Cyclopropanation of Styrene with Ethyl Diazoacetate Catalyzed by Chiral and Achiral Ruthenium 2,6-Bis(imino)pyridyl Complexes

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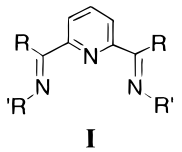
The optically pure 2,6-bis(imino)pyridyl ligands (*R*)-2,6-bis{1-[α-methylbenzylimine]ethyl}-pyridine [(*R*)-2,6-py(NCHMePh)$_2$] and (*S*)-2,6-bis{1-(1-naphthyl)ethylimine]ethyl}pyridine [(*S*)-2,6-py(NCHMeNaph)$_2$] have been prepared by condensation of 2,6-diacetylpyridine with (*R*)-(+)-α-methylbenzylamine and (*S*)-(−)-1-(1-naphthyl)ethylamine, respectively. These two ligands and others bearing different substituents on the imine nitrogen atoms (i.e., *c*-C_6H_{11}, C_6H_5, 2,6-Me_2Ph) form, in combination with ruthenium(II) fragments, efficient catalysts for the cyclopropanation of styrene with ethyl diazoacetate (EDA). The catalyst precursors have the general formula $RuCl_2(PPh_3)$\{2,6-py(NR)$_2$\} (R = Cy, **1**; Ph, **6**; CHMeNaph, **7**; CHMePh, **8**). It is generally found that the catalytic activity increases with the size of the substituents on the imine nitrogen atoms. Consistently, the solvento complex $RuCl_2$\{2,6-py(N(2,6-Me_2-Ph_2)$_2$\}·CH_2Cl_2 is the most efficient in the series. Best results in terms of activity, diastereoselectivity, and enantioselectivity have been obtained with the chiral precursor **7**. In the presence of $AgPF_6$ as cocatalyst, a remarkable improvement in both productivity and chemoselectivity of the cyclopropanation reactions was observed with the catalysts **1** and **6**, whereas a substantial decrease in enantioselectivity occurred with the chiral precursors **7** and **8**. The carbene complex *trans*-$RuCl_2$(=$CHCO_2$Et)\{2,6-py(NCy)$_2$\} (*trans*-**3**) has been isolated upon reaction of **1** with EDA. A kinetic product, *cis*-$RuCl_2$(=$CHCO_2$Et)\{2,6-py(NCy)$_2$\}, was intercepted at low temperature. Compound *trans*-**3** was also obtained by reaction of the ethylene complex $RuCl_2(\eta^2$-H_2C=$CH_2)$[2,6-py(NCy)$_2$] with EDA. Treatment of *trans*-**3** with $AgPF_6$ led to the formation of the unsaturated complex [RuCl(=$CHCO_2$Et)\{2,6-py(NCy)$_2$\}]PF_6. The overall reactivity of the Ru(II) 2,6-bis(imino)pyridyl six-coordinate complexes toward either EDA alone or EDA/styrene mixtures suggests that the carbene transfer from EDA to the olefin is apparently mediated by Ru(II) carbene species in an intermolecular fashion. This mechanistic view may not be true for the reactions performed in the presence of a halide scavenger.

Introduction

Remarkable advances in homogeneous catalyst technology have recently been achieved with systems comprising late transition metals and 2,6-bis(imino)pyridyl ligands (**I**). Successful reactions span from the polymerization[1] and epoxidation of olefins[2] to the enantioselective reduction of prochiral ketones, especially α,β-unsaturated ones.[3] To the best of our knowledge, no report has ever appeared in the relevant literature showing the active role of 2,6-bis(imino)pyridyls metal complexes in the cyclopropanation of olefins. This is quite surprising, as the structurally related bis(oxazolinyl)pyridine ligands (**II**) form some of the most active catalytic systems for the cyclopropanation of olefins with diazo compounds.[4] Moreover, the great availability of primary amines in the chiral pool could allow for a large variety of chiral 2,6-bis[(imino)ethyl]pyridine ligands to be readily synthesized and eventually employed in asymmetric cyclopropanation reactions to give optically pure cyclopropanes, which are valuable building blocks for the elaboration of important organic molecules.[4,5,13]



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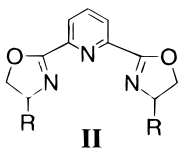

II

In this work, we show that 2,6-bis[(imino)ethyl]-pyridine ligands (R = CH_3) in conjuction with ruthenium(II) ions give rise to effective catalyst systems for

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the metal-mediated carbene transfer from ethyl diazoacetate (EDA) to styrene.[6] Also, we show that 2,6-bis[(imino)ethyl]pyridine ligands may be successfully employed in asymmetric cyclopropanation reactions when chiral substituents are introduced onto the imine nitrogen atoms.

With cyclohexyl substituents on the imine nitrogen atoms, the resulting 2,6-{bis(cyclohexylimine)ethyl}-pyridine ligand has been found to form rather stable fragments with ruthenium(II) in combination with various ligating groups, especially with the participative carbene moiety $CH(CO_2Et)$. This has allowed us to gain insight into the mechanism of the cyclopropanation reaction of styrene with EDA and ultimately show that the reactions proceed via the carbenoid path when coordinatively saturated precursors are employed.

Experimental Section

General Information. All manipulations were carried out under a dinitrogen atmosphere using standard Schlenk techniques. Solvents were distilled under dinitrogen over sodium benzophenone (hexane, diethyl ether, THF) or calcium hydride (dichloromethane). The starting materials $RuCl_2(PPh_3)_3$,[7] $[(p\text{-cymene})RuCl_2]_2$,[8] 2,6-bis{1-(cyclohexylimine)ethyl}pyridine [2,6-py(NCy)$_2$],[9] 2,6-bis{1-(phenylimine)ethyl}pyridine [2,6-py(NPh)$_2$],[10] and Ru{2,6-py(N(Me$_2$C$_6$H$_3$))$_2$}Cl$_2$[2] [2,6-py(N-(Me$_2$C$_6$H$_3$))$_2$) = 2,6-bis{1-[(2,6-dimethyphenyl)imine]ethyl}-pyridine] were prepared according to literature methods. All the other reagents were used as purchased from Aldrich or Strem Chemical Co. Microanalyses were performed by ISSECC-CNR. ^{1}H, ^{31}P{^{1}H}, and ^{13}C{^{1}H} NMR spectra were collected on either a Bruker ACP-200 (200.13, 81.01, and 50.32 MHz, respectively) or a Bruker Advance DRX-500 spectrometer equipped with a variable-temperature control unit accurate to ±0.1 °C (500.13, 202.47, and 125.76 MHz, respectively). ^{1}H and ^{13}C NMR chemical shifts are relative to TMS; ^{31}P NMR chemical shifts are relative to 85% H_3PO_4. 2D NMR spectra were recorded using pulse sequences suitable for phase-sensitive representations using TPPI at 294 K on degassed, nonspinning CD_2Cl_2 solutions. The ^{1}H NOESY spectrum was acquired with 1024 increments of size 2K (with 16 scans each) covering the full range in both dimensions (ca. 12 000 Hz), with a relaxation delay of 2.0 s and a mixing time of 700 ms, respectively.[11] GC analyses were performed on a Shimadzu GC-14 A gas chromatograph equipped with a flame ionization detector and a 30 m (0.25 mm i.d., 0.25 mm FT) SPB-1 Supelco fused silica capillary column. Calibration curves were constructed using the GC internal standard biphenyl and known amounts of diethyl fumarate, diethyl maleate, ethyl *trans*-2-phenylcyclopropanecarboxylate, and ethyl *cis*-2-phenylcyclopropanecarboxylate. Yields of catalytic runs were determined from the calibration curves using the same GC standard. GC/MS analyses were performed on a Shimadzu QP 2000 apparatus equipped with a column identical to that used for GC analysis. Chiral capillary GC analyses were performed on a Shimadzu GC-17A gas chromatograph equipped with a flame ionization detector and a chiraldex G-TA capillary column (40 m × 0.25 mm i.d.).

(*S*)-(+)-2,6-Bis{1-[1-naphthyl)ethylimine]ethyl}pyridine [(*S*)-2,6-py(NCHMeNaphth)$_2$]. A mixture of 2,6-diacetylpyridine (1.0 g, 6.1 mmol) and (*S*)-(−)-1-(1-naphthyl)-ethylamine (4.1 g, 24.0 mmol) without solvent was heated in a closed flask at 95 °C for 4 days. The residual oil was recrystallized with CH_2Cl_2/MeOH to give a yellow crystalline solid. Yield: 1.7 g, 60%. Mp = 114−117 °C. Anal. Calcd for $C_{33}H_{31}N_3$: C, 84.40; H, 6.65; N, 8.95. Found: C, 84.30; H, 6.61; N, 9.00. IR (Nujol, cm^{-1}): ν(C=N) 1632 (s). ^{1}H NMR ($CDCl_3$, 200.13 MHz): δ 1.75 (d, ^3J(HH) = 6.5 Hz, 6 H, CHCH_3), 2.48 (s, 3 H, N=CCH_3), 5.66 (q, ^3J(HH) = 6.5 Hz, 2 H, CHCH$_3$); 7.46−7.62 (m, 6 H), 7.76−7.93 (m, 7 H), 8.34−8.38 (d, ^3J(HH) = 7.8 Hz, 4 H); Ar and Py protons. ^{13}C{^{1}H} NMR ($CDCl_3$, 50.33 MHz): δ 14.8 (CH_3), 25.1 (CH_3), 57.7 (CH), 122.2 (CH), 124.3 (CH), 124.7 (CH), 126.0 (CH), 126.4 (CH), 127.8 (CH), 129.7 (quaternary C), 131.4 (quaternary C), 137.3 (CH), 142.7 (quaternary C), 157.0 (quaternary C), 166.3 (quaternary C). $[\alpha]^{20}_D$ = +206.62° (c = 1.286, $CHCl_3$).

(*R*)-(−)-2,6-Bis{1-[α-methylbenzylimine]ethyl}pyridine [(*R*)-2,6-py(NCHMePh)$_2$]. A mixture of 2,6-diacetylpyridine (0.3 g, 2.0 mmol) and (*R*)-(+)-α-methylbenzylamine (1.2 g, 10.0 mmol) without solvent was heated in a closed flask at 95 °C for 3 days. Then the mixture was subjected to high vacuum for 4 h at 95 °C to eliminate the excess amine. The residual oil could be used as a ligand without further purification. Yield: 0.7 g, 97%. IR (Nujol, cm^{-1}): ν(C=N) 1634 (s). ^{1}H NMR (200.13 MHz, $CDCl_3$): δ 1.58 (d, ^3J(HH) = 6.5 Hz, 6 H, CHCH_3), 2.48 (s, 3 H, N=CCH_3), 4.95 (q, ^3J(HH) = 6.5 Hz, 2 H, CHCH$_3$), 7.23−7.55 (m, 10 H, Ph), 7.77 (t, ^3J(HH) = 7.7 Hz, 1 H, py H-4), 8.27 (d, ^3J(HH) = 7.7 Hz, 2 H, py H-3,4). ^{13}C{^{1}H} NMR ($CDCl_3$, 50.33 MHz): δ 14.5 (CH_3), 25.5 (CH_3), 61.0 (CH), 122.2 (CH), 127.4 (CH), 129.1 (CH), 146.7 (quaternary C), 157.1 (quaternary C), 165.6 (quaternary C). $[\alpha]^{20}_D$ = −36.26° (c = 2.530, $CHCl_3$).

***cis*-RuCl$_2$(PPh$_3$){2,6-py(NCy)$_2$} (1).** An acetone solution (20 mL) containing 2,6-py(NCy)$_2$ (150 mg, 0.462 mmol) and $RuCl_2(PPh_3)_3$ (398 mg, 0.415 mmol) was refluxed under nitrogen for 4 h. During the reaction, the color of the solution changed to deep red and a purple microcrystalline solid was formed. The volume of the solution was reduced to ca. 10 mL under a strong stream of nitrogen, and 20 mL of diethyl ether was slowly added to ensure the complete formation of the microcrystalline solid, which was collected on a frit, washed with diethyl ether, and dried under a slow stream of nitrogen. Yield: 230 mg (73%). Anal. Calcd for $C_{39}H_{46}Cl_2N_3PRu$: C, 61.65; H, 6.10; N, 5.53. Found: C, 61.60; H, 6.18; N, 5.49. ^{1}H NMR (200.13 MHz, CD_2Cl_2): δ 0.65−1.77 (m, 18 H, Cy), 2.48 (s, 6 H, N=CCH_3), 2.55 (br, 2 H, Cy), 4.98 (br, 2 H, =NCH); 7.10−7.31(m, 12 H), 7.60−7.70 (m, 6 H), aromatic protons. ^{31}P-{^{1}H} NMR (81.02 MHz, CD_2Cl_2): δ 31.4 (s).

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***trans*-$RuCl_2(\eta^2\text{-}H_2C{=}CH_2)$\{2,6-py$(NCy)_2$\} (2).** A solution of 2,6-py$(NCy)_2$ (150 mg, 0.462 mmol) and [(*p*-cymene)$RuCl_2]_2$ (122 mg, 0.208 mmol) in 20 mL of dichloromethane was refluxed under nitrogen for 15 min and then under ethylene overnight. The volume of the solution was reduced under a strong stream of ethylene until a purple solid began to form. The precipitation was completed by addition of petroleum ether. The solid was collected on a frit, washed with petroleum ether, and dried under a slow stream of nitrogen. Yield: 192 mg (88%). Anal. Calcd for $C_{23}H_{35}Cl_2N_3Ru$: C, 52.57; H, 6.71; N, 8.00. Found: C, 52.90; H, 6.53; N, 7.98. ^{1}H NMR (200.13 MHz, CD_2Cl_2): δ 0.51−2.67 (m, 22 H, Cy), 2.76 (s, 6 H, N=CCH_3), 2.90 (s, 4 H, ethylene), 7.57−7.71(m, 3 H, aromatic protons).

Reaction of *trans*-$RuCl_2(\eta^2\text{-}H_2C{=}CH_2)$\{2,6-py$(NCy)_2$\} and PPh_3. To a CD_2Cl_2 solution (0.5 mL) of **2** (12.0 mg, 0.023 mmol) in a 5 mm NMR tube was added PPh_3 (6.0 mg, 0.023 mmol). ^{1}H and ^{31}P NMR spectra were recorded immediately. In the ^{31}P NMR spectrum, the only signal observed was that due to **1** at 31.4 ppm. In the ^{1}H NMR spectrum, besides the signals of the phosphine complex, a singlet due to the free ethylene gas was observed at 5.40 ppm.

***trans*-$RuCl_2$(=$CHCO_2Et$\{2,6-py$(NCy)_2$\} (*trans*-3). Method A.** To a dichloromethane solution (10 mL) containing **2** (150 mg, 0.285 mmol) was added EDA (54 μL, 0.513 mmol). The solution was allowed to stir for 2 h at room temperature. The volume was then reduced to ca. 1 mL under high vacuum. Petroleum ether was added to give a purple solid, which was collected on a frit, washed with petroleum ether, and dried under a slow stream of nitrogen. Yield: 143 mg (86%). **Method B.** To a dichloromethane solution (30 mL) containing **1** (543 mg, 0.712 mmol) was addded EDA (300 μL, 2.853 mmol). The solution was allowed to stir for 6 h at room temperature. The volume was reduced under a stream of nitrogen, and 30 mL of diethyl ether was slowly added until a purple microcrystalline solid was formed. The solid was collected on a frit, washed with diethyl ether, and dried under a slow stream of nitrogen. Yield: 370 mg (89%). Anal. Calcd for $C_{25}H_{37}Cl_2N_3O_2Ru$: C, 51.48; H, 6.39; N, 7.20. Found: C, 51.75; H, 6.51; N. 7.22. ^{1}H NMR (200.13 MHz, CD_2Cl_2): δ 1.23−1.84 (m, 20 H, Cy), 1.42 (t, ^3J(HH) = 7.2 Hz, 3 H, $CO_2CH_2CH_3$), 2.91 (s, 6 H, N=CCH_3), 3.81 (br s, 2 H, =NCH), 4.49 (q, ^{3}J(HH) = 7.2 Hz, 2 H, $CO_2CH_2CH_3$), 8.02−8.17 (m, 3 H, aromatic protons), 20.41 (s, 1 H, =CH). ^{13}C{^{1}H} NMR (50.33 MHz, CD_2Cl_2): δ 15.3 (CH_2, Cy), 19.3 (CH_2, Cy), 25.1(CH_3), 26.2 (CH_3), 30.0 (CH_2, Cy), 33.8 (CH_2, Cy), 60.3 (=NCH), 68.5 ($CO_2CH_2CH_3$), 123.5 (CH, py), 137.8 (CH, py), 151.3 (quaternary C, py), 170.0 (N=C), 186.7 ($CO_2CH_2CH_3$), 299.9 (=CH).

[RuCl(=$CHCO_2Et$\{2,6-py$(NCy)_2$\}]PF_6 (4). Into a 5 mm NMR tube containing a CD_2Cl_2 solution (1 mL) of *trans*-**3** (10.0 mg, 0.017 mmol) was introduced $AgPF_6$ (5.0 mg, 0.020 mmol). The color of the solution changed immediately from deep red to light red. A proton NMR spectrum was acquired immediately at room temperature. ^{1}H NMR (200.13 MHz, CD_2Cl_2): δ 0.97−1.79 (m, 20 H, Cy), 1.60 (t, ^3J(HH) = 7.1 Hz, 3 H, $CO_2CH_2CH_3$), 2.99 (s, 6 H, N=CCH_3), 3.74 (m, 2 H, =NCH), 4.55 (q, ^3J(HH) = 7.1 Hz, 2 H, $CO_2CH_2CH_3$), 8.23−8.45 (m, 3 H, aromatic protons), 21.34 (s, 1 H, =CH). All our attempts to isolate this product in the solid state by scaling up the reaction were unsuccessful due to its great instability.

[RuCl(PPh_3)(=$CHCO_2Et$\{2,6-py$(NCy)_2$\}]PF_6 (5). To a NMR solution of **4** prepared as described above was added PPh_3 (10.2 mg, 0.039 mmol). A color change from red to pale yellow occurred immediately. ^{1}H and ^{31}P NMR spectra were recorded. ^{1}H NMR (200.13 MHz, CD_2Cl_2): δ 0.80−1.79 (m, 20 H, Cy), 1.61 (t, ^3J(HH) = 7.1 Hz, 3 H, $CO_2CH_2CH_3$), 2.93 (s, 3 H, N=CCH_3), 3.02 (s, 3 H, N=CCH_3'), 3.74 (m, 2 H, =NCH), 4.60 (q, ^3J(HH) = 7.1 Hz, 2 H, $CO_2CH_2CH_3$), 8.19−8.41 (m, 3 H, py), 7.39−7.57 (m, 15 H, PPh_3), 20.98 (d, ^3J(HP) = 6.1 Hz, 1 H, =CH). ^{31}P{^{1}H} NMR (81.02 MHz, CD_2Cl_2): δ 18.2 (s).

***cis*-$RuCl_2(PPh_3)$\{2,6-py$(NPh)_2$\} (6).** A solution of THF (30 mL) containing 2,6-py$(NPh)_2$ (230 mg, 0.734 mmol) and $RuCl_2(PPh_3)_3$ (633 mg, 0.660 mmol) was refluxed under nitrogen for 2 days. During the reaction, the color of the solution changed to deep red. The volume of the solution was reduced to ca. 10 mL under a strong stream of nitrogen, and 20 mL of diethyl ether was slowly added to give a dark brown solid, which was collected on a frit, washed with diethyl ether, and dried under a slow stream of nitrogen. Yield: 400 mg, (81%). Anal. Calcd for $C_{39}H_{34}Cl_2N_3PRu$: C, 62.65; H, 4.58; N, 5.62. Found: C, 62.70; H, 4.56; N. 5.65. ^{1}H NMR (200.13 MHz, CD_2Cl_2): δ 2.35 (s, 6 H, CH_3), 6.89−7.45 (m, aromatic protons). ^{31}P{^{1}H} NMR (81.02 MHz, CD_2Cl_2): δ 33.6 (s).

(*S*)-*cis*-$RuCl_2(PPh_3)$\{2,6-py(NCHMeNaph)$_2$\} (7). A solution of THF (30 mL) containing (*S*)-2,6-py(NCHMeNaph)$_2$ (200 mg, 0.428 mmol) and $RuCl_2(PPh_3)_3$ (369 mg, 0.385 mmol) was refluxed under nitrogen for 6 h. During the reaction, the color of the solution changed to deep red. The volume of the solution was reduced to ca. 10 mL under a strong stream of nitrogen, and 20 mL of diethyl ether was slowly added to give a red solid, which was collected on a frit, washed with diethyl ether, and dried under a slow stream of nitrogen. Yield: 240 mg, (91%). Anal. Calcd for $C_{51}H_{46}Cl_2N_3PRu$: C, 67.77; H, 5.13; N, 4.65. Found: C, 67.90; H, 4.95; N, 4.69. ^{1}H NMR (200.13 MHz, CD_2Cl_2): δ 1.02 (d, ^3J(HH) = 7.2 Hz, 3 H, CHCH_3), 2.00 (d, ^3J(HH) = 7.2 Hz, 3 H, CHCH_3'), 2.41 (s, 3 H, N=CCH_3), 2.64 (s, 3 H, N=CCH_3'); 6.84−7.89 (m, 32 H), 7.99 (d, ^3J(HH) = 8.4 Hz, 1 H), 8.21 (d, ^3J(HH) = 8.4 Hz, 1 H), aromatic protons and =NCH. ^{31}P{^{1}H} NMR (81.02 MHz, CD_2Cl_2): δ 29.8 (s).

(*R*)-*cis*-$RuCl_2(PPh_3)$\{2,6-py(NCHMePh)$_2$\} (8). The complex was prepared similarly to **7**. (*R*)-2,6-py(NCHMePh)$_2$ (352 mg, 0.953 mmol) and $RuCl_2(PPh_3)_3$ (777 mg, 0.810 mmol) were used. A red solid was obtained. Yield: 500 mg, (77%). Anal. Calcd for $C_{43}H_{42}Cl_2N_3PRu$: C, 64.26; H, 5.27; N, 5.23. Found: C, 64.44; H, 5.30; N, 5.31. ^{1}H NMR (200.13 MHz, CD_2Cl_2): δ 1.06 (d, ^3J(HH) = 7.2 Hz, 3 H, CHCH_3), 2.01 (s, 3 H, N=CCH_3), 2.06 (d, ^3J(HH) = 6.8 Hz, 3 H, CHCH_3'), 2.18 (s, 3 H, N=CCH_3'), 6.36 (m, 2 H, =NCH); 6.58 (m, 2 H), 6.90−7.36 (m, 19 H), 7.79−7.96 (m, 7 H), aromatic protons. ^{31}P{^{1}H} NMR (81.02 MHz, CD_2Cl_2): δ 29.3 (s).

Variable-Temperature NMR Study of the Reaction between $RuCl_2(PPh_3)$\{2,6-py$(NCy)_2$\} and EDA. To a CD_2Cl_2 solution (0.5 mL) of **1** (15.0 mg, 0.020 mmol) was added EDA (6.2 μL, 0.059 mmol) at −78 °C. ^{1}H and ^{31}P NMR spectra at −80 °C were obtained immediately. In the ^{31}P NMR spectrum, the signals due to the starting complex and to the ylid PPh_3=$CHCO_2Et$, roughly in a ratio of 9:1, were observed at 33.3 and 18.4 ppm, respectively. In the low-field region of the ^{1}H NMR spectrum were observed two singlets at 20.14 and 20.77 ppm that we assign to the carbene C−H protons of *trans*-**3** and *cis*-$RuCl_2$(=$CHCO_2Et$\{2,6-py$(NCy)_2$\} (*cis*-**3**), respectively. On warming to −70 °C, the intensities of the two signals increased. On further warming to −60 °C, the signals of the *cis* isomer at ca. 20.8 ppm decreased in intensity, while that of the *trans* isomer at ca. 20.2 ppm increased. At −50 °C, the signal of the *cis* isomer disappeared. On further warming, the signal due to the *trans* isomer gained in intensity. Eventually, the signal was observed at 20.41 ppm at room temperature.

Catalytic Cyclopropanation Reactions. A dichloromethane solution (1 mL) of EDA (1.5 mmol) was added to a dichloromethane solution (1 mL) containing the catalyst precursor (0.02 mmol) and styrene (1.72 mL, 15 mmol) at room temperature over ca. 8 h using a syringe pump. Then the mixture was allowed to stir for another 16 h. In some cases, similar reactions were carried out in the presence of an excess of benzyltriethylammonium chloride ($BzEt_3NCl$).

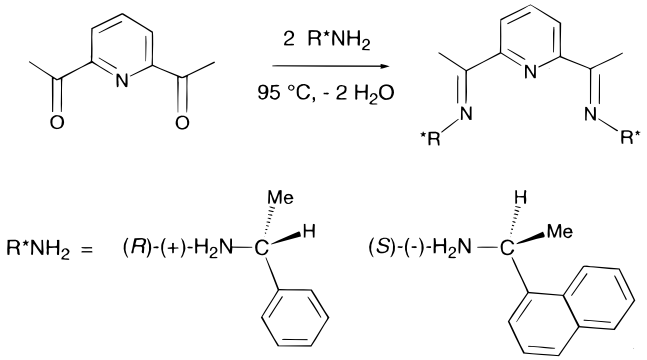
Alternatively, the reactions were carried out as above but in the presence of either silver hexafluorophosphate or silver triflate (0.03 mmol). Independent reactions with either silver salt did not show any cyclopropanation activity.

Table 1. Styrene Cyclopropanation with EDA by Ru(II) 2,6-Bis(imino)pyridyl Complexes[a]

entry	catalyst	co-reagent[b]	**A**+**B** (%)[c] (**A**:**B**)	**C**+**D** (%) (**C**:**D**)	total yield (%)	ee of **B** (%)
1	**8**		68.1 (86:14)	3.3 (21:79)	71.4	41.3 (1*S*, 2*R*)
2	**8**	1.5 $AgPF_6$	62.3 (38:62)		62.3	4.1 (1*S*, 2*R*)
3	**7**		64.8 (86:14)	4.1 (29:71)	68.9	75.6 (1*R*, 2*S*)
4	**7**	1.5 $AgPF_6$	60.2 (53:47)	2.0 (14:86)	62.2	4.0 (1*R*, 2*S*)
5	**1**		21.3 (82:18)	18.3 (10:90)	39.6	
6	**1**	$AgPF_6$	58.6 (65:35)		58.6	
7	**2**		17.6 (80:20)	22.7 (6:94)	40.3	
8	**2**	AgOTf	43.3 (63:19)	4.8 (13:87)	48.1	
9	**2**	$AgPF_6$	52.2 (60:40)		52.2	
10	**2**	$[Et_4N]Cl$	18.3 (79:21)	11.1 (13:87)	29.4	
11	**6**		47.5 (73:27)	10.6 (19:81)	58.1	
12	**6**	1.5 $AgPF_6$	70.1 (52:48)		70.1	
13	*trans*-**3**		10.0 (80:20)	4.8 (33:67)	14.8	
14	*trans*-**3**	$AgPF_6$	52.9 (58:42)		52.9	
15	*trans*-**3**	AgOTf	43.0 (61:39)	2.7 (9:91)	45.7	
16	**11**		71.2 (84:16)	4.2 (27:73)	75.4	

[a] Catalytic conditions: catalyst (0.02 mmol), EDA (1.5 mmol), styrene (15 mmol), dichloromethane (2 mL), 8 h addition followed by 16 h stirring. % ee of *trans*: not determined. All data represent average of at least three runs. [b] Equivalents of silver salt. [c] Based on EDA.

Scheme 1



The product composition was determined by GC; biphenyl was used as internal standard. The percent ee were determined by chiral capillary GC. The results of all reactions are collected in Table 1.

Isolation of the Metal Products after the Cyclopropanation Reactions with 2,6-py(NCy)$_2$ Precursors. The solvent was removed completely under high vacuum. Petroleum ether (5 mL × 4) was added to dissolve the biphenyl, cyclopropanes, and residual styrene. The solution was carefully removed via a cannula. The residual solid was pumped dried under vacuum. ^{1}H and ^{31}P NMR spectra were then obtained. When **1** and **2** were the catalyst precursors, the carbene complex *trans*-**3** was isolated as confirmed by NMR spectroscopy. When the carbene complexes was used as catalyst precursor, it was recovered intact after the catalytic run.

Results and Discussion

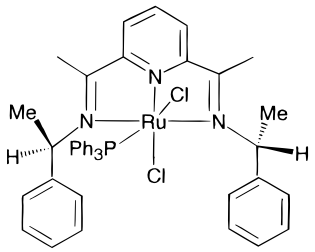
Synthesis of Chiral 2,6-Bis(imino)pyridyl Ligands. The new tridentate ligands (*R*)-2,6-bis{1-[α-methylbenzylimine]ethyl}pyridine [(*R*)-2,6-py(NCHMePh)$_2$] and (*S*)-2,6-bis{1-(1-naphthyl)ethylimine]ethyl}-pyridine [(*S*)-2,6-py(NCHMeNaph)$_2$] were prepared by condensation of 2,6-diacetylpyridine with the commercially available optically pure primary amines (*R*)-(+)-α-methylbenzylamine and (*S*)-(−)-1-(1-naphthyl)-ethylamine, respectively, as shown in Scheme 1. The synthesis of these ligands by employing the common procedure of refluxing 2,6-diacetylpyridine with 2 equiv of the corresponding primary amine in the presence of a catalytic amount of acid in an alcohol for a period of even 1 week still led to incomplete reactions. Instead, we found that by heating 2,6-diacetylpyridine with 4 equiv of the corresponding chiral amine without solvent at ca. 95 °C for 3−4 days led to complete formation of the desired products. In the case of (*R*)-2,6-py(NCHMePh)$_2$, the excess amine could be distilled away under reduced pressure. The residual oil could then be used as ligand without further purification. In the case of (*S*)-2,6-py(NCHMeNaph)$_2$, recrystallization of the residue with dichloromethane/methanol gave a yellow crystalline solid.

Synthesis of Ruthenium Complexes with 2,6-Bis(imino)pyridyl Ligands. The ruthenium triphenylphosphine complex $RuCl_2(PPh_3)$\{2,6-py(NCy)$_2$\} (**1**) was synthesized by refluxing an acetone solution of 2,6-py(NCy)$_2$ and $RuCl_2(PPh_3)_3$ for 4 h. Subsequent reduction of the solvent and precipitation with diethyl ether gave **1** as a purple microcrystalline solid. The reactions between $RuCl_2(PPh_3)_3$ and the chiral ligands (*R*)-2,6-py(NCHMePh)$_2$ and (*S*)-2,6-py(NCHMeNaph)$_2$ in the same solvent were found to be slow and incomplete. By changing to THF instead, the ruthenium complexes (*S*)-*cis*-$RuCl_2(PPh_3)$\{2,6-py(NCHMeNaph)$_2$\} (**7**) and (*R*)-*cis*-$RuCl_2(PPh_3)$\{2,6-py(NCHMePh)$_2$\} (**8**) were obtained readily in 6 h. The reaction of $RuCl_2(PPh_3)_3$ with the less basic ligand 2,6-py(NPh)$_2$ was sluggish, and the complex *cis*-$RuCl_2(PPh_3)$[2,6-py(NPh)$_2$] (**6**) was only obtained after a prolonged reflux in THF for 2 days. A related complex $RuCl_2(PPh_3)$\{(2,6-py(CH_3C═N(4-MeO-C_6H_4)$_2$\} has been prepared recently in a similar fashion by refluxing the tridentate ligand with $RuCl_2(PPh_3)_3$ in toluene.[2]

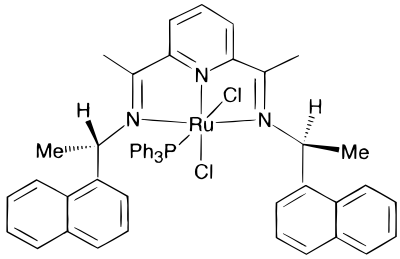
The ^{31}P\{^{1}H\} NMR spectra of the ruthenium complexes **1** and **6** show singlets at δ 31.4 and 33.6, respectively, indicating that only one PPh_3 molecule is coordinated to the ruthenium center. In the ^{1}H NMR spectra, the presence of only one methyl resonance is in accord with the existence of a symmetry plane bisecting the two halves of the coordinated ligand and hence the ligand coordinated in a meridional fashion. Both *cis* and *trans* dispositions of the chlorides would be possible, however. Efforts to get crystals suitable for X-ray analyses were unsuccessful. Recently, similar complexes with the formula *trans*- and *cis*-[$RuCl_2(PPh_3)$-\{κ^3-*N*,*N*,*N*-(*SS*)-^{i}Pr-pybox)\}] (*trans*-**9** and *cis*-**9**) containing the pybox ligand 2,6-bis(dihydrooxazolin-2′-yl]-pyridine have been synthesized via the substitution

reaction of *trans*-[$RuCl_2(\eta^2$-$H_2C{=}CH_2)\{\kappa^3$-*N*,*N*,*N*-(*SS*)-^{i}Pr-pybox)}] with PPh_3.[12] The thermodynamically stable *cis* isomer was indeed obtained from the *trans* isomer by refluxing the latter in acetone. Under our experimental conditions, the thermodynamically stable *cis* products would similarly be formed. Moreover, *trans*-**9** shows a slightly downfield phosphorus resonance as compared to *cis*-**9** (δ 38.11 vs 35.34), while the $^{31}P\{^1H\}$ NMR signal in the achiral complex *trans*-[$RuCl_2(PPh_3)$-$\{\kappa^3$-*N*,*N*,*N*-pybox)}] (**10**) was observed at δ 46.48.[12] On the basis of these spectroscopic data, **1** and **6** may be assigned a *cis* geometry.

In the $^{31}P\{^1H\}$ NMR spectra of the chiral complexes **7** and **8**, singlets are observed for the coordinated PPh_3 group at δ 29.8 and 29.3, respectively. These chemical shifts are quite comparable to those of **1** and **6**; hence a *cis* disposition of the chlorides is assigned to the chiral complexes too. The *cis* structural formulation for **7** and **8** was confirmed by the ^1H NMR spectra that contain two different sets of resonances for the methyl groups on both the stereocenters and the C=N groups. Indeed, this will only be possible with a *cis* geometry (**III** and **IV**) in which there is no C_2 symmetry to render the two halves of the complexes equivalent as in the case of the *trans* isomer.



III



IV

The ethylene complex $RuCl_2(\eta^2$-$H_2C{=}CH_2)$[2,6-py-$(NCy)_2$] (**2**) was prepared following the procedure reported by Nishiyama et al. for *trans*-[$RuCl_2(\eta^2$-H_2-$C{=}CH_2)\{\kappa^3$-*N*,*N*,*N*,-(*SS*)-^{i}Pr-pybox)}],[4,13] by refluxing a mixture of $[RuCl_2(p\text{-cymene})_2]_2$ with 2,6-py$(NCy)_2$ in dichloromethane under an ethylene atmosphere. Subsequent solvent reduction and slow precipitation by petroleum ether gave **2** as a purple solid. The compound is stable in the solid state. However, loss of ethylene occurs in solution, as evidenced by the presence of the free ethylene signal at δ 5.40 in the ^1H NMR spectrum. In contrast to the rigidity of the ethylene ligand in *trans*-[$RuCl_2(\eta^2$-$H_2C{=}CH_2)\{\kappa^3$-*N*,*N*,*N*,-(*SS*)-^{i}Pr-pybox)}], which shows well-distinguishable ^1H NMR multiplets for the two sets of CH_2 groups,[4,13] only one singlet for the four hydrogens of the coordinated ethylene is observed for **2** at δ 2.90. Examples of ruthenium(II) complexes with fluxional ethylene ligands have previously been reported.[14] Consistent with the presence of a labile ethylene ligand, the reaction of **2** with PPh_3 in CH_2Cl_2 gave **1** as the only product (Scheme 2). No intermediate *trans* isomer was observed by NMR spectroscopy.

Reactions of $RuCl_2(PPh_3)\{$2,6-py$(NR_2)\}$ and $RuCl_2(\eta^2$-$H_2C{=}CH_2)\{$2,6-py$(NCy)_2\}$ with Ethyl Diazoacetate. To prove the formation of a carbene complex in the cyclopropanation of styrene with EDA catalyzed by the present Ru(II) bis(imino)pyridyl complexes, we have investigated their stoichiometric reactions with EDA (Scheme 2). A carbene complex was successfully isolated only from the reactions with either **1** or **2**, i.e., when R = Cy (Scheme 2). In all the other cases, no well-defined Ru compound was isolated while the dimerization of EDA to a mixture of diethyl fumarate and diethyl maleate occurred.

In the reaction of **2** with EDA, the carbene complex *trans*-$RuCl_2(=CHCO_2Et)\{$2,6-py$(NCy)_2\}$ (*trans*-**3**) was cleanly isolated. The reaction presumably proceeds via the thermodynamically favorable ethylene substitution by EDA with formation of nitrogen and ethylene gases as byproducts. It is also possible that the initial EDA attacks the coordinated ethylene to give ethyl cyclopropanecarboxylate, which opens up a coordination site. However, no cyclopropanation product was detected by GC/MS of the reaction mixture. By reacting **1** with EDA, the same carbene complex *trans*-**3** was obtained. In this case, the reaction involves the nucleophilic attack by EDA onto PPh_3 with formation of the ylid $PPh_3{=}CHCO_2$-Et as byproduct ($^{31}P\{^1H\}$ NMR signal δ 18.0).[15,16] The formation of ylid-type compounds has also been observed in cyclopropanation reactions catalyzed by copper phosphine complexes.[16]

Compound *trans*-**3** is stable in both the solid state and solution. Similar ruthenium carbene complexes $RuCl_2$-(ttp)$(=CHCO_2Et)$ [ttp = $Ph(CH_2CH_2CH_2PPh_2)_2$] and $RuCl_2$(ttp*)$(=CHCO_2Et)$ [ttp* = (*S*,*S*)-$Ph(CH_2CHMeCH_2$-$PPh_2)_2$] have recently been isolated by treating the corresponding five-coordinate ruthenium dichloride complexes with EDA.[17]

The presence of a carbene ligand in *trans*-**3** is unambiguously shown by the $^{13}C\{^1H\}$ and ^1H NMR spectra which contain typical resonances at 299.9 and 20.44 ppm for the carbene carbon atom and its hydrogen atom, respectively.[5b,13,17] NMR spectroscopy shows also that the two halves of the tridentate ligand are magnetically equivalent, as indicated by the presence of only one signal for the methyl groups on the C=N nitrogen atoms. The equivalence of these methyl groups can take place when the carbene ligand lies either *trans* to the pyridine nitrogen atom and the molecule possesses a C_2 axis or in a mirror plane perpendicular to the Ru−N_3 plane and encompassing the Ru and pyridine nitrogen atoms. Since the ^1H NOESY spectrum of *trans*-**3** shows strong NOE cross-peaks relating the protons belonging to the ethyl group of the carbene ligand with

(14) Bianchini, C.; Masi, D.; Peruzzini, M.; Casarin, M.; Maccato, C.; Rizzi, G. A. *Inorg. Chem.* **1997**, *36*, 1061.
(15) Speziale, A. J.; Ratts, K. W. *J. Am. Chem. Soc.* **1963**, *85*, 2790.
(16) Díaz-Requejo, M. M.; Nicasio, M. C.; Pérez, P. J. *Organometallics* **1998**, *17*, 3051.
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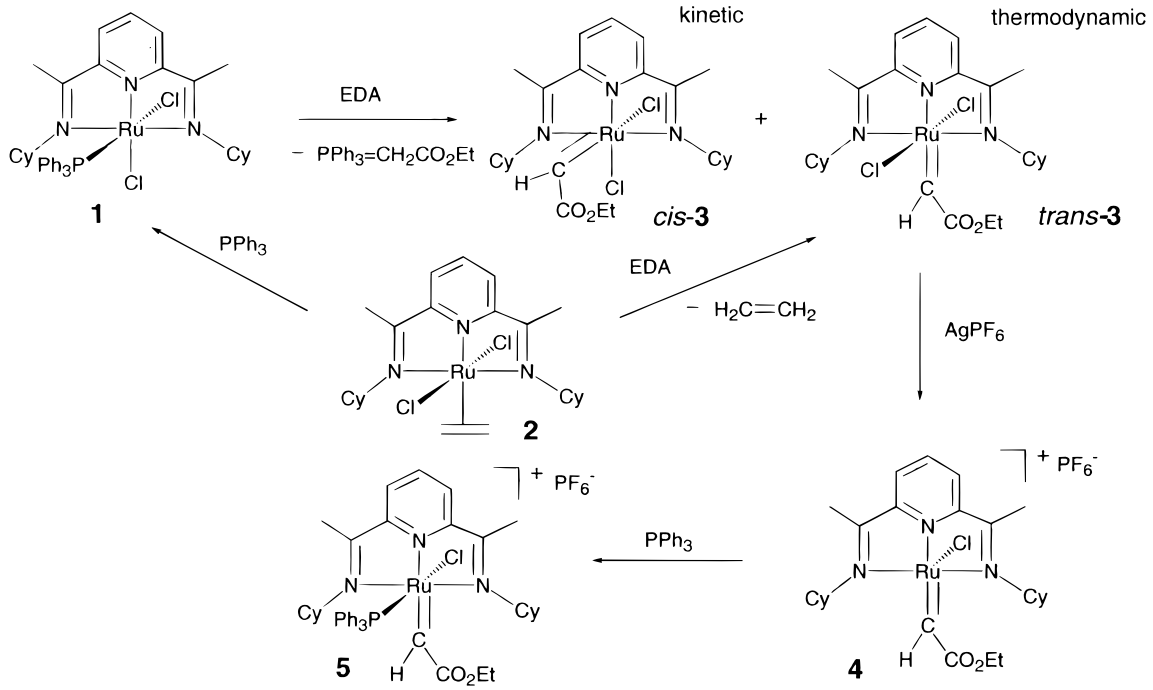
Scheme 2



cyclohexyl protons, the Ru=C bond most likely lies in the plane of the tridentate ligand, and thus a *trans* coordination of the chlorides can be hypothesized for this product as represented in Scheme 2.

In an attempt to intercept intermediate species preceding the formation of *trans*-**3**, the reaction between **2** and EDA was carried out in a 5 mm NMR tube at low temperature. Already at −80 °C, the ^{31}P NMR spectrum contained the signals due to the starting complex and to the ylid PPh_3=$CHCO_2Et$, roughly in a ratio of 9:1, at 33.3 and 18.4 ppm, respectively. In the low-field region of the ^{1}H NMR spectrum, two singlets at 20.14 and 20.77 ppm were observed that we assign to the carbene C−H protons of *trans*-**3** and its *cis* isomer *cis*-$RuCl_2$(=$CHCO_2Et$){2,6-py($NCy)_2$} (*cis*-**3**), respectively (Scheme 2). On warming to −70 °C, the intensities of the two signals increased while also the concentration of the ylid increased. On further warming to −60 °C, the signals of the *cis* isomer at ca. 20.8 ppm decreased in intensity, while that of the *trans* isomer at ca. 20.2 ppm increased. At −50 °C, the signal of the *cis* isomer disappeared. Elimination of the solvent under reduced pressure gave *trans*-**3** as the only product. The low-temperature experiments thus suggest the formation of a kinetic carbene product in which the carbene ligand is *trans* to chloride instead of nitrogen (Scheme 2). Given the paucity of spectroscopic data available for the low-temperature product, other structural formulations cannot be disregarded. However, the selective formation of *trans*-**3** and the ^{1}H NMR signal at 20.77 ppm are indeed consistent with a carbene structure similar to that of *trans*-**3**.

As coordinatively unsaturated Ru(II) carbene complexes are being extensively used in metathesis reactions,[18] it would be of great interest to obtain a five-coordinate Ru(II) carbene complex with bis(imino)pyridyl ligands and then study its catalytic performance.

By treating a degassed CD_2Cl_2 solution of *trans*-**3** with an equivalent amount of $AgPF_6$ in a NMR tube, a new complex was readily formed, as evidenced by an immediate color change from deep red to a lighter color and by the appearance in the ^{1}H NMR spectrum of a signal due to a carbene hydrogen at δ 21.34, slightly downfield with respect to the analogous resonance in *trans*-**3** (δ 20.41). The other proton signals are similar to those of *trans*-**3**. On the basis of these spectroscopic data, the product obtained by scavenging a chloride ligand from *trans*-**3** is assigned the formula [RuCl(=$CHCO_2Et$){2,6-py($NCy)_2$}]PF_6 (**4**). Several attempts have been made to isolate the complex, which, however, is too unstable in solution to allow for its separation. The principal decomposition path (80%) is, however, an intermolecular carbene trasfer to give the *trans* and *cis* olefins, which were detected by GC/MS in a 1:9 ratio, respectively.

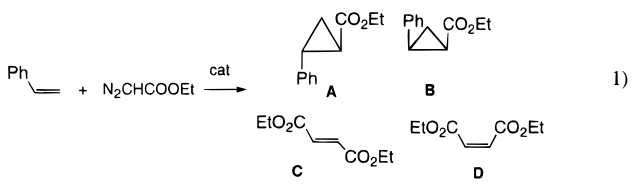
Consistent with the coordinatively unsaturated nature of **4**, the addition of a slight excess of PPh_3 to a dichloromethane solution of **4** resulted in the formation of [RuCl(PPh_3)(=$CHCO_2Et$){2,6-py($NCy)_2$}]PF_6 (**5**). An immediate color change from red to pale yellow was actually observed upon addition of PPh_3, while a doublet at δ 20.98 (J(HP) = 6.1 Hz) appeared in the region of carbene hydrogens. In the new product, the two methyl groups on the C=N moiety give rise to two different signals, indicating that the two halves of the meridionally coordinated ligand are not magnetically equivalent. Like the unsaturated species **4**, the phosphine adduct **5** is unstable even in solution, thus preventing a reliable characterization. Consistent with the incorporation of PPh_3 in the complex structure, the decomposition path of **5** is different from that of **4**, as the ylid PPh_3=$CHCO_2$-Et and not the olefin is formed on standing in solution.

(18) (a) Grubbs, R. H.; Dias, E. L. *Organometallics* **1998**, *17*, 2758 (b) Weskamp, T.; Kohl, F. J.; Hieringer, W.; Gleich, D.; Herrmann, W. A. *Angew. Chem., Int. Ed.* **1999**, *38*, 2416. (c) Schwab, P.; Grubbs, R. H.; Ziller, J. W. *J. Am. Chem. Soc.* **1996**, *118*, 100. (d) Nguyen, S. T.; Grubbs, R. H.; Ziller, J. W. *J. Am. Chem. Soc.* **1993**, *115*, 2790. (e) Nguyen, S. T.; Johnson, L. K.; Grubbs, R. H.; Ziller, J. W. *J. Am. Chem. Soc.* **1992**, *114*, 3974.

A structural assignment for **5** may tentatively be made on the basis of the ^{31}P chemical shift of the PPh_3 ligand (δ 18.2), which is that at the lowest field in the present series of bis(imino)pyridyl−PPh_3 complexes. Provided the ^{31}P NMR trend observed by Gimeno[12] and by us is valid, then the PPh_3 group should not be *trans* to the pyridine nitrogen atom, and hence a structure like that shown in Scheme 2 may be proposed for **5**. In accord with this structural formulation, the carbene hydrogen atom shows a rather large coupling to the phosphine (ca. 60 Hz). The value of this constant, the chemical shift of PPh_3, which is close to that of the ylid, and the facile elimination of the ylid from **5**, taken altogether, indeed suggest that the phosphine and carbene ligands are spatially close to each other as occurs in a *cis* structure. Since the two methyl groups on the C═N moieties of **5** give rise to two different signals in the ^1H NMR spectrum, the two halves of the meridionally coordinated bis(imino)pyridyl ligand are magnetically inequivalent: this feature is consistent with the proposed structure in which PPh_3 is perpendicular to the coordination plane of the nitrogen atoms and *cis* to the carbene ligand. In this eventuality, an out-of-plane steric interaction between PPh_3 and the cyclohexyl rings may indeed account for the inequivalence of the methyl groups as reported for *cis*-**9**.[12] In the latter complex, an X-ray structure revealed an out-of-plane steric interaction between PPh_3 and the isopropyl substituent, causing one of the oxazoline rings to be puckered. This type of steric interaction might probably occur in **5** too due to the presence of even more bulkier substituents on the imino nitrogen atoms.

Catalytic Cyclopropanation with the Ruthenium Complexes. The catalytic performance of the newly synthesized Ru(II) bis(imino)pyridyl complexes for styrene cyclopropanation with EDA has been investigated. At the time of this work, a series of solvento complexes with the general formula $RuCl_2\{2,6\text{-py}(CH_3C{=}N(R_n{-}Ar)_2\}\cdot S$ (n = 1 or 2) had already been described in the literature.[2] The catalytic activity of one of these complexes, namely, $RuCl_2\{2,6\text{-py}(N(2,6\text{-}Me_2\text{-}Ph)_2\}\cdot CH_2Cl_2$ (**11**), has also been studied by us. Selected results are listed in Table 1.

The slow addition of EDA to a dichloromethane solution containing excess styrene and one of the catalyst precursors listed in Table 1 led generally to the formation of both cyclopropanation (**A**, **B**) and dimerization products (**C**, **D**) (eq 1). No evidence for the formation of metathesis products, i.e., $PhCH{=}CH(CO_2Et)$, was obtained by either GC/MS or ^1H NMR spectroscopy.[17]



1)

In metal-catalyzed decompositions of diazo compounds in the presence of olefins, the formation of **C** and **D** may kinetically compete with that of cyclopropanes.[6,17,19] However, the formation of the olefins can be reduced by slow addition of EDA to the catalytic solution containing an excess amount of olefin via a syringe pump.[6] We have found that the addition over a period of 8 h with a catalyst/EDA/styrene ratio of 1:75:750 gives partially optimized results.

All the six-coordinated ruthenium bis(imino)pyridyl−PPh_3 complexes described in this work are effective cyclopropanation catalysts with activities decreasing in the order **8** > **7** > **6** > **1** (entries 1, 3, 11, 5). The new chiral catalysts **7** and **8** are indeed very selective and efficient cyclopropanation catalysts with a good *trans*−*cis* diastereoselectivity (86:14). A good enantioselectivity (75.6% ee) was also obtained with **7**, bearing the sterically demanding naphthyl substituent on the stereocenters (entry 3). Complex **6**, with phenyl substituents on the imine nitrogen atom, gave an average activity, while **1,** with cyclohexyl substituents, was the least efficient and gave only 21.3% of cyclopropanation products (entries 11, 5). The poor activity of **1** might indeed be due to the stability of the carbene derivative *trans*-**3**, which is also the termination metal product of the catalytic cyclopropanation reactions.[5b] Consistently, the ethylene complex **2** (Scheme 2) gave a cyclopropane production similar to that for the analogous PPh_3 complex **1** (17.6 vs 21.3%) (entries 5, 7).

As we discovered that **1** and **2** react with EDA stoichiometrically to give the carbene complex *trans*-**3** as thermodynamic product, this carbene complex was employed as catalyst precursor in the same experimental conditions. Complex *trans*-**3** was indeed found to be an active precursor for styrene cyclopropanation, but to our suprise, it was less efficient than **1** and **2** (entry 13).

A reasonable interpretation of these results has been provided by the variable-temperature in situ study of the reaction between **1** and EDA. A kinetic carbene complex, assigned as *cis*-**3**, is actually formed at low temperature, which might be more reactive than the thermodynamic isomer *trans*-**3** for the transfer of the carbene moiety to the olefin. This might explain why the reactions catalyzed by either **1** or **2** produce more cyclopropanes than those carried out in the presence of isolated *trans*-**3**. Increased cyclopropanation activity would occur at the early stages of the reaction when a larger concentration of the kinetic carbene complex is present in solution. The results obtained by adding silver hexafluorophosphate as cocatalyst confirm, to a certain extent, this interpretation (see below).

So far the results obtained shows that ligands with larger substituents on the nitrogen atoms display higher activities. To further verify this point, complex **11**, with $2,6\text{-}Me_2Ph$ substituents on the imine nitrogen atoms, was also tested in styrene cyclopropanation. As shown in entry 16, **11** catalyzed very efficiently the reaction, yielding 71.2% of cyclopropanes. The similarities of catalytic activities and *trans*−*cis* selectivities displayed by **7**, **8**, and **11** might imply the same degree of steric bulkiness around the metal center. As the 2,6-bis(imino)pyridyl ligand $2,6\text{-py}\{N(2,6\text{-}^iPr_2{-}Ph)\}_2$ is being extensively used in catalytic polymerization of ethylene,[1] it would be of interest to see whether a ruthenium complex of this ligand, which bears even bulkier substituents on the imine nitrogen atoms than those in complex **11**, would give a better result. Several attempts had been made using both $RuCl_2(PPh_3)_3$ and [(*p*-cymene)-

(19) Díaz-Requejo, M. M.; Belderrain, T. R.; Nicasio, M. C.; Prieto, F.; Pérez, P. J. *Organometallics* **1999**, *18*, 2601.

$RuCl_2]_2$ as starting ruthenium materials. Unfortunately, due to steric reasons, no well-defined complex was isolated in either case.

In the presence of $AgPF_6$, a remarkable improvement in both productivity and chemoselectivity of the cyclopropanation reactions was observed with the catalyst precursors **1** and **6** (entries 6, 12). Indeed, the yield of cyclopropanes obtained with **1** increased by more than 250%, while **6** gave 70.1% of cyclopropanes with no formation of dimerization products. The chiral complexes **7** and **8** were slightly less active in the presence of $AgPF_6$, however (entries 2, 4).

As shown in Table 1, the addition of $AgPF_6$ to the reaction mixture reduced the *trans*−*cis* diastereoselectivity, in general. Indeed, the *trans*−*cis* selectivity was practically reversed with **8** in the presence of the silver salt and the *cis*-cyclopropane became the predominant product (entry 2). Also, the enantioselectivity was greatly reduced, as an almost racemic mixture of *cis*-cyclopropane was obtained (entries 2, 4).

Notably, the co-presence of $AgPF_6$ in the reaction mixtures makes **1**, **2**, and *trans*-**3** equally active catalysts (entries 6, 9, 14). The formation of the same catalytically active species, most likely the unsaturated carbene **4**, would account for the comparable catalytic activity exhibited by the precursors **1**, **2**, and *trans*-**3** in the presence of $AgPF_6$.

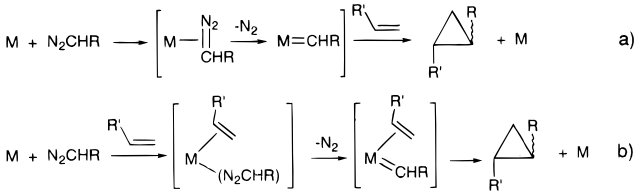
To further verify whether coordinatively and electronically unsaturated carbenes of the formula $[RuCl(=CHCO_2Et)\{2,6\text{-}py(NR)_2\}]^+$ are more efficient and chemoselective catalysts as compared to the saturated analogues with PPh_3, some reactions were carried out in the presence of silver triflate (AgOTf), whose anion possesses nucleophilic character.[20] In all the cases investigated, the substitution of AgOTf for $AgPF_6$ led to a remarkable decrease in the cyclopropanation activity as well as chemoselectivity (entries 8, 15). On the contrary, the addition of an excess of chloride ions (from tetraalkylammonium salts) to the catalytic mixtures did not affect the activity in general (entry 10).

Concluding Remarks

The overall reactivity of the Ru(II) 2,6-bis(imino)pyridyl six-coordinate complexes toward either EDA alone or EDA/styrene mixtures is quite comparable to that of the pybox analogues.[4,5b,13] The latter, however, are generally more enantioselective with ee's up to 100%. Like the pybox catalysts, the carbene transfer from EDA to the olefin is apparently mediated by Ru(II) carbene species in an intermolecular fashion (Scheme 3a). The only Ru(II) 2,6-bis(imino)pyridyl carbene complex that has been isolated is just the one exhibiting the lowest catalytic activity, which again is consistent with the chemistry of the pybox-based catalysts.[5b]

The most intriguing result obtained with the catalysts supported by the 2,6-bis(imino)pyridyl ligands is perhaps the interception of a kinetic Ru(II) carbene complex differing from the thermodynamic isomer by the mutual positions of the carbene and chloride ligands and, most importantly, by a higher catalytic activity. This finding opens up new perspectives in the development of more efficient cyclopropanation catalysts through the design of ligand systems capable of controlling the coordination site of the carbene group.

Scheme 3



Within the family of six-coordinate 2,6-bis(imino)pyridyl catalysts, the activity increases with the size of the substituents on the imine nitrogen atoms. This experimental observable may be interpreted qualitatively in terms of both steric and electronic effects. The presence of bulky groups around the metal center would promote the elimination of the cyclopropane product, while a weaker bonding interaction between the metal center and the carbene ligand would enhance the electrophilic character of the latter and ultimately favor the carbene transfer. On the other hand, the good activity and enantioselectivity exhibited by the chiral complex **7** witness the importance of the substituents on the imine nitrogen atoms in controlling both the rate and the stereoselectivity of the carbene transfer.

Removing one chloride ligand from the six-coordinate complexes using $AgPF_6$ as halide scavenger has been found to generally improve the catalytic activity and chemoselectivity but not the stereoselectivity. A remarkable decrease in the enantioselectivity is observed, in fact. Most likely, a change in the cyclopropanation mechanism occurs due to the participation in the catalytic cycle of five-coordinate carbene species $[RuCl(=CHCO_2Et)\{2,6\text{-}py(NR)_2\}]^+$ that can simultaneously coordinate carbene and olefin moieties. Experiments with a silver salt containing a nucleophilic anion support this hypothesis. No clear-cut conclusion about the possible occurrence of an intramolecular mechanism (Scheme 3b), involving the concomitant coordination of the olefin and carbene groups,[6,17] can be drawn at this stage, however. Indeed, the higher activity of the catalyst systems comprising $AgPF_6$ as cocatalyst may simply be due to the increased electrophilic character of the carbene moiety in electronically unsaturated Ru(II) species.

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