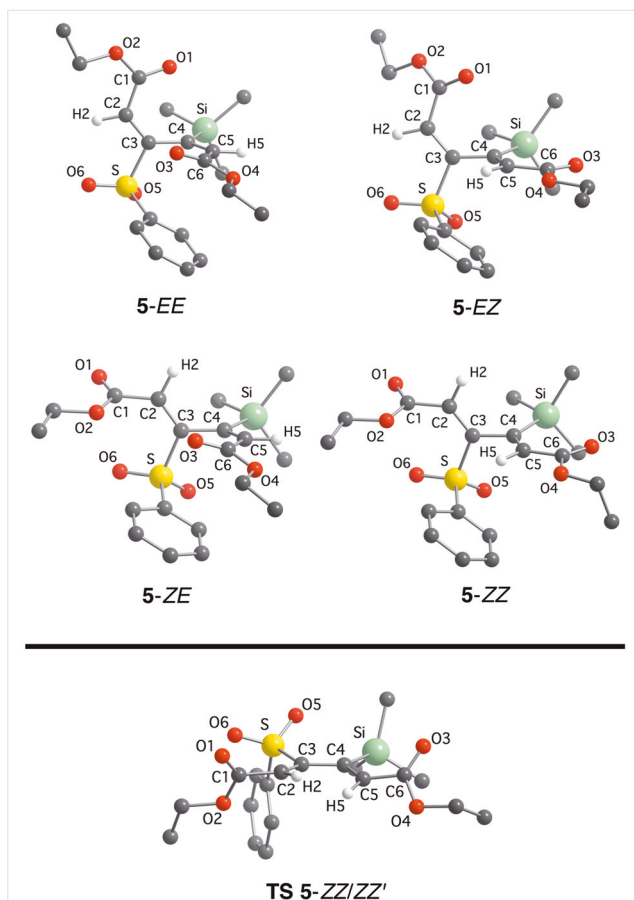


expectedly, **5-ZZ** and **5-EZ** proved to be stable toward iodine-catalyzed isomerization under similar conditions.

B97D/Def2-TZVPP( $\text{CH}_2\text{Cl}_2$ ) calculations enabled the investigation of relative energy and structural features of the four diastereomers of **5** (Table 1, Figure 1).<sup>17</sup> The relative free energies are **5-EE** (0 kcal/mol) < **5-ZE** (1.49 kcal/mol) < **5-EZ** (1.50 kcal/mol) < **5-ZZ** (1.92 kcal/mol).<sup>19</sup> The computed free energies harmonize with the observed isomerization of **5-ZE** to **5-EE** by iodine, and suggest that a nonstereospecific oxidative demetallation of **5-ZE**, **5-EZ**, and **5-ZZ** by CAN would have generated significant amounts of **5-EE**. The similar and high free-energy values for **5-ZE** and **5-EZ** suggest that, in contrast with correlated isomerization between complexes **4-ZE** and **4-EZ** (cf. Scheme 2), **5-ZE** and **5-EZ** are more likely to form **5-EE** than interconvert with each other. The steric bulk of the phenyl sulfone and trimethylsilyl substituents at C3 and C4, respectively, leads to minimum energy structures in which the S–C3–C4–Si torsion angles are close to  $90^{\circ}$ : **5-EE**-calc ( $87.1^{\circ}$ ), **5-ZE**-calc ( $86.1^{\circ}$ ), **5-EZ**-calc ( $96.1^{\circ}$ ), and **5-ZZ**-calc ( $92.2^{\circ}$ ). The barrier to rotation about the C3–C4 bond in **5-ZZ** is computationally found to be 18.5 kcal/mol ( $\text{CH}_2\text{Cl}_2$ ), which would indicate an isomerization slow relative to the NMR time scale at room temperature, but still too fast to resolve atropisomers cleanly by normal separation methods at room temperature.

**Table 1** Select B97D/Def2-TZVPP(CH<sub>2</sub>Cl<sub>2</sub>) Bond Distances (Å), Angles (°), and Relative Energies (kcal/mol) for **5**<sup>18</sup>

Isomer	5-ZE	5-EZ	5-EE	5-ZZ	TS 5-ZZ/ZZ'
C2–C3	1.337	1.340	1.344	1.337	1.353
C3–C4	1.480	1.475	1.465	1.486	1.501
C4–C5	1.350	1.351	1.350	1.352	1.360
C3–S	1.820	1.839	1.843	1.819	1.838
C4–Si	1.926	1.941	1.931	1.934	1.967
S–C3–C4–Si	86.11	96.06	87.08	92.24	–6.65
C1–C2–C3–S	3.47	–175.76	–174.60	–0.64	13.29
Si–C4–C5–C6	178.27	–2.29	178.20	–3.58	21.26
C3–C2–C1–O1	–109.36	–30.91	14.46	–104.49	–124.11
C4–C5–C6–O3	–22.79	1.10	–18.17	3.23	38.41
relative energy	1.49	1.50	0.0	1.92	20.4 (18.5) <sup>a</sup>

<sup>a</sup> Relative to 5-Z.**Figure 1** B97D/Def2-TZVPP(CH<sub>2</sub>Cl<sub>2</sub>) calculated ground-state structures for the four diastereomers of **5**, plus the TS 5-ZZ/ZZ'. Energies and geometries are listed in Table 1.

The DFT computations predict **5-EZ** and **5-EE** to have *anti*-periplanar C3=C2–C1=O and C4=C5–C6=O3 conformations (1.1 to –18.2°), which permits  $\pi$ -delocalization within each  $\alpha,\beta$ -unsaturated ester. In the case of **5-ZE** and **5-ZZ**, steric congestion between the *syn*-sulfone and ester substituents disrupts  $\pi$ -delocalization and results in minimum-energy clinal C3=C2–C1=O conformations (–109.4 and –104.5°). A similar steric effect presumably contributes to the thermal isomerization of **4-ZE** to **4-EZ** (cf. Scheme 2).

Comparison of the experimental NMR and NOE intensities to the computed chemical shifts and closest H(TMS)–H(#)) distances provides additional support for the configurational assignments (Scheme 3, Table 2). The minimum average deviation of experimental from calculated shifts for H1 and H2 is  $\delta = 0.27$  and 0.49 ppm, respectively. The computed distances between the hydrogens of TMS and H1 and H2 as assigned allowed a threshold value of 3.5 Å for the observation of a NOE; all distances below the threshold correlated with the experimentally observed NOEs; distances above the threshold did not.

**Table 2** Experimental and Computed NMR and NOE Data for **5**

Isomer:	5-ZE	5-EZ	5-EE	5-ZZ
$\delta$ H1 exptl	6.02	6.77	6.77	5.98
$\delta$ H1 calcd	6.20	7.15	7.10	6.15
$\delta$ H2 exptl	6.21	5.49	6.11	5.80
$\delta$ H2 calcd	6.51	4.75	6.22	5.01
$\delta$ (TMS–H1) <sup>a</sup>	2.14	3.57	3.86	3.00
NOE	yes	yes	–	yes
$\delta$ (TMS–H2) <sup>a</sup>	2.57	4.61	2.44	4.61
NOE	yes	no	–	no

<sup>a</sup> Closest TMS hydrogen to vinyl hydrogen nonbonded distances.

In summary, all four diastereomers of **5** can be obtained selectively, by either direct stereospecific oxidative demetalation of the configurationally correspondent complex of **4** to form **5-ZZ**, **5-EZ**, and **5-ZE** or by stereoselective oxidative demetalation of **4-ZE** with iodine to form the thermodynamically favored **5-EE**. Such clean processes bode well for the further application of metal-mediated alkyne-to-diene chemistry in organic synthesis.

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## Supporting Information

Supporting information for this article is available online at <http://dx.doi.org/10.1055/s-0035-1560092>.

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- (16) **Representative Oxidation Procedure**  
Diene complex ZZ-( $\eta^5$ -C<sub>5</sub>H<sub>5</sub>)Co[ $\eta^4$ -CH(CO<sub>2</sub>Et)=C(SO<sub>2</sub>Ph)C(TMS)=CH(CO<sub>2</sub>Et)] (**4-ZZ**; 0.120 g, 0.224 mmol) was dissolved in a 1:1 mixture (20 mL) of MeCN–pentane, and CAN (0.369g, 0.673 mmol) was added at –78 °C. The reaction was stirred at 4 °C for 18 h. Removal of volatiles, extraction of the residue with benzene, and chromatography (silica gel, 10% EtOAc–hexanes) gave **5-ZZ** (76 mg, 83%) as a yellow oil. For representative spectroscopic data see ref. 18.
- (17) See Supporting Information for characterization data.
- (18) The experimental (CDCl<sub>3</sub>) and calculated (CH<sub>2</sub>Cl<sub>2</sub>) vinyl hydrogen chemical shifts and assignments are as follows. For **5-ZZ**:  $\delta$  = 5.98 (H<sub>2</sub>; calcd 6.14), 5.80 (H<sub>5</sub>, calcd 5.01); for **5-EZ**:  $\delta$  = 6.77 (H<sub>2</sub>; calcd 6.88), 5.49 (H<sub>5</sub>, calcd 4.75); for **5-ZE**:  $\delta$  = 6.21 (H<sub>2</sub>; calcd 6.20), 6.02 (H<sub>5</sub>, calcd 6.51); for **5-EE**:  $\delta$  = 6.77 (H<sub>2</sub>; calcd 7.10), 6.11 (H<sub>5</sub>, calcd 6.22).
- (19) See Supporting Information for all computational details.