Mechanism of Cyclopropanation Reactions Mediated by (5,10,15,20-Tetra-*p*-tolylporphyrinato)osmium(II) Complexes

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Catalytic systems derived from $[Os(TTP)]_2$ or Fe(TTP) (TTP = 5,10,15,20-tetra-*p*-tolylporphyrinato) are extremely efficient at converting styrenes and diazo reagents to cyclopropanes in high yields and high stereoselectivity. A number of mechanistic studies have been undertaken to elucidate the catalytic pathway. A mono(carbene) complex, (TTP)Os=$CHCO_2Et$, has been isolated but is not the catalytically active species. An electron-withdrawing ligand *trans* to the carbene in (TTP)Os=$CHCO_2Et$ activates the carbon fragment toward transfer to an olefin. Labeling studies with (TTP)Os=CHX and N_2CHY and substrate reactivity profiles are consistent with a *trans*-osmium(II) bis(carbene) species as the active catalyst.

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Introduction

On the basis of the volume of publications, one can place cyclopropanation of alkenes with diazoalkanes, carbon−hydrogen bond insertion, and olefin formation among the most studied metal-mediated organic transformations.[1] Although a good understanding of the factors influencing the stereochemistry and chemoselectivity has been obtained from systematic studies, the nature of the actual intermediates involved in these processes, often called "carbenoids," is still the subject of speculation. Most of the above-mentioned transformations involve interaction of the diazoalkane reagent with the active metal center of the catalyst.[2] The nature of the resulting organometallic species has been ascertained only in rare cases as being a metal−carbene, metal−diazoalkyl, or metal−ylide complex. Due to the transient nature of these intermediates, spectroscopic detection has been achieved in few cases.[3] Recent spectroscopic studies of (porphyrinato)rhodium(III)-catalyzed cyclopropanation reactions provided evidence for the formation of a (porphyrinato)rhodium−diazoalkyl complex when the former complex was treated with ethyl diazoacetate at low temperature.[4] During the course of our work in this area, Simonneaux,[5] Che,[6] and Nishiyama[7] reported evidence for the involvement of ruthenium carbene complexes in catalytic cyclopropanation studies.

In our recent reports we described the efficiency of osmium(II) porphyrin complexes, such as (TTP)OsLL′ (L = L′ = py, **1a**; L = py, L′ = CO, **1b**) and $[Os(TTP)]_2$[8]

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(8) Abbreviations used: TTP = dianion of *meso*-tetra-*p*-tolylporphyrin; py = pyridine; THF = tetrahydrofuran; EDA = ethyl diazoacetate; Mes = 1,3,5-trimethylphenyl; Por = generic porphyrinato dianion.

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(**2**), and iron (II) porphyrin complexes, Fe(TTP) (**3**), for the catalysis of olefin formation from diazoalkanes and for the stereoselective cyclopropanation of alkenes with diazoalkanes.[9] We demonstrated that neutral mono(alkylidene) species form upon treatment of $[Os(TTP)]_2$ by diazoalkanes. Two examples of these mono(alkylidene) complexes have been characterized by X-ray crystallography.[10] These isolable mono(alkylidene) complexes can act as catalysts or stoichiometric reagents in cyclopropanation reactions. Preliminary studies showed that (TTP)Os=CH(CO_2Et) (**4a**), used stoichiometrically or catalytically, can promote stereoselectively the cyclopropanation of styrene, giving similar yields of products in both cases. However, mono(alkylidene) complexes react slowly with alkenes compared to the analogous catalytic reaction. Herein, we bring further insight into the mechanism of osmium(II) porphyrin catalyzed cyclopropanation of alkenes by diazoalkanes.

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Experimental Section

General Methods. All manipulations of reagents and products were carried out under a dry nitrogen atmosphere using a Vacuum Atmospheres glovebox equipped with a Model MO40H DriTrain gas purification system or on a vacuum line using Schlenk techniques. All solvents were dried and distilled from purple solutions of sodium benzophenone ketyl radical. ^{1}H NMR and ^{13}C NMR spectra were recorded on Nicolet NT300, Varian VXR300, Bruker DRX400, and Unity 500 spectrometers. ^{1}H NMR peak positions were referenced against residual proton resonances of deuterated solvents (δ (ppm): $CDCl_3$, 7.24; C_6D_6, 7.15). ^{13}C NMR signals were referenced against the center line of the deuterated solvent resonance (δ (ppm): $CDCl_3$, 77.10; C_6D_6, 128.00). ^{2}H NMR experiments were performed with a Bruker DRX400 spectrometer using $CDCl_3$ as the internal standard. UV−visible spectra were obtained using a Hewlett-Packard HP8452A diode array spectrometer. IR spectra were recorded using a FTS-7 BioRad Fourier transform spectrometer. Gas chromatographic analyses were performed with a HP 5890 Series II[11] or a Finnigan Magnum GC-MS.[12] Dodecane or hexamethylbenzene was used as an internal standard. High-resolution mass spectroscopy for exact mass determination was performed on a Kratos MS50 spectrometer using electron impact (EI) ionization. Ethyl diazoacetate, (trimethylsilyl)diazomethane, and olefins (Aldrich Chemical Co.) were dried over molecular sieves, degassed by three or more freeze−pump−thaw cycles, and passed through a plug of alumina (1 × 2 cm). Aryldiazomethanes were prepared by oxidation of hydrazones with yellow mercury(II) oxide in toluene or hexane[13] or by solution pyrolysis of the corresponding tosyl hydrazone.[14] Diester or β-keto ester diazo reagents were prepared by transferring a diazo group to the corresponding diester or β-keto ester α-carbon from $CH_3SO_2N_3$ under basic conditions.[15] Propyl diazoacetate was made by diazo transfer to propyl acetoacetate from $CH_3SO_2N_3$ followed by acetyl group cleavage under basic conditions in a manner similar to the preparation of other diazo reagents.[2a] Propyl acetoacetate was made by acetoacetylation of 1-propanol with 2,2,6-trimethyl-4*H*-1,3-dioxin-4-one (diketene−acetone adduct) in refluxing xylenes.[16] A literature procedure was used in the preparation of *trans*-β-deuteriostyrene.[17] Bis[(5,10,15,20-tetra-*p*-tolylporphyrinato)osmium(II)], $[Os(TTP)]_2$, was prepared from $(TTP)Os(py)_2$, according to a published procedure.[18] The bis(pyridine) complex, $(TTP)Os(py)_2$, was prepared from either (TTP)Os(CO)(py) or $(TTP)OsO_2$ by using reported methods.[19] Literature procedures were used to prepare (TTP)Os=CHCO_2Et[9a] (**4a**), (TTP)Os=C(*p*-tolyl)$_2$ (**4b**), and (TTP)Os=CHTMS (**4c**).[10] Authentic samples of ethyl 2-(4-methylphenyl)cyclopropanecarboxylic acid ester (**5d**) and ethyl 2-(4-(trifluoromethyl)-phenyl)cyclopropanecarboxylic acid ester (**5f**) were gifts from Thomas Kodadek of the University of Texas at Austin.

(TTP)Os=CH(Mes) (4d). In a glovebox, $[Os(TTP)]_2$ (53 mg, 31 μmol) was dissolved in toluene (6 mL). A solution of mesityldiazomethane (35 mL, 6.6 mM, 230 μmol) in toluene was added over a period of 5 h. The resulting mixture was concentrated to ca. 20 mL, and the product was eluted as a red-brown band on a 1 cm × 10 cm Florisil column (toluene/THF = 10/1). The red-brown fraction was taken to dryness under reduced pressure to afford an orange-brown solid (51 mg, 84% yield). ^{1}H NMR (C_6D_6): δ 20.78 (s, =C*H*Mes), 8.19 (s, 8H, H-β), 7.99 (d, 4H, $C_6H_4CH_3$, J_{HH} = 7.2 Hz), 7.89 (d, 4H, $C_6H_4CH_3$, J_{HH} = 7.2 Hz), 7.25 (m, 8H, $C_6H_4CH_3$), 5.59 (s, 2H, *m*-C_6H_2), 2.36 (s, 12H, $C_6H_4CH_3$), 1.77 (s, 3H, *p*-CH_3), −0.39 (s, 6H, *o*-CH_3). ^{13}C NMR (C_6D_6): δ 248 (d, J_{CH} = 141.1 Hz, Os=*C*). UV−vis (C_6H_6): 418 (Soret), 518, 550 nm.

(TTP)Os=CHCO$_2$CH$_2$CH$_2$CH$_3$ (4e). In a glovebox, 44 mg (26 μmol) of $[Os(TTP)]_2$ was dissolved in ca. 5 mL of benzene. A solution of propyl diazoacetate (22 mg, 170 μmol) in 5 mL of benzene was added dropwise over a period of 5 min. The solution was vigorously stirred for 2 h, after which the solvent was removed in vacuo. The crude residue was purified by chromatography on a Florisil column (1 × 10 cm), first with toluene as eluent to remove organic impurities and then with 10/1 (v/v) toluene/THF to elute a red-brown band. Removal of solvents from the red-brown fraction under reduced pressure afforded approximately 29 mg (59.1%) of a brownish red waxy solid contaminated with approximately 1 equiv of dipropyl maleate. ^{1}H NMR (C_6D_6): δ 21.82 (s, 1H, C*H*CO_2Pr), 8.36 (s, 8H, H-β), 8.03 (dd, 4H, $C_6H_4CH_3$, J_{HH} = 7.5, 1.8 Hz), 7.97 (dd, 4H, $C_6H_4CH_3$, J_{HH} = 7.5, 1.8 Hz), 7.28 (d, 4H, $C_6H_4CH_3$, J_{HH} = 7.5 Hz), 7.19 (d, 4H, $C_6H_4CH_3$, J_{HH} = 7.5 Hz), 2.61 (t, 2H, $CO_2CH_2CH_2CH_3$, J_{HH} = 6.9 Hz), 2.34 (s, 12H, $C_6H_4CH_3$), 0.67 (m, 2H, $CO_2CH_2CH_2CH_3$), 0.07 (t, 3H, $CO_2CH_2CH_2CH_3$, J_{HH} = 7.2 Hz). UV/vis (C_6H_6): 408 nm (Soret). ^{1}H NMR data for maleate: δ 5.73 (s, 2H, C=C*H*), 3.94 (t, 4H, $CO_2CH_2CH_2CH_3$, J_{HH} = 6.6 Hz), 1.39 (m, 4H, $CO_2CH_2CH_2CH_3$), 0.68 (br t, 6H, $CO_2CH_2CH_2CH_3$, J_{HH} = 7.2 Hz).

(TTP)Os=CH(*p*-tolyl) (4f). A hexanes solution of N_2CH(*p*-tolyl) (97 mM, 2.1 mL, 200 μmol) was added to a vigorously stirred solution of 62 mg (36 μmol) of $[Os(TTP)]_2$ in 10 mL of a 1/1 (v/v) mixture of toluene and THF. After 30 min, the solvents were removed in vacuo. The crude residue was purified by chromatography on a Florisil column (1 × 10 cm), first with hexanes as eluent and then 50/1 (v/v) hexanes/toluene to remove organic impurities. Complex **4f** was eluted as a red band using toluene. The red fraction was taken to dryness to yield ca. 10 mg (14%) of complex **4f**. ^{1}H NMR (C_6D_6): δ 19.85 (s, =C*H*$C_6H_4CH_3$), 8.21 (s, 8H, H-β), 8.01 (dd, 4H, $C_6H_4CH_3$, J_{HH} = 7.8, 1.2 Hz), 7.89 (dd, 4H, $C_6H_4CH_3$, J_{HH} = 7.8, 1.2 Hz), 7.27 (d, 4H, $C_6H_4CH_3$, J_{HH} = 7.8 Hz), 7.14 ($C_6H_4CH_3$, partially obscured by C_6D_5H), 5.68 (d, 2H, =CHC_6H_4-

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CH_3, J_{HH} = 7.8 Hz), 4.77 (d, 2H, =$CHC_6H_4CH_3$, J_{HH} = 8.6 Hz), 2.34 (s, 12H, $C_6H_4CH_3$), 0.41 (s, 3H, =$CHC_6H_4CH_3$).

(TTP)Os=CH(*p*-ethylphenyl) (4g). Into a round-bottom flask was placed 98 mg (57 μmol) of [Os(TTP)]$_2$ and 15 mL of a 7/2 (v/v) mixture of toluene and THF. To the vigorously stirred solution was added 5.0 mL of a 42 mM solution of N_2-CH(*p*-ethylphenyl) (210 μmol) in hexanes. After 45 min, the solvents were removed in vacuo. The crude residue was purified by chromatography on a Florisil column (1 × 10 cm), first with hexanes as eluent (ca. 400 mL) and then 50/1 (v/v) hexanes/toluene (ca. 400 mL) to remove organic impurities. Complex **4g** was eluted as a red band using toluene. The red fraction was taken to dryness to yield ca. 15 mg (13%) of complex **4g**. ^{1}H NMR (C_6D_6): δ 19.93 (s, =CHC_6H_4Et), 8.21 (s, 8H, H-β), 8.02 (dd, 4H, $C_6H_4CH_3$, J_{HH} = 7.6, 1.2 Hz), 7.88 (dd, 4H, $C_6H_4CH_3$, J_{HH} = 7.6, 1.2 Hz), 7.27 (d, 4H, $C_6H_4CH_3$, J_{HH} = 8.4 Hz), 7.14 ($C_6H_4CH_3$, partially obscured by C_6D_5H), 5.74 (d, 2H, C_6H_4Et, J_{HH} = 8.4 Hz), 4.85 (d, 2H, C_6H_4Et, J_{HH} = 8.4 Hz), 2.34 (s, 12H, $C_6H_4CH_3$), 0.99 (q, 2H, $C_6H_4CH_2$-CH_3, J_{HH} = 7.6 Hz), 0.52 (t, 3H, $C_6H_4CH_2CH_3$, J_{HH} = 7.6 Hz).

(TTP)Os=C(CO_2Et)(C(=O)$CH_2CH_2CH=CH_2$) (4h). To a solution of [Os(TTP)]$_2$ (15 mg, 8.7 μmol) in toluene (5 mL) was added a solution of $N_2C(CO_2Et)(C(=O)CH_2CH_2CH=CH_2)$ (70 mg, 360 μmol) in toluene (15 mL) over 2 h. The mixture was stirred for 20 min, at which time the solution had changed from brown to red-orange, and the solvents were removed in vacuo. The crude residue was eluted on a 1 × 10 cm Florisil column as a red-brown band, and complex **4h** was recovered quantitatively as an orange waxy solid after evaporation of solvents from the red-brown fraction. ^{1}H NMR (C_6D_6): δ 8.40 (s, 8H, H-β), 8.27 (d, 4H, $C_6H_4CH_3$, J_{HH} = 6.4 Hz), 8.03 (d, 4H, $C_6H_4CH_3$, J_{HH} = 6.4 Hz), 7.26 (m, 8H, $C_6H_4CH_3$), 5.17 (m, 1H, $CH_2CH_2CH=CH_2$), 4.65 (d, 1H, $CH_2CH_2CH=CH_2$, J_{HH} = 9.6 Hz), 4.55 (dd, 1H, $CH_2CH_2CH=CH_2$, J_{HH} = 17.2, 1.6 Hz), 2.85 (q, 2H, $CO_2CH_2CH_3$, J_{HH} = 7.2 Hz), 2.42 (s, 12H, $C_6H_4CH_3$), 1.31 (m, 2H, $CH_2CH_2CH=CH_2$), 0.34 (t, 3H, $CO_2CH_2CH_3$, J_{HH} = 7.2 Hz), −0.37 (m, 2H, $CH_2CH_2CH=CH_2$). UV−vis (toluene): 398 nm (Soret), 420 (sh), 432 (sh), 518, 572 nm. IR (KBr): ν 1704−1674 cm^{-1} (broad band, C=O). MS (FAB$^+$): *m/z* 1028 [M]$^+$, 953 [M − $CO_2C_2H_5$]$^+$, 943 [M − C_5H_7O]$^+$, 873 [M − $CO_2C_2H_5$ − C_5H_7O]$^+$, 858 [M − {C($CO_2C_2H_5$)(C_5H_7O)}]$^+$.

(TTP)Os=CMePh (4i). To a solution of [Os(TTP)]$_2$ (16 mg, 9.3 μmol) in 6 mL of benzene was added an excess of N_2CMePh in 5 mL of benzene dropwise over a period of 8 min. The resulting mixture became orange and was stirred for 1 h. The solution was placed onto a neutral alumina column. Olefins were removed by elution with benzene, and complex **4i** was eluted using 10% THF in benzene. The solvent was removed under vacuum to yield complex **4i**. ^{1}H NMR (C_6D_6): δ 8.16 (s, 8H, H-β), 8.00 (d, 4H, $C_6H_4CH_3$, J_{HH} = 7.5 Hz), 7.93 (d, 4H, $C_6H_4CH_3$, J_{HH} = 7.2 Hz), 7.26 (m, 8H, $C_6H_4CH_3$), 6.54 (t, 1H, *p*-C_6H_5, J_{HH} = 7.5 Hz), 6.26 (t, 2H, *m*-C_6H_5, J_{HH} = 7.5 Hz), 4.10 (d, 2H, *o*-C_6H_5, J_{HH} = 7.5 Hz), 2.35 (s, 12H, $C_6H_4CH_3$), −4.36 (s, 3H, =CCH_3). ^{13}C NMR (C_6D_6): δ 263.9 (d, $^2J_{CH}$ = 7.87 Hz, Os=*C*). UV−vis (C_6H_6): 410 (Soret), 424 (sh), 516, 540 nm.

Ethyl 2-Phenylcyclopropanecarboxylic Acid Ester (5a). Method A. In a typical experiment, (TTP)Os(CO)(py) (3 mg, 3 μmol), styrene (0.220 mL, 1.90 mmol), and dodecane (internal standard) were vigorously stirred in toluene (3 mL). A toluene solution (12 mL) of N_2CHCO_2Et (0.100 mL, 952 μmol) was added dropwise over 1 h. GC analysis: 14 ± 3% yield of olefin, 54 ± 8% yield of cyclopropane **5a** (trans/cis = 8.9 ± 0.5). *trans*-**5a**: ^{1}H NMR ($CDCl_3$) δ 7.3−7.0 (m, C_6H_5, partially obscured by $CHCl_3$), 4.15 (q, 2H, $CO_2CH_2CH_3$, J_{HH} = 7.1 Hz), 2.49 (m, 1H, C_3H_4), 1.87 (m, 1H, C_3H_4), 1.58 (m, 1H, C_3H_4), 1.30 (m, 1H, C_3H_4), 1.23 (t, 3H, $CO_2CH_2CH_3$, J_{HH} = 7.1 Hz). *cis*-**5a**: ^{1}H NMR ($CDCl_3$) δ 7.3−7.0 (m, C_6H_5, partially obscured by $CHCl_3$), 3.85 (q, 2H, $CO_2CH_2CH_3$, J_{HH} = 7.1 Hz), 2.50 (m, 1H, C_3H_4), 2.05 (m, 1H, C_3H_4), 1.71 (m, 1H, C_3H_4), 1.30 (m, 1H, C_3H_4), 0.95 (t, 3H, $CO_2CH_2CH_3$, J_{HH} = 7.1 Hz). Proton assignments for the major cyclopropane isomer were made by comparison to the ^{1}H NMR spectrum of an authentic sample. MS (EI): *m/z* 190 [M]$^+$, 162 [M − Et + H]$^+$, 144, 127, 117 [M − CO_2Et]$^+$, 115.

Method B. In a typical experiment, [Os(TTP)]$_2$ (3 mg, 2 μmol) and styrene (0.110 mL, 961 μmol) were vigorously stirred in toluene (3 mL). A toluene solution (12 mL) of N_2CHCO_2Et (0.100 mL, 952 μmol) was added dropwise over 1 h. GC analysis revealed only a trace of olefin and 79 ± 2% yield of cyclopropane **5a** (*trans*/*cis* = 10.2 ± 0.1).

Method C. In a typical experiment, (TTP)Os=$CHCO_2Et$ (**4a**; 4 mg, 4 μmol) and styrene (0.100 mL, 874 μmol) were vigorously stirred in toluene (3 mL). A toluene solution (12 mL) of N_2CHCO_2Et (0.100 mL, 952 μmol) was added dropwise over 1 h. GC analysis revealed only traces of diethyl maleate and diethyl fumarate and 66 ± 4% yield of cyclopropane **5a** (*trans*/*cis* = 8.9 ± 0.6).

Method D. An NMR tube was loaded with 3 mg (3 μmol) of (TTP)Os=$CHCO_2Et$ and 0.4 mL of C_6D_6. After an initial ^{1}H NMR spectrum was taken, 1 μL (9 μmol) of styrene was added via syringe and the tube was shaken vigorously. The reaction was monitored by ^{1}H NMR spectroscopy. After 4 h, the reaction was 96% complete. GC analysis indicated a *trans*/*cis* ratio of 3.3 ± 0.3.

Method E. A mixture of (TTP)Os(CO) (3 mg, 3 μmol), styrene (0.980 mL, 7.90 mmol), and 22.5 μL of dodecane was dissolved in 5 mL of toluene. A solution of ethyl diazoacetate (88 μL, 840 μmol) in 10 mL of toluene was added dropwise over 5 min. After 2 h, the GC analysis of the product mixture showed 2 ± 2% diethyl maleate and 100 ± 8% cyclopropane (*trans*/*cis* = 8.4 ± 0.2).

Ethyl 2-*n*-Hexylcyclopropanecarboxylic Acid Ester (5b). A mixture of [Os(TTP)]$_2$ (ca. 2 mg, 1 μmol), 1-octene (1.40 mL, 8.92 mmol), and 21 μL of dodecane was dissolved in 5 mL of toluene. Ethyl diazoacetate (100 μL, 951 μmol) in 10 mL of toluene was added either all in one aliquot or dropwise over a period of ca. 7 min. The reaction mixture was analyzed by GC. For the one-aliquot addition of EDA, the yields of cyclopropane and diethyl maleate fumarate were 11 ± 1% and 89 ± 4%, respectively. Using a slow addition, the cyclopropane and diethyl maleate fumarate yields were 66 ± 3% and 34 ± 2%, respectively. The cyclopropane trans/cis ratio was 4.8 ± 0.2. The *cis* and *trans* isomers have very similar ^{1}H NMR spectra. Purification of the cyclopropane was accomplished by column chromatography on SiO_2 (33 × 3.8 cm) using hexanes/ethyl acetate (25/1 v/v). The *cis* isomer was eluted with diethyl maleate fumarate and could not be isolated in pure form. The *trans* isomer was eluted as a wider band and could be isolated cleanly by collecting the latter portion of the band (222 mg, 43%). ^{1}H NMR (trans, $CDCl_3$): δ 4.09 (q, 2H, $CO_2CH_2CH_3$), 1.31 (m, 15H, *n*-$(CH_2)_5CH_3$ + 2 C_3H_4 + $CO_2CH_2CH_3$, J_{HH} = 7.2 Hz), 1.12 (m, 1H, C_3H_4), 0.86 (approximately t, 3H, *n*-$(CH_2)_5CH_3$, J_{HH} = 6.8 Hz), 0.65 (m, 1H, C_3H_4). MS (CI): *m/z* 198 [M]$^+$.

Ethyl 2-(4-Methoxyphenyl)cyclopropanecarboxylic Acid Ester (5c). Using method B, cyclopropane **5c** was prepared by treating a toluene (2 mL) mixture of [Os(TTP)]$_2$ (12 mg, 7.0 μmol) and 4-methoxystyrene (536 mg, 3.98 mmol) with a toluene (25 mL) solution of N_2CHCO_2Et (456 mg, 4.00 mmol). The addition of the diazoalkane was carried out over 4 h, and the resulting mixture was stirred overnight. The solvent was removed in vacuo, and the brown residue was dissolved in diethyl ether. The resulting solution was passed through a silica gel column in order to remove porphyrinic compounds. The solvent was removed under reduced pressure, and **5c** precipitated as pure white crystals (647 mg, 70%). Only one isomer was isolated, and it was identified as having *trans* stereochemistry by comparison of NMR data with those of **5a** and **9**. ^{1}H NMR ($CDCl_3$): δ 7.00 (d, 2H, $C_6H_4OCH_3$, J_{HH} = 8.7 Hz), 6.78 (d, 2H, $C_6H_4OCH_3$, J_{HH} = 8.7 Hz), 4.12 (q, 2H, $CO_2CH_2CH_3$, J_{HH} = 7.2 Hz), 3.75 (s, 3H, OCH_3), 2.44 (m, 1H,

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C_3H_4), 1.78 (m, 1H, C_3H_4), 1.51 (m, 1H, C_3H_4), 1.24 (t + m, 4H, $C_3H_4 + CO_2CH_2CH_3$ $J_{HH} = 7.2$ Hz). MS (EI): *m/z* 220 $[M]^+$, 191 $[M - C_2H_5]^+$, 147 $[M - C_3H_5O_2]^+$, 131, 115, 103.

Ethyl 2-(4-Chlorophenyl)cyclopropanecarboxylic Acid Ester (5e). In a glovebox, $[Os(TTP)]_2$ (2 mg, 1 μmol) and 4-chlorostyrene (2.30 mL, 44.1 mmol) were dissolved in 5 mL of THF. A solution of EDA (770 μL, 7.32 mmol) in 20 mL of THF was added dropwise over a period of 15 h. The THF was removed by rotary evaporation, and the residue was chromatographed on neutral alumina (3.5 × 35 cm) using 50/1 (v/v) hexanes/ethyl acetate. The first band was excess 4-chlorostyrene, followed by cyclopropane **5e** and then diethyl maleate and furmarate. The fractions containing only **5e** were combined, and the solvent was removed by rotary evaporation to yield 1.26 g (77%) of cyclopropane **5e**. *trans*-**5e**: ^{1}H NMR (C_6D_6) δ 6.96 (d, 2H, C_6H_4Cl, $J_{HH} = 8.4$ Hz), 6.39 (d, 2H, C_6H_4-Cl, $J_{HH} = 8.4$ Hz), 3.97 (q, 2H, $CO_2CH_2CH_3$, $J_{HH} = 7.2$ Hz), 2.39 (m, 1H, C_3H_4), 1.68 (m, 1H, C_3H_4), 1.49 (m, 1H, C_3H_4), 0.95 (t, 2H, $CO_2CH_2CH_3$, $J_{HH} = 7.2$ Hz), 0.78 (m, 1H, C_3H_4). *cis*-**5e**: ^{1}H NMR (C_6D_6) δ 7.07 (d, 2H, C_6H_4Cl, $J_{HH} = 8.4$ Hz), 6.92 (d, 2H, C_6H_4Cl, $J_{HH} = 8.4$ Hz), 3.69 (q, 2H, $CO_2CH_2CH_3$, $J_{HH} = 7.2$ Hz), 1.88 (m, 1H, C_3H_4), 1.73 (m, 1H, C_3H_4), 1.49 (m, 1H, C_3H_4), 0.75 (t, 2H, $CO_2CH_2CH_3$, $J_{HH} = 7.2$ Hz), 0.70 (m, 1H, C_3H_4).

1-Mesityl-2-phenylcyclopropane (5g). A procedure similar to method A was used to prepare cyclopropane **5c** from the complex (TTP)Os(CO)(py) (2 mg, 2 μmol), styrene (0.100 mL, 874 μmol), and N_2CH(Mes) (20 mL, 0.033 M in toluene, 660 μmol). GC analysis revealed less than 1% olefin and 99% yield of cyclopropane **5g** (*trans*/*cis* = 0.4). Assignment of the cyclopropane major isomer was made by 2D-NOESY ^{1}H NMR (500 MHz) correlation. ^{1}H NMR ($CDCl_3$): *cis* isomer, 7.02 (m, 3H, C_6H_5), 6.72 (s, 2H, $C_6H_2(CH_3)_2$), 6.44 (m, 2H, C_6H_5), 2.66 (s, 6H, CH_3), 2.54 (s, 3H, CH_3), 2.02 (m, 1H, C_3H_4), 1.97 (m, 1H, C_3H_4), 1.40 (m, 1H, C_3H_4), 1.04 (m, 1H, C_3H_4): *trans* isomer, 7.32 (t, 2H, C_6H_5, $J_{HH} = 7.6$ Hz), 7.20 (m, 3H, C_6H_5), 6.86 (s, 2H, $C_6H_2(CH_3)_2$), 2.50 (s, 3H, CH_3), 2.45 (s, 6H, CH_3), 1.84 (m, 1H, C_3H_4), 1.76 (m, 1H, C_3H_4), 1.17 (m, 1H, C_3H_4), 1.02 (m, 1H, C_3H_4). MS (EI): *m/z* 236 $[M]^+$, 221 $[M - Me]^+$, 143, 132, 115, 91 $[C_7H_7]^+$.

Propyl 2-Phenylcyclopropanecarboxylic Acid Ester (5h). In a typical experiment, 2 mg (1 μmol) of $[Os(TTP)]_2$ was dissolved in 5 mL of toluene. Styrene (1.00 mL, 906 mg, 8.70 mmol) and 21 μL of dodecane (internal standard) were added. A solution of propyl diazoacetate (109 mg, 851 μmol) was added dropwise over a period of ca. 25 min. The solution was stirred for an additional 15 h. GC analysis of the reaction mixture indicated that the yield of cyclopropane was 100 ± 3% with a *trans*/*cis* ratio of 11.5:1. ^{1}H NMR (*trans*, $CDCl_3$): δ 7.26 (t, 2H, C_6H_5, $J_{HH} = 5.4$ Hz), 7.18 (t, 1H, C_6H_5, $J_{HH} = 5.4$ Hz), 7.08 (d, 2H, C_6H_5, $J_{HH} = 5.7$ Hz), 4.06 (t, 2H, $CO_2CH_2CH_2CH_3$, $J_{HH} = 5.1$ Hz), 2.50 (m, 1H, C_3H_4), 1.89 (m, 1H, C_3H_4), 1.65 (sextet, 2H, $CO_2CH_2CH_2CH_3$, $J_{HH} = 5.4$ Hz), 1.58 (m, 1H, C_3H_4), 1.30 (m, 1H, C_3H_4), 0.94 (t, 3H, $CO_2CH_2CH_2CH_3$, $J_{HH} = 5.4$ Hz).

***endo,endo*-2,4-Bis(ethoxycarbonyl)-1-phenyl[1.1.0]bicyclobutane (6a).** Using method A, compound **6a** was prepared from (TTP)Os(CO)(py) (4 mg, 4 μmol), 50 μL (460 μmol) of phenylacetylene, and N_2CHCO_2Et (0.100 mL, 952 μmol). GC analysis indicated formation of olefin (41 ± 1% yield) along with bicyclobutane **6a** (46 ± 1% based on starting alkyne). ^{1}H NMR and GC analysis indicated that only one bicyclobutane isomer formed. The stereochemistry of compound **6a** was established as the *endo,endo* configuration on the basis of its 2D NOESY and 1D ^{1}H NMR spectra. ^{1}H NMR (C_6D_6): δ 7.66 (m, 2H, C_6H_5), 7.06 (m, 3H, C_6H_5), 3.7 (m, 4H, $CO_2CH_2CH_3$), 3.41 (s, 1H, C_4H_3), 1.71 (s, 2H, C_4H_3), 0.70 (t, 6H, $CO_2CH_2CH_3$, $J_{HH} = 7.2$ Hz). MS (EI): *m/z* 274 $[M]^+$, 229 $[M - C_2H_5O]^+$, 201 $[M - C_3H_5O_2]^+$, 183, 173, 155, 144, 127, 115. Using method B, compound **6a** was prepared from $[Os(TTP)]_2$ (4.1 mg, 2.4 mmol), 0.50 mL (4.56 mmol) of phenylacetylene in 6 mL of toluene, and N_2CHCO_2Et (1.00 mL, 9.52 mmol) in 24 mL of toluene. GC analysis indicates the formation of olefin (21% yield) and bicyclobutane **6a** (46%).

***endo,exo*-2,4-Dimesityl-1-phenyl[1.1.0]bicyclobutane (6b).** Using method A, bicyclobutane **6b** was prepared from (TTP)Os(CO)(py) (4 mg, 4 μmol), 0.100 mL (912 μmol) of phenylacetylene, and $N_2CH(2,4,6\text{-}(CH_3)_3C_6H_2)$ (31.6 mL, 0.045 M in toluene, 1.4 mmol). GC analysis indicated formation of bicyclobutane **6b** (77 ± 4% yield) along with a trace of olefin (2 ± 1% yield). ^{1}H NMR ($CDCl_3$): δ 7.09 (m, 3H, C_6H_5), 6.97 (dd, 2H, C_6H_5, $J_{HH} = 7.8$, 1.8 Hz), 6.84 (s, 2H, C_6H_2), 6.77 (s, 2H, C_6H_2), 3.39 (d, 1H, C_4H_3, $J_{HH} = 3.2$ Hz), 2.65 (dd, 1H, C_4H_3, $J_{HH} = 3.2$, 1.8 Hz), 2.56 (s, 3H, CH_3), 2.48 (s, 3H, CH_3), 2.39 (br-s, 1H, C_4H_3), 2.26 (s, 3H, CH_3), 2.24 (s, 3H, CH_3), 2.22 (s, 6H, CH_3). A 2D COSY experiment showed cross-peaks between both the doublet at 3.39 ppm and the broad singlet at 2.39 ppm with the doublet of doublets at 2.65 ppm. The product was assigned to have *endo,exo* stereochemistry on the basis of 1D and 2D ^{1}H NMR studies. High-resolution MS (EI): *m/z* found (calcd) 366.234 54 (366.234 75).

1,1-Di-*p*-tolyl-2-phenylcyclopropane (7a). $[Os(TTP)]_2$ (1 mg, 0.6 μmol), styrene (0.200 mL, 1.75 mmol), and $N_2C(tolyl)_2$ (20 mg, 90 μmol) were vigorously stirred in THF (3 mL). After 4 days the solvent was removed under reduced pressure. The yield was determined by ^{1}H NMR peak integration analysis of the porphyrin β-pyrrole proton (8.18 ppm) to the cyclopropane derivative (**7a**) signal at 2.78 ppm and confirmed by integration of styrene resonances at 5.6 and 5.1 ppm. GC analysis indicated the formation of only one cyclopropane derivative **7a** (39% yield). ^{1}H NMR (C_6D_6): δ 7.20 (d, 2H, C_6H_4-CH_3, $J_{HH} = 8.1$ Hz), 7.02 (d, 2H, $C_6H_4CH_3$, $J_{HH} = 8.1$ Hz), 7.0−6.8 (m, 7H, $C_6H_5 + C_6H_4CH_3$), 6.78 (d, 2H, $C_6H_4CH_3$, $J_{HH} = 7.8$ Hz), 2.78 (dd, 1H, C_3H_3, $J_{HH} = 8.7$, 6.6 Hz), 2.11 (s, 3H, CH_3), 1.96 (s, 3H, CH_3), 1.83 (dd, 1H, C_3H_3, $J_{HH} = 6.6$, 5.4 Hz), 1.60 (dd, 1H, C_3H_3, $J_{HH} = 9.0$, 5.4 Hz). MS (EI): *m/z* 298 $[M]^+$.

Dimethyl 2-Phenylcyclopropane-1,1-dicarboxylic Acid Diester (7b). In a typical reaction, 3 mg (2 μmol) of $[Os(TTP)]_2$ styrene (890 mg, 8.53 mmol), and dodecane (21 μL) were dissolved in 15 mL of benzene. Dimethyl diazomalonate (150 mg, 949 μmol) was added to the reaction mixture. The solution was stirred, and yields were determined periodically by gas chromatography. The reaction takes ca. 7 h to complete, significantly longer than with monoester diazo reagents. The yield was 100 ± 4% by GC analysis. ^{1}H NMR ($CDCl_3$): δ 7.30−7.15 (m, 5H, C_6H_5), 3.79 (s, 3H, CO_2CH_3), 3.36 (s, 3H, CO_2CH_3), 3.23 (t, 1H, C_3H_3, $J_{HH} = 8.7$ Hz), 2.20 (dd, 1H, C_3H_3, $J_{HH} = 8.1$ Hz, 5.2 Hz), 1.74 (dd, 1H, C_3H_3, $J_{HH} = 9.3$ Hz, 5.1 Hz). MS (EI): *m/z* 235 $[M + H]^+$, 202 $[M - OMe - H]^+$, 170 $[M - 2OMe - 2H]^+$, 121, 115.

Diethyl 2-Phenylcyclopropane-1,1-dicarboxylic Acid Diester (7c). To 15 mL of benzene was added 900 mg (8.7 mmol) of styrene, 4 mg (2 μmol) of $[Os(TTP)]_2$, and dodecane (internal standard). Diethyl diazomalonate (176 mg, 946 μmol) was added. The reaction mixture was stirred vigorously and monitored periodically by GC. The reaction was complete in ca. 8 h. The yield was 100 ± 7% by GC analysis. ^{1}H NMR ($CDCl_3$): δ 7.21 (m, 5H, C_6H_5), 4.22 (m, 2H, $CO_2CH_2CH_3$), 3.82 (q, 2H, $CO_2CH_2CH_3$, $J_{HH} = 7.2$ Hz), 3.20 (t, 1H, C_3H_3, $J_{HH} = 8.4$ Hz), 2.15 (dd, 1H, C_3H_3, $J_{HH} = 8.0$, 5.2 Hz), 1.68 (dd, 1H, C_3H_3, $J_{HH} = 9.2$, 5.2 Hz), 1.28 (t, 3H, $CO_2CH_2CH_3$, $J_{HH} = 7.2$ Hz), 0.84 (t, 3H, $CO_2CH_2CH_3$, $J_{HH} = 7.2$ Hz). MS (EI): *m/z* 262 $[M^+]$, 216 $[M - OEt + H]^+$, 170 $[M - 2OEt + 2H]^+$, 135, 115.

Ethyl 2-Oxo[3.1.0]bicyclohexanecarboxylic Acid Ester (8). Method A. To a solution of $[Os(TTP)]_2$ (4 mg, 2 μmol) in toluene (20 mL) was added 270 μL (1.4 mmol) of $N_2C(CO_2Et)$-$[C(=O)CH_2CH_2CH=CH_2]$. The solution was refluxed for 2 days. Solvent was removed under reduced pressure. The mixture was taken up in pentane and purified by chromatography over Al_2O_3 (2 × 20 cm) using pentane as the eluent. The fractions containing **8** were combined and the pentane removed by rotary evaporation (42% yield). ^{1}H NMR (C_6D_6):

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δ 4.03 (m 2H, $CO_2CH_2CH_3$), 2.00 (m, 1H), 1.72 (m, 1H), 1.66 (m, 1H), 1.48 (m, 1H), 1.27 (m, 1H), 1.06 (m, 1H), 1.01 (t, 3H, $CO_2CH_2CH_3$, J_{HH} = 7.8 Hz), 0.57 (br t, 1H, J_{HH} = 5.0 Hz). MS (EI): *m*/*z* 168 $[M]^+$, 139 $[M - C_2H_5]^+$, 123 $[M - OC_2H_5]^+$, 95 $[M - CO_2C_2H_5]^+$, 85, 67, 55.

Method B. A frozen benzene-d_6 or toluene-d_8 solution of complex **4h** in an NMR tube was pressured to less than 1 atm of carbon monoxide. The tube was flame-sealed, the frozen solid was thawed, and the reaction was monitored by ^{1}H NMR spectroscopy in a cooled NMR probe. Formation of cyclopropane **8** was rapid, even at 10 °C.

Ethyl 2-Methyl-2-phenylcyclopropanecarboxylic Acid Ester (9). In a typical reaction, ca. 4 mg (2 μmol) of $[Os(TTP)]_2$ was dissolved in 5 mL of toluene. Dodecane (18 μL, internal GC standard) and α-methylstyrene (1.00 mL, 7.62 mmol) were added. A solution of ethyl diazoacetate (89 mg, 780 μmol) in 10 mL of toluene was added dropwise over ca. 10 min. The reaction mixture was stirred for approximately 3 h and analyzed by gas chromatography. The yield of cyclopropane **9** was 100 ± 5% (*trans*/*cis* ratio of 2.5 ± 0.1). The major isomer, as determined by 500 MHz NOESY ^{1}H NMR correlation, had the ethyl carboxylate group *trans* to the phenyl group. Compound **9**, *trans* isomer: ^{1}H NMR ($CDCl_3$) δ 7.3−7.1 (m, C_6H_5, partially obscured by $CHCl_3$), 4.15 (m, 2H, $CO_2CH_2CH_3$, J_{HH} = 7.1 Hz), 1.92 (m, 1H, C_3H_3), 1.49 (s, 3H, CH_3), 1.40 (m, 1H, C_3H_3), 1.37 (m, 1H, C_3H_3), 1.26 (t, 3H, $CO_2CH_2CH_3$, J_{HH} = 7.1 Hz). Compound **9**, *cis* isomer: ^{1}H NMR ($CDCl_3$) δ 7.3−7.1 (m, C_6H_5, partially obscured by $CHCl_3$), 3.8 (m, 2H, $CO_2CH_2CH_3$, J_{HH} = 7.1 Hz), 1.86 (m, 1H, C_3H_3), 1.74 (m, 1H, C_3H_3), 1.43 (s, 3H, CH_3), 1.10 (m, 1H, C_3H_3), 0.90 (t, 3H, $CO_2CH_2CH_3$, J_{HH} = 7.1 Hz). MS (EI): *m*/*z* 204 $[M]^+$, 189 $[M - CH_3]^+$, 175 $[M - C_2H_5]^+$, 159 $[M - C_2H_5O]^+$, 147, 131 $[M - C_3H_5O_2]^+$, 115.

Ethyl *cis*-2-Methyl-*trans*-3-phenylcyclopropanecarboxylic Acid Ester (10). Using method A, cyclopropane **10** was prepared from 4 mg (4 mmol) of (TTP)Os(CO)(py), 0.120 mL (926 μmol) of *trans*-β-methylstyrene, and N_2CHCO_2Et (0.100 mL, 952 μmol). GC analysis indicated major formation of olefin (43 ± 2% yield) and minor formation of cyclopropane **10** (13 ± 2% yield). ^{1}H NMR ($CDCl_3$): δ 7.3−7.1 (m, 5H, C_6H_5), 3.99 (m, 2H, $CO_2CH_2CH_3$), 2.61 (~t, 1H, C_3H_3, J_{HH} = 9.0 Hz), 2.05 (dd, 1H, C_3H_3, J_{HH} = 9.0, 17 Hz), 1.38 (m, 1H, C_3H_3), 1.27 (d, 3H, CH_3, J_{HH} = 6.6 Hz), 0.97 (t, 3H, $CO_2CH_2CH_3$, J_{HH} = 7.1 Hz). MS (EI): *m*/*z* 204 $[M]^+$, 189 $[M - CH_3]^+$, 175 $[M - C_2H_5]^+$, 158, 131 $[M - C_3H_5O_2]^+$, 115, 103, 91.

Reaction of (TTP)Os=CHCO$_2$Et (4a) with Styrene and Ethyl Diazoacetate. To a solution of complex **4a** (4 mg, 4 μmol) in toluene (3 mL) was added styrene (100 μL, 874 μmol). Ethyl diazoacetate (100 μL, 952 μmol) in toluene (12 mL) was added dropwise for 50 min. The resulting solution was stirred overnight and analyzed by GC-MS. GC analysis: cyclopropane **5a**, 65 ± 4% yield (*trans*/*cis* = 9) with traces of diethyl maleate/diethyl fumarate.

Reaction of (TTP)Os=CH(Mes) (4d) with N_2CHCO_2Et and Styrene. Complex **4d** (10 mg, 11 μmol) was stirred in 0.5 mL of toluene. A toluene mixture (0.5 mL) of ethyl diazoacetate (1.1 μL, 9.6 μmol) and styrene (10.9 mg, 0.105 μmol) was injected. GC analysis followed immediately. Cyclopropane **5a** was detected as the major product (20% overall yield, *trans*/*cis* = 10.2) along with diethyl maleate (60% yield).

Reaction of (TTP)Os=CHCO$_2$Et (4a) with N_2CH(Mes) and Styrene. To a solution of complex **4a** (28 mg, 30 μmol) in ca. 1 mL of toluene was added a mixture of styrene (50 mg, 31 μmol) and N_2CH(Mes) (1.26 mL, 0.026 M, 31 μmol). GC analysis followed immediately and indicated the formation of cyclopropane **5a** (37 ± 3% yield, *trans*/*cis* = 10 ± 1) and cyclopropane **5g** (28 ± 3% yield, *trans*/*cis* = 0.40 ± 0.04).

Competitive Cyclopropanation of Two Olefins with [Os(TTP)]$_2$. In a typical experiment, 2 mg (1 μmol) of $[Os(TTP)]_2$, 7.6 mmol of each olefin (styrene and a substituted styrene), and dodecane (internal GC standard) were placed in a round-bottom flask and dissolved in 3 mL of toluene. A solution of 41.5 μL (400 μmol) of ethyl diazoacetate in 12 mL of toluene was added dropwise for approximately 20−30 min with vigorous stirring. GC analysis was performed to determine product ratios. Products were identified by GC using coinjection of authentic samples with the reaction mixtures.

Competitive Cyclopropanation of Styrene and α-Methylstyrene using (TTP)Os(CO). A mixture of styrene (980 μL, 8.53 mmol), α-methylstyrene (1.11 mL, 8.46 mmol), 23 μL of dodecane, and (TTP)Os(CO) (4 mg, 4 μmol) was dissolved in 10 mL of toluene. Ethyl diazoacetate (87 μL, 830 μmol) was added in one aliquot, and the reaction mixture was stirred for at least 10 h. GC analysis showed 14 ± 2% olefin, 24 ± 3% ethyl 2-phenylcyclopropane carboxylic acid ester (**5a**; *trans*/*cis* = 8.1 ± 0.9), and 66 ± 4% ethyl 2-methyl-2-phenylcyclopropane carboxylic acid ester (**9**; *trans*/*cis* = 2.4 ± 0.1). The ratio of **9** to **5a** was 2.7 ± 0.4.

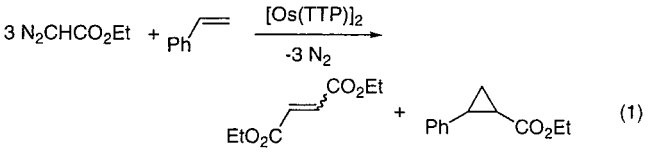
Competitive Catalytic Cyclopropanation of α-Methylstyrene and *trans*-α-Methylstyrene with (TTP)Os=CHCO$_2$Et. To a solution of (TTP)Os=CH(CO_2Et) (**4a**; 5 mg, 5 μmol) in toluene (2.5 mL) was added dropwise for 0.5 h a mixture of α-methylstyrene (103.5 μL, 789 μmol), *trans*-α-methylstyrene (103.5 μL, 789 μmol), and ethyl diazoacetate (10 mg, 88 μmol). The resulting mixture was stirred for 6 h and analyzed. GC analysis: cyclopropane **9**, 100%, *trans*/*cis* = 2.5.

Competitive Stoichiometric Cyclopropanation of Styrene and α-Methylstyrene with (TTP)Os=CHCO$_2$Et. To an equimolar amount of styrene and α-methylstyrene was added 1.0 mL of a toluene solution containing 6.5 μmol (<0.1 equiv) of (TTP)Os=$CHCO_2$Et. The reaction mixture was stirred for ca. 18 h and dodecane (3.2−6.6 μL) added. The reaction mixtures were then analyzed by gas chromatography to determine product ratios.

Labeling Experiments at −78 °C. A stock solution of osmium carbene complex in toluene was prepared in a 5 mL volumetric flask with concentrations in the range 1−4 mM. Concentrations were determined by ^{1}H NMR using triphenylmethane as an internal standard. A second toluene stock solution containing styrene, diazo reagent, and the internal GC standard (dodecane for diazo esters or hexamethylbenzene or fluorene for aryldiazomethanes) was prepared in a 10 mL volumetric flask. In a glovebox, a 5 mL round-bottom flask was charged with ca. 800 μL of carbene complex solution and a stir bar. The flask was capped with a rubber septum and sealed with Parafilm. The flask was removed from the glovebox and placed in a −78 °C dry ice/acetone slurry bath, and the contents were stirred to allow the solution to reach thermal equilibrium (ca. 5 min). Approximately 25−30 μL of the second stock solution (1 equiv of diazo reagent and 5 equiv of styrene with respect to the carbene complex) was added by syringe into the cold reaction flask. The initial concentrations of carbene complex and diazoacetate were 1−3 mM. These initial concentrations were chosen so that reasonable GC detection of the products could be accomplished. The mixture was analyzed by GC as fast as mechanically possible (3−8 s) to determine product ratios.

Results

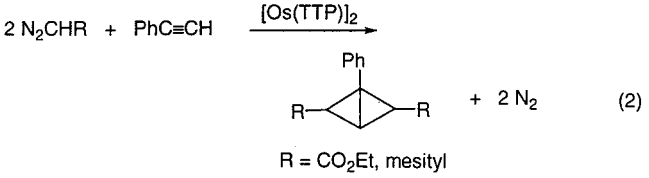
Osmium-Catalyzed Cyclopropanation. The catalytic cyclopropanation of styrene with ethyl diazoacetate mediated by $[Os(TTP)]_2$ (**2**) is a relatively rapid process. At ambient temperature with 0.5 mol % $[Os(TTP)]_2$, 100 mM of styrene, and 100 mM of ethyl diazoacetate, reactions were typically complete after 25 s. A competing side reaction, self-condensation of the diazo reagent to form fumarates and maleates, was also catalyzed by the osmium porphyrin complex (eq 1). In fact, maleates and fumarates were the major products and were



(1)

formed in approximately 70% yield if all reagents were present prior to addition of $[Os(TTP)]_2$. The cyclopropane yields were typically 30%. However, the unwanted self-condensation reaction was minimized by using an excess of styrene or by slowly adding the diazo reagent to the reaction mixture. For example, slow addition of a toluene solution of ethyl diazoacetate (960 μmol) over 2 h to 960 μmol of styrene and 0.2 mol % $[Os(TTP)]_2$ in toluene produced 79(2)% (GC yield) ethyl-2-phenylcyclopropane carboxylic acid ester (**5a**; *trans*/*cis* = 10.2). Only traces of diethyl maleate were observed by GC.

Nonactivated linear and cyclic olefins were less reactive than styrene. Dropwise addition of ethyl diazoacetate to a solution of 1-octene and $[Os(TTP)]_2$ (0.3 mol %) produced ethyl 2-*n*-hexylcyclopropane carboxylic acid ester (**5b**) in 66% yield with 34% diethyl maleate and fumarate present. With phenylacetylene as a substrate, both π-bonds undergo cyclopropanation to afford *endo*,*endo*-2,4-bis(ethoxycarbonyl)-1-phenyl[1.1.0]bicyclobutane (**6a**) in 46% yield using ethyl diazoacetate (eq 2).

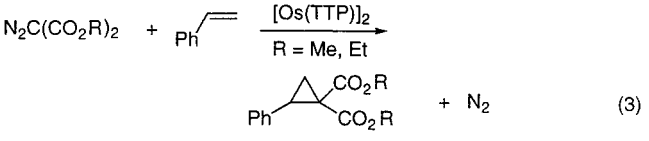


(2)

When mesityldiazomethane was used, the yield of *endo*,*exo*-2,4-dimesityl-1-phenyl[1.1.0]bicyclobutane (**6b**) was 77%.

Qualitative Effect of Diazo Substituents. Catalytic cyclopropanation reactions of styrene were slower when di-*p*-tolyldiazomethane was used as the carbene source compared to using EDA. Only a 3% yield of 1,1-di-*p*-tolyl-2-phenylcyclopropane (**7a**) was obtained from a reaction mixture containing $[Os(TTP)]_2$ (2 mg, 0.4 mol %), di-*p*-tolyldiazomethane (143 mg, 640 μmol), and styrene (680 mg, 6.6 mmol) after 23 h at 19 °C. When (trimethylsilyl)diazomethane was the carbene source, no cyclopropanation products were produced in the presence of styrene and $[Os(TTP)]_2$. The only observed species were unreacted styrene and (TTP)Os=CHTMS (**4c**). In a qualitative sense, steric and electronic properties of the substituents on the α-carbon of the diazo reagent significantly influence cyclopropanation.

Diazomalonates, $N_2C(CO_2R)_2$ (R = Me, Et), were also effective as carbene sources. The reaction proceeded more slowly with diester diazo reagents than with monoester diazo reagents (eq 3). For example, the



(3)

cyclopropanation of styrene (10 equiv per diazo reagent) with approximately 850 μmol of ethyl diazoacetate was complete in less than 1 min using $[Os(TTP)]_2$ as a catalyst. However, under similar conditions, the reaction took 7−8 h when diethyl or dimethyl diazomalonate was used as the carbene source. The yield of diester cyclopropanes was quantitative, with no olefin byproducts from carbene dimerization.

Relative Rate Studies. In a typical competition experiment, a 1/1 mixture of styrene and *p*-X-styrene containing 0.3 mol % $[Os(TTP)]_2$ in toluene was treated dropwise with a solution of ethyl diazoacetate for ca. 30 min. GC analysis of the product mixture gave relative rate ratios. The k_X/k_H data were 2.24 ± 0.03 (*p*-OMe), 1.66 ± 0.06 (*p*-CH_3), and 0.83 ± 0.02 (*p*-Cl). A competition between *p*-CF_3-styrene and *p*-methoxystyrene produced the ratio $k_{MeO}/k_{CF_3} = 4.8 \pm 1.1$. These relative rates yielded a Hammett plot with a slope of −0.80 ± 0.09 ($R^2 = 0.926$), indicating a modest electronic effect. In a competition reaction of α-methylstyrene and *trans*-β-methylstyrene, only α-methylstyrene reacted to form cyclopropane. α-Methylstyrene was also found to react 2.39 ± 0.06 times faster than styrene.

Catalytic and Stoichiometric Cyclopropanation with (TTP)Os=$CHCO_2Et$. Mechanistically, a carbene complex may be involved in the catalytic cycle for cyclopropanation. If so, it should also serve as a stoichiometric reagent for cyclopropanation. Since (TTP)Os=$CHCO_2Et$ can be isolated and purified, it was examined for its ability to promote stoichiometric cyclopropanation. On treatment of (TTP)Os=$CHCO_2Et$ with a 3-fold excess of styrene at ambient temperature in toluene, ethyl 2-phenylcyclopropane carboxylic acid ester formed slowly in 96% (*trans*/*cis* = 3.3) yield after 4 h. In contrast, when (TTP)Os=$CHCO_2Et$ was used in catalytic amounts with styrene and ethyl diazoacetate, the cyclopropanation reaction was complete in seconds—a rate that was qualitatively comparable to the $[Os(TTP)]_2$-catalyzed reaction.

***σ*-Donor Ligand Additives.** On the basis of the stoichiometric study described above, it was apparent that a mono(carbene) complex could not be the active catalyst in this system. A possible alternative was that the carbene ligand is activated toward transfer by coordination of an additional axial ligand. Ligands such as PPh_3 and THF did bind to the carbene complex, as observed by ^1H NMR studies. For example, treatment of (TTP)Os=C(*p*-tolyl)$_2$ (**4b**) with excess THF in C_6D_6 produced new upfield resonances for a singly bound THF at 2.91 and 1.07 ppm. In comparison, free THF exhibits resonances at 3.55 and 1.41 ppm. However, the presence of *σ*-donor ligands such as PPh_3 in a catalytic reaction inhibited the cyclopropanation reaction. Similarly, 4-picoline and other pyridine derivatives also bind to osmium carbene complexes. These ligands produced six-coordinate ylides in which one pyridine was bound to the α-carbon of the carbene ligand and a second pyridine was bound to the trans position on osmium.[20] Cyclopropanation of styrene with these ylide complexes occurred slowly over a period of days.

Bis(carbene) Intermediates. Since bis(carbene) complexes of Os(TTP) were observed when $[Os(TTP)]_2$ was treated with $N_2C(p\text{-tolyl})_2$,[9a] experiments to test for a catalytically active bis(carbene) species were under-

(20) Djukic, J.-P.; Young, V. G.; Woo, L. K. *Organometallics* **1994**, *13*, 3995.

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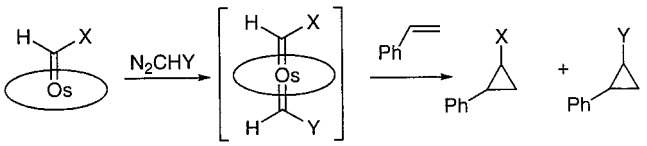
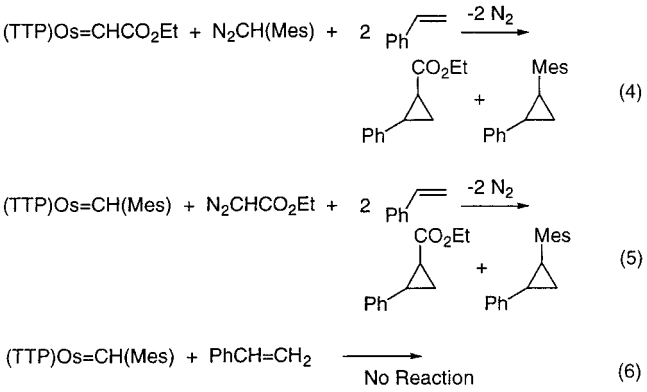
Scheme 1



taken. When 1 equiv of (TTP)Os=$CHCO_2Et$ was treated with a mixture of 1 equiv of mesityldiazomethane and 10 equiv of styrene in toluene at ambient temperature (eq 4), a rapid reaction ensued which produced cyclopropane products resulting from the transfer of the ester carbene (37%, trans/cis = 10) and the mesityl carbene (28%, trans/cis = 0.4). When the substituents were interchanged on the carbene complex and the diazo reagent, the same products and stereoselectivities were observed, but much less mesitylcyclopropane was formed. In eq 5, 10 times more ester cyclopropane was produced, relative to the mesityl product. In an important control experiment, the mesityl carbene complex did not undergo stoichiometric cyclopropanation with styrene at ambient temperature (eq 6). Thus, the mesitylmethylidene ligand, relative to the ethyl carboxyl carbene ligand, had a much lower propensity for transfer to an olefin. Moreover, transfer of the mesitylmethylidene ligand from (TTP)Os=CH(Mes) (**4d**) did not occur until a diazo reagent was added.



Labeling Experiments. In hopes of gaining further insight into the mechanism of $[Os(TTP)]_2$-catalyzed cyclopropanation, a series of labeling studies was undertaken, as illustrated in Scheme 1, in which ester groups were initially used on both the starting mono(carbene) complex and the diazo reagent. For ease of synthesis and purification of the diazo reagents, ethyl and *n*-propyl labels were used. Note that for all monoester carbene sources used in this work, bis(carbene) complexes have not been isolated or spectroscopically observed. Labeling experiments were repeated several times using carbene complexes that were purified by column chromatography. Ideally, a single turnover experiment is preferred so that no dilution of the mixed bis(carbene) transient with a homoleptic bis(carbene) intermediate occurs. The undesirable symmetric bis(carbene) species (TTP)Os[=CHY]$_2$ would form from the remaining diazo reagent and result in overincorporation of the Y label into the product mixture. Since the catalytic cyclopropanation reaction was complete in about 25 s with 0.5 mol % of the osmium precatalyst at ambient temperature, labeling experiments were too fast to monitor at this temperature. Consequently, labeling studies were performed at −78 °C in toluene so that product ratios could be monitored at the lowest possible conversions. In a typical run, a mixture of 1 equiv of N_2CHCO_2Pr, 5 equiv of styrene, and dodecane as an internal standard in toluene was added under N_2 to a stirred toluene solution of 1 equiv of (TTP)Os=$CHCO_2Et$ at −78 °C. The excess amount of styrene was optimized to minimize the olefin-forming side reaction but not speed up the rate of cyclopropanation too much. The reaction was sampled as quickly as mechanically possible (3−8 s) to determine product ratios. Complementary experiments with N_2CHCO_2Et and (TTP)Os=$CHCO_2Pr$ (**4e**) were also examined. Under these conditions, conversions were as low as 20% but were typically about 50%. Attempts to quench the reaction with dioxygen to destroy the osmium catalyst did not completely stop cyclopropanation activity. Quenching the reaction with excess picoline was also undependable. Conversions were still variable and ranged from 10 to 50%. Additionally, it was found that the monoester carbene complexes in several samples decomposed to (TTP)Os(CO), which is also an active cyclopropanation catalyst (vide infra). A similar decomposition of (TPP)Ru=$CHCO_2Et$ to (TPP)Ru(CO) was reported by Simonneaux.[21] Contamination with small amounts of the carbonyl complex resulted in overincorporation of the diazo label into the products. Product ratios were scattered over a range of 1.1−3.8. As a result of the problems described above, the ester labeling experiments were erratic and unreliable.

A series of labeling studies using aryl diazo reagents was subsequently undertaken, using *p*-tolyl and *p*-ethylphenyl labels. Conditions analogous to the experiments with the ester labels were employed, except that hexamethylbenzene or fluorene was used as the internal GC standard. The rate of cyclopropanation reactions with aryl diazo reagents was slower than that for diazo esters. Thus, low conversions were more readily achieved. Results using (TTP)Os=CH(*p*-tolyl) (**4f**) and (*p*-ethylphenyl)diazomethane have shown that at early times (3−8 s), the product ratio for the two labels is near 1 at low conversions (5−20%). The data gave an average *p*-ethylphenyl to *p*-tolyl product ratio of 0.96 ± 0.20. When the labels were reversed ([TTP]Os=CH(*p*-ethylphenyl) (**4g**) and *p*-tolyldiazomethane), the ratio of *p*-tolyl to *p*-ethylphenyl products was 0.99 ± 0.11. The aryl labeling studies also suggest that both carbene fragments have similar transfer rates.

Activation by CO. A carbene ligand, with its π-acid character, is generally an electron-withdrawing species.[22] Thus, a strong π-acid ligand such as CO may also activate mono(carbene) complexes toward transfer. To test this hypothesis, a mono(carbene) complex containing an appended olefin, (TTP)Os=C(CO_2Et)[C(O)CH_2-CH_2CH=CH_2] (**4h**), was prepared. At 70 °C in toluene, complex **4h** showed no evidence of cyclopropanation after 2 h. However, at 110 °C, intramolecular cyclopropanation was observed with the formation of ethyl 2-oxo[3.1.0]bicyclohexanecarboxylic acid ester (**8**) (Scheme 2). In contrast, at 10 °C under an atmosphere of CO,

(21) Galardon, E.; Le Maux, P.; Toupet, L.; Simonneaux, G. *Organometallics* **1998**, *17*, 565.

(22) Crabtree, R. H. *The Organometallic Chemistry of the Transition Elements*, 2nd ed.; Wiley: New York, 1994; p 270.

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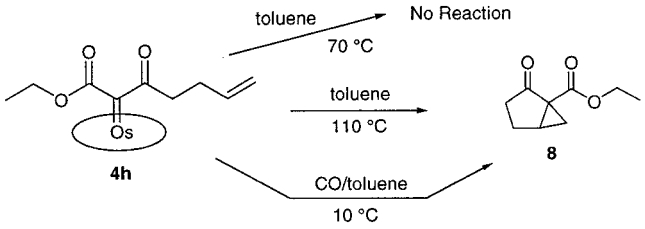
Scheme 2

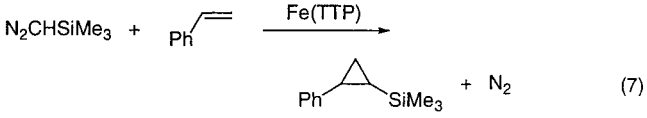


complex **4h** underwent rapid intramolecular cyclopropanation. The reaction was approximately 50% complete in 6 min.

In addition, when (TTP)Os(CO) was used as the catalyst, results similar to those in the $[Os(TTP)]_2$-catalyzed reactions were obtained. Using a 10-fold excess of styrene and adding ethyl diazoacetate in one portion, a 76% yield of cyclopropane with a trans/cis ratio of 8.4 ± 0.2 and a 24% yield of olefin was obtained in less than 60 s. When the diazo reagent was added slowly over 5 min, only 2% of the olefin byproduct was observed.

Stoichiometric Competition Reactions. Upon treatment of (TTP)Os=$CHCO_2Et$ (**4a**) with an excess of styrene and α-methylstyrene, cyclopropanes **5a** and **9** were both formed. The ratio of cyclopropane products **9**/**5a** was 2.3 ± 0.2. This is the same, within experimental error, as the product ratio from catalytic reactions using $[Os(TTP)]_2$. However, the *trans*/*cis* ratio for cyclopropane **5a** was 3.3 ± 0.3 in the stoichiometric reaction, compared to 10.2 in the $[Os(TTP)]_2$-catalyzed reaction. The *trans*/*cis* ratio for compound **9** was 5.8 ± 0.5 in the stoichiometric competition reaction, compared to 2.5 in the catalytic reaction.

Iron(II) Porphyrin Precatalysts. The CO activation experiments indicated that reducing the electron density of the metal center facilitated cyclopropanation mediated by metalloporphyrin complexes. In line with this observation, iron(II) porphyrins were also potent cyclopropanation catalysts.[9c] Further evidence for the effectiveness of Fe(TTP) was derived from the cyclopropanation of styrene with (trimethylsilyl)diazomethane (eq 7). The cyclopropane product yield was 90% (*trans*/



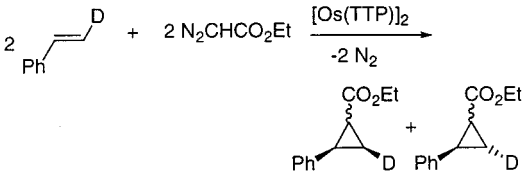
(7)

cis = 10 in toluene) at ambient temperature.[23] Under the same conditions, $[Os(TTP)]_2$ did not produce any observable cyclopropane.

Reactivity Profile. Several substituted olefins were tested as substrates for the $[Os(TTP)]_2$-catalyzed cyclopropanation with ethyl diazoacetate. Monosubstituted and 1,1-disubstituted styrenes were excellent substrates for the $[Os(TTP)]_2$-mediated cyclopropanation reactions. Phenylacetylene was also a good substrate, yielding bicyclobutanes. This is in contrast to Rh_2L_4-catalyzed reactions which produced cyclopropenes.[24] Monosubstituted olefins such as 1-octene could be cyclopropanated, but carbene coupling was a competitive side reaction (66% yield of ethyl 2-*n*-hexylcyclopropanecarboxylic acid ester and 34% yield of diethyl maleate and fumarate). Additionally, 1,2-substituted olefins (cis or trans) were generally poor substrates and led to large amounts of olefin side products. For example, when *trans*-β-methylstyrene was the substrate, ethyl 2-methyl-3-phenylcyclopropane carboxylic acid ester (**10**) was formed in only 13% yield. The major products of the reaction were diethyl maleate and fumarate.

Interestingly, α-methylstyrene was cyclopropanated 2.4 times faster than styrene, showing the preference of the osmium catalyst for electron-rich olefins. However, α-methylstyrene led to a lower trans/cis ratio in the cyclopropane product than that observed for styrene (2.5:1 versus 10:1). Not surprisingly, in a competition reaction between α-methylstyrene and *trans*-β-methylstyrene, only α-methylstyrene reacted.

When *trans*-β-deuteriostyrene was the substrate, a mixture of cyclopropanes with cis and trans deuterium labels (with respect to the phenyl group) was detected by ^2H NMR. The *trans*/*cis* product ratio (deuterium relative to the phenyl group) was 6.7:1 (eq 8), corre-



(8)

sponding to an 87 ± 4% retention of stereochemistry. In the complementary experiment, using *cis*-β-deuteriostyrene as the substrate, the retention of deuterium to phenyl stereochemistry was 92 ± 4%.

Discussion

Cyclopropanation reactions mediated by transition-metal complexes can be divided into two categories: stoichiometric and catalytic. Isolable carbene complexes generally do not cyclopropanate olefins under mild conditions.[25] In stoichiometric reactions, a reactive carbene complex is typically generated in situ as the active carbene transfer reagent. Catalytic processes typically involve Lewis acidic transition-metal complexes which mediate carbene transfer from a diazo reagent to an olefin. The commonly accepted mechanism in the diazo-based system involves formation of a transient carbene complex as the active cyclopropanation species. The primary basis for the involvement of transition-metal carbene species in catalytic cyclopropanation processes is derived mainly from indirect evidence. This includes asymmetric induction and reactivity correlations between catalytic and stoichiometric reactions. The trans/cis product ratios, as a function of olefin, correlate well in a comparison of the stoichiometric cyclopropanation with $(CO)_5W$=CHPh relative to the $Rh_2(OAc)_4$-catalyzed cyclopropanation reaction with N_2CHPh.[26] Similar stereoselective correlations, as a function of olefin, were observed for ethyl diazoacetate

(23) Hamaker, C. G.; Mirafzhal, G. A.; Woo, L. K. *Organometallics*, in press.

(24) Doyle, M. P.; Protopopova, M.; Müller, P.; Ene, D.; Shapiro, E. A. *J. Am. Chem. Soc.* **1994**, *116*, 8492.

(25) (a) Brown, F. J. *Prog. Inorg. Chem.* **1980**, *27*, 1−122. (b) Brookhart, M.; Studabaker, W. G. *Chem. Rev.* **1987**, *87*, 411.

(26) Doyle, M. P.; Griffin, J. H.; Bagheri, V.; Dorow, R. L. *Organometallics* **1984**, *3*, 53.

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with other catalysts.[27,28] Also, the observation of enantiomeric excesses in chiral copper- and rhodium-catalyzed[1d,29] cyclopropanation processes suggested that the metal complex was intimately involved in the product-forming step. Moreover, production of free carboethoxy carbene from EDA does not result in the formation of diethyl maleates or fumarates.[30] The results observed in the $[Os(TTP)]_2$ system are inconsistent with free carbenes.[28b,30]

Recently, Nishiyama and co-workers have isolated (trimethylsilyl)methylidene and (aryloxycarbonyl)methylidene complexes of a bis(oxazolinyl)pyridine ruthenium complex by treatment of an active cyclopropanation catalyst with bulky diazo reagents.[7] These carbene complexes stoichiometrically cyclopropanated styrene with the same selectivity observed in the corresponding catalytic system. Moreover, the ruthenium carbene complexes were also cyclopropanation catalysts. The rates for stoichiometric and catalytic reactions were similar in the Nishiyama system.

Kodadek and co-workers observed a rhodium(III) porphyrin adduct with ethyl diazoacetate at low temperature by treatment of (TTP)RhI with EDA at −40 °C.[4a] The EDA adduct lost N_2 above −20 °C, forming a transient carbene complex which underwent nucleophilic attack by iodide to give a rhodium(III) iodoalkyl porphyrin complex. This iodoalkyl species was believed to be the active catalyst in rhodium porphyrin catalyzed cyclopropanation reactions. Presumably, the rhodium(III) alkyl complex reacted with EDA to yield a *trans*-alkyl rhodium(III) carbene complex. However, the *trans*-alkyl rhodium(III) carbene complex was not observed spectroscopically. Subsequent nucleophilic attack of olefin on the carbene ligand afforded cyclopropane and the steady-state rhodium(III) iodoalkyl complex.[4d] Kodadek ruled out participation of the iodoalkyl fragment in cyclopropanation by using an ethoxycarbonyl iodoalkyl rhodium(III) porphyrin complex as a catalyst for cyclopropanation with *tert*-butyl diazoacetate. At the end of the reaction, only *tert*-butyl 2-phenylcyclopropanecarboxylic acid ester had been produced. In addition, the final iodoalkyl rhodium(III) complex was the ethyl ester derivative, (TTP)RhCH[C(O)OEt]I.

Our ability to isolate carbene complexes from osmium porphyrin catalyzed cyclopropanation reactions suggested that a study of this system would provide important mechanistic insight into this process. Experiments utilizing diazo and olefin substituent effects both supported a mechanism which involves formation of an osmium carbene complex. For example, as more electron-rich olefins were used, the catalytic production of cyclopropanes increased in rate. Thus, *p*-methoxystyrene reacted 4.8 times faster than *p*-(trifluoromethyl)-styrene. This observation is inconsistent with prior coordination of the olefin to osmium followed by nucleophilic attack on the π-bound olefin by the α-carbon of the diazo reagent. The most likely mechanism involves formation of a carbene complex and subsequent nucleophilic attack of the olefin at the carbene carbon. In support of this pathway is the qualitative decrease in rate of cyclopropanation as the substitution about the incipient carbene carbon is changed. Hence, the cyclopropanation of styrene was much slower with di-*p*-tolyldiazomethane than it was with ethyl diazoacetate. Moreover, when (trimethylsilyl)diazomethane was used as the carbene source, no cyclopropanation was observed. The reaction stopped at the formation of (TTP)-Os=CH(TMS). It was also possible to rule out a pathway involving a free carbene species. The 1-phenylethylidene complex (TTP)Os=CMePh (**4i**) can be isolated. If dissociation of the carbene ligand occurs, rearrangement of the free 1-phenylethylidene to styrene would occur with a rate constant of 10^6 s^{-1}.[31] However, solutions of (TTP)Os=CMePh did not produce any detectable amounts of styrene at ambient temperature.

As further evidence for the involvement of carbene complexes, (TTP)Os=$CHCO_2Et$ was examined as a cyclopropanation catalyst. Under similar conditions, both $[Os(TTP)]_2$ and the mono(carbene) complex produced similar yields of cyclopropane products from styrene and ethyl diazaoacetate in qualitatively similar rates. However, in the stoichiometric reaction between (TTP)Os=$CHCO_2Et$ and an excess of styrene, the production of cyclopropane occurred over a time span of hours. In addition, the stereoselectivities differed. In the catalytic process, the *trans*/*cis* ratio was 10.2/1, whereas for the stoichiometric reaction the ratio was 3.3/1. Consequently, the mono(carbene) complex could not be the active catalytic species. Additionally, activation of the carbene toward transfer could not be achieved through addition of σ-donor ligands. Thus, the presence of triphenylphosphine or pyridine ligands inhibited the cyclopropanation reaction.

Under catalytic conditions in the presence of excess diazo reagent, a likely alternative for activation of the carbene ligand toward transfer is through formation of a bis(carbene) complex. Carbene ligands are typically electron withdrawing in character;[22] thus, a bis(carbene) intermediate would be more susceptible toward nucleophilic attack. In addition, bis(carbene) complexes of osmium porphyrins have been observed and isolated with di-*p*-tolyldiazomethane and 1-phenyldiazoethane.[9a] We have not been able to observe a bis(carbene) complex by low-temperature spectroscopic techniques when ethyl diazoacetate was used as the carbene source. Presumably this is due to the strongly electron withdrawing nature of the ester functionality and relative accessibility of the carbene carbon. If any bis(carbene) formation occurs from the reaction between (TTP)Os=$CHCO_2Et$ and ethyl diazoacetate, build up of the bis(carbene) intermediate is prevented by a rapid reaction with additional ethyl diazoacetate to form diethyl maleates, diethyl fumarates, and (TTP)Os=$CHCO_2Et$.

Recently, Simonneaux and co-workers used (Por)Ru(CO) complexes as catalysts for the cyclopropanation of styrene with ethyl diazoacetate.[32] A carbene carbonyl

(27) Doyle, M. P.; Griffin, J. H.; Conceicão, J. *J. Chem. Soc., Chem. Commun.* **1985**, 328.

(28) (a) Doyle, M. P.; Dorow, R. L.; Buhro, W. E.; Griffin, J. H.; Tamblyn, W. H.; Trudell, M. L. *Organometallics* **1984**, *3*, 44. (b) Doyle, M. P.; Dorow, R. L.; Tamblyn, W. H.; Buhro, W. E. *Tetrahedron Lett.* **1982**, *23*, 2261.

(29) The first enantioselective example gave approximately 6% ee; see: Nozaki, H.; Moriuti, S.; Takaya, H.; Noyori, R. *Tetrahedron Lett.* **1966**, 5239. For a recent example using copper, see: Evans, D. A.; Woerpel, K. A.; Hinman, M. M. *J. Am. Chem. Soc.* **1991**, *113*, 726.

(30) Kirmse, W. *Carbene Chemistry*; Academic Press: New York, 1964.

(31) Sugiyama, M. H.; Celebi, S.; Platz, M. S. *J. Am. Chem. Soc.* **1992**, *114*, 966.

(32) Galardon, E.; LeMaux, P.; Simonneaux, G. *Chem. Commun.* **1997**, 927.

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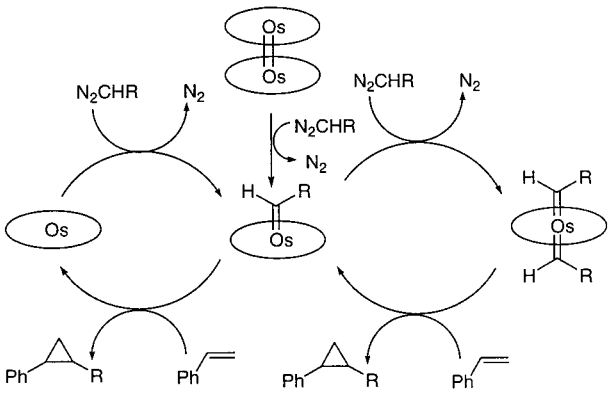
complex, (Por)Ru(=$CHCO_2Et$)(CO), was detected spectroscopically. This species, with an electron-withdrawing carbon monoxide ligand trans to the carbene ligand, is related to our proposed bis(carbene) osmium intermediate. Che and Cheng also recently reported using carbonyl ruthenium porphyrin and porphycene complexes as cyclopropanation catalysts.[33] These catalytic systems are comparable in efficiency and selectivity to the Os analogues.

Key evidence for a bis(carbene) intermediate was derived from a series of experiments which compare the carbene transfer abilities of isolated carbene complexes in the presence and absence of diazo reagents. For example, the mono(carbene) complex (TTP)Os=$CHCO_2$-Et slowly produced cyclopropane from styrene over a period of hours in a stoichiometric reaction at ambient temperature. However, addition of mesityldiazomethane to a mixture of (TTP)Os=$CHCO_2Et$ and styrene in toluene resulted in the rapid formation of cyclopropanes containing the ester group or the mesityl substituent. More compelling was the complementary experiment using (TTP)Os=CH(Mes). As shown in eq 6, this mono(carbene) complex was unable to produce, stoichiometrically, cyclopropane on treatment with styrene over the course of days. However, addition of ethyl diazoacetate to the mixture resulted in rapid cyclopropane production over a period of minutes. Although the major product was ethyl 2-phenylcyclopropane carboxylic acid ester, approximately 10% of the product was 1-mesityl-2-phenylcyclopropane. Clearly, addition of the diazo reagent resulted in activation of the mesityl carbene ligand.

To investigate the mechanism of $[Os(TTP)]_2$-catalyzed cyclopropanation, a series of labeling experiments was undertaken to address the formation of a bis(carbene) intermediate. Initial studies utilized alkyl diazoacetates and (alkoxycarbonyl)carbene complexes, because substitution of the alkyl groups on the ester moieties provided a simple means of labeling the different carbene sources. The rapid rate of cyclopropanation in this system at −78 °C prevented sampling at low conversions. For example, after 3−8 s of reaction time at −78 °C, conversions as high as 80% were observed. Attempts to quench the reaction at low conversions also proved to be limited in determining product ratio measurements at low conversions. A further complication arose from the decomposition of (TTP)Os=$CHCO_2R$ to (TTP)Os(CO). The carbonyl complex was an efficient cyclopropanation catalyst and artificially increased the diazo label incorporation. Consequently, a series of labeling experiments using aryl labels was also undertaken. The labeling studies using *p*-tolyl and *p*-ethylphenyl labels were also consistent with a bis(carbene) intermediate. At early reaction times and low conversions, the average ratio of cyclopropane products from the diazo reagent to the cyclopropane products with labels derived from the initial osmium carbene fragment was 0.97 ± 0.17. This result strongly suggested that a bis(carbene) was the active catalytic species.

A recent communication by Che[34] provides additional evidence that a bis(carbene) porphyrin complex is an active intermediate in the stoichiometric cyclopropanation of styrene. The mono(carbene) complex (TPFPP)-Os=CPh_2 (TPFPP = *meso*-tetrakis(pentafluorophenyl)-porphyrinato) did not undergo stoichiometric cyclopropanation with styrene at 80 °C. However, treatment of the bis(carbene) complex *trans*-(TPFPP)Os(=$CPh_2)_2$ with styrene at 80 °C produced 1,1,2-triphenylcyclopropane (70%) and (TPFPP)Os=CPh_2.

Scheme 3



The higher reactivity and more transient nature of bis(carbene) osmium porphyrin complexes can be attributed to the electron-withdrawing nature of carbene ligands in general.[22] Thus, a bis(carbene) complex would be more susceptible to nucleophilic attack than the related mono(carbene) complex. Consistent with this rationale is the demonstration that CO will activate a mono(carbene) complex toward cyclopropanation. This was cleanly demonstrated with the internal cyclopropanation of (TTP)Os=$C(CO_2Et)[C(=O)CH_2CH_2CH=CH_2]$ (**4h**). As shown in Scheme 2, complex **4h** did not produce any cyclopropane at 70 °C. However, at 10 °C under an atmosphere of carbon monoxide, cyclopropane formation was relatively rapid. Presumably, the CO binds trans to the carbene ligand. The strong π-acceptor character of CO activates the carbene toward nucleophilic attack and promotes cyclopropanation.

A single-crystal X-ray structure of *trans*-(TPFPP)Os-(=$CPh_2)_2$ also provides an explanation of the higher reactivity of bis(carbene) complexes. The Os=C distances in (TPFPP)Os(=$CPh_2)_2$ are substantially longer (2.035(2) and 2.027(3) Å)[34] compared to the Os=C distance in the mono(carbene) complex (TTP)Os=$C(tolyl)_2$ (1.856(8) Å).[10] Thus, the longer, weaker Os=C bonds in the bis(carbene) complex account for the dramatic increase in cyclopropanation activity.

The importance of the electrophilicity of the metal complex was supported by studies with (TTP)Os(CO) and Fe(TTP). Both complexes are extremely effective cyclopropanation catalysts. The trans/cis cyclopropane ratio and rate of reaction for (TTP)Os(CO) are comparable to those for the $[Os(TTP)]_2$-catalyzed reactions. In addition, Fe(TTP) was more active than $[Os(TTP)]_2$, as the iron complex was capable of catalyzing the cyclopropanation of styrene with N_2CHTMS. This latter reaction was not observed with osmium porphyrins.

Additional mechanistic insights were obtained from deuterium labeling studies using *cis*- and *trans*-β-deuteriostyrene. Some scrambling of the deuterium labels was observed, implying that carbon−carbon bond

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(34) Li, Y.; Huang, J.-S.; Zhou, Z.-Y.; Che, C.-M. *J. Am. Chem. Soc.* **2001**, *123*, 4843.

formation proceeds along a stepwise rather than a concerted pathway. However, since the level of scrambling was low, ring closure must be rapid compared to rotation about the C−C bond.

Conclusions

Osmium porphyrins are excellent catalysts for the stereoselective cyclopropanation of olefins with diazo reagents. Isolated carbene complexes of osmium porphyrins have allowed a systematic mechanistic study. Although a mono(carbene) complex, (TTP)Os=$CHCO_2$-Et, is able to mediate the stoichiometric cyclopropanation of styrene, this reaction is much slower than the catalytic process. Chemical and mechanistic investigations are consistent with a bis(carbene) osmium(II) porphyrin as the active catalytic species (Scheme 3). Activation of ligand transfer by formation of a bis(carbene) intermediate is a new mechanism for the cyclopropanation process.

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