Chiral Dirhodium(II) Catalysts with Ortho-Metalated Arylphosphine Ligands: Synthesis and Application to the Enantioselective Cyclopropanation of α-Diazo Ketones

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Received December 6, 2001

Chiral dirhodium(II) compounds, $Rh_2(O_2CR)_2(pc)_2$ (pc = ortho-metalated arylphosphine), with a head-to-tail arrangement (**1**−**21**) are used in the cyclopropanation of α-diazo ketones. The influence of catalyst ligands and substrate structure on enantioselectivity is studied. Temperature and solvent dependence assays are performed, the best ee values being obtained in refluxing pentane. Results compare favorably with those reported in the literature using Ru, Cu, and other Rh(II) catalysts.

Introduction

The cyclopropyl moiety is increasingly regarded and used as a functional group involved in reactions of preparative importance, due to the ring strain.[1] Also, a large number of natural and synthetic cyclopropanes display interesting biological activities.[2] Consequently, a great deal of effort is presently being devoted to the development of methods which make the construction of cyclopropanes with high enantioselectivities possible.[2,3]

The metal-catalyzed cyclopropanation of olefins with diazo compounds is a general strategy for the obtention of three-membered carbocycles;[3] the utility of this approach is directly related to the level of selectivity of the process. There is indirect evidence that these reactions take place via metal carbenes as intermediates;[4] consistently, the selectivity of the process strongly depends on the nature of the metal and the catalyst structure. Achievements in asymmetric catalytic metal carbene transformations are impressive, but they are by no means complete. Although chiral dirhodium(II) carboxamide catalysts have proven to be the most selective catalysts for intramolecular cyclopropanation reactions of diazoacetates and diazoacetamidates,[5] they have failed to induce even moderate levels of enantioselectivities with diazo ketones.[6] However, diazo ketones have found a large number of successful applications in racemic synthesis.[7] In 1995, Pfaltz et al.[8] achieved cyclopropanation of diazo ketones with a moderate yield (less than 60%) using chiral semicorrin−copper catalysts. Later, new chiral catalysts were unsuccessfully sought for improving the enantioselectivity in the intramolecular cyclopropanation of diazo ketones. Thus, Ru(II) with chiral (diphenylphosphino)-(oxazolinyl)quinoline ligands provided high yields in the cyclization, although with less enantiocontrol compared to Pfaltz's catalysts (Tables 1 and 4).[9] Chiral biferrocene-based bis(oxazoline) Cu(I) compounds showed low reactivity and low to moderate enantiocontrol (Table 1, entry 23; Table 4, entry 9; Table 5, entry 8).[10] As a result, until now, Pfaltz's catalysts were the most efficient compounds for inducing enantiocontrol in the cyclization of the above-mentioned substrates. However, their enantioselectivities (14−95%) strongly depended on the substitution pattern of the C−C double bond (see Tables 1 and 3−5).

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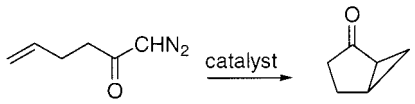
10.1021/om0110437 CCC: $22.00
Publication on Web 03/21/2002

Table 1. Catalyst-Dependent Stereocontrol in the Cyclization of 22



22 23

		23[a–c]		
entry	catalyst	yield (%)	ee (%)	
1	(*M*)-**1**	83	47	1*R*,5*S*
2	(*M*)-**2**	98	56	1*R*,5*S*
3	(*M*)-**3**	99	34	1*R*,5*S*
4	(*M*)-**4**	88	27	1*R*,5*S*
5	(*M*)-**5**	95	24	1*R*,5*S*
6	(*M*)-**6**	92	60	1*R*,5*S*
7	(*M*)-**7**	96	65	1*R*,5*S*
8	(*M*)-**8**	98	64	1*R*,5*S*
9	(*M*)-**9**	92	60	1*R*,5*S*
10	(*M*)-**10**	96	65	1*R*,5*S*
11	(*M*)-**11**	98	35	1*R*,5*S*
12	(*M*)-**12**	98	46	1*R*,5*S*
13	(*M*)-**13**	99	57	1*R*,5*S*
14	(*P*)-**14**	89	17	1*S*,5*R*
15	(*M*)-**15**	97	27	1*R*,5*S*
16	(*P*)-**16**	83	40	1*S*,5*R*
17	(*M*)-**17**	82	34	1*R*,5*S*
18	(*P*)-**18**	85	38	1*S*,5*R*
19	(*M*)-**19**	84	18	1*R*,5*S*
20	(*P*)-**20**	80	17	1*S*,5*R*
21	(*M*)-**21**	82	14	1*R*,5*S*
22	Cu(I)[d]	50	75	1*S*,5*R*
23	Cu(I)[e]		25	
24	Cu(I)[f]	54	77	1*R*,5*S*
25	Rh(II)[g]	85	23	
26	Ru(II)[h]	84	5	1*R*,5*S*

[a] Cyclopropanation yield based on the diazo ketone. [b] ee values calculated in this report were based on GC analysis with a 2,3-di-*O*-acetyl-6-*O*-(*tert*-butyldimethylsilyl)−beta-CDX column. [c] Reactions with Rh(II) catalysts with ortho-metalated arylphosphines were performed in refluxing dichloromethane for 1 h. [d] Copper semicorrin complexes, in $(ClCH_2)_2$ as solvent.[8] [e] Biferrocene-based bis(oxazoline) copper complex, in dichoromethane as solvent.[10] [f] Chiral salicylaldimine copper complexes, in benzene as solvent.[20] [g] $Rh_2(4S\text{-IPOX})_4$, in dichloromethane as solvent.[6] [h] Ru(II) with chiral (diphenylphosphino)(oxazolinyl)quinoline ligands, in chloroform as solvent.[9]

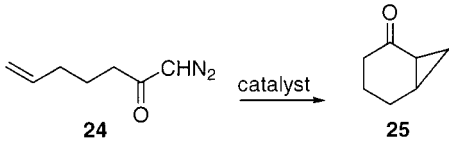
Table 2. Solvent and Temperature Effects on Enantioselectivities in the Rh(II)-Catalyzed Cyclopropanation of 22

					23	
entry	Rh	*T* (°C)	time (h)	solvent	yield (%)	ee (%)
1	**2**	40[a]	1	CH_2Cl_2	98	56
2	**2**	83[a]	1	$(CH_2Cl_2)_2$	94	49
3	**7**	40[a]	1	CH_2Cl_2	96	65
4	**7**	25[b]	1	*n*-C_5H_{12}	91	68
5	**7**	36[a]	1	*n*-C_5H_{12}	90	74
6	**7**	−15[b]	72	*n*-C_7H_{14}[c]	77[d]	41
7	**7**	25[b]	4	*n*-C_7H_{14}[c]	40	55
8	**7**	50[b]	1	*n*-C_7H_{14}[c]	59	67
9	**7**	74[b]	1	*n*-C_7H_{14}[c]	74	66
10	**7**	98[a]	1	*n*-C_7H_{14}[c]	94	62

[a] Refluxing solvent. [b] Bath temperature. [c] 0.02% water. [d] 22% diazo compound recovered.

Dirhodium(II) complexes derived from ortho-metalated arylphosphines, $Rh_2(O_2CR)_2(pc)_2$ (pc = ortho-metalated arylphosphine, with head-to-tail arrangement), are readily prepared by the thermal reaction of $Rh_2(O_2CCH_3)_4$ and arylphosphines.[11] They were shown to be regio- and chemoselective catalysts in the transformation of α-diazo ketones.[12] These rhodium compounds have backbone chirality, and they have been obtained as pure enantiomers by conventional resolution methods.[13] They are the first examples of dirhodium(II) chiral catalysts without chiral ligands, and they induce moderate asymmetry in the C−H insertion of diazo ketones.[13a] Recently, we have demonstrated that chiral dirhodium(II) complexes $Rh_2(O_2CCF_3)_2(pc)_2$ (pc = $(p\text{-}CH_3C_6H_4)_2P(p\text{-}CH_3C_6H_3)$ $(m\text{-}CH_3C_6H_4)_2P(m\text{-}CH_3C_6H_3)$) provide a high yield and a good level of enantiocontrol in the cyclopropanation of diazo ketones.[14] In this work we wish to report in full our results on the influence of catalyst ligands, substrate structure, solvent, and temperature on the process enantioselectivity.

Table 3. Cyclopropanation of Diazo Ketone 24

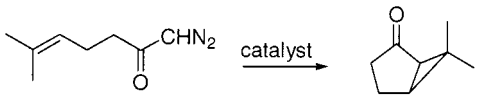


24 25

			25		
entry	catalyst	solvent	yield (%)	ee (%)	
1	(*M*)-**2**	CH_2Cl_2	93	84	1*S*,6*R*
2	(*M*)-**7**	*n*-C_5H_{12}	96	90	1*S*,6*R*
3	(*M*)-**7**	CH_2Cl_2	85	87	1*S*,6*R*
4	(*M*)-**8**	*n*-C_5H_{12}	90	95	1*S*,6*R*
5	(*M*)-**8**	CH_2Cl_2	92	89	1*S*,6*R*
6	(*M*)-**13**	CH_2Cl_2	97	79	1*S*,6*R*
7	Cu(I)[a]	$(ClCH_2)_2$	57	95	1*S*,6*R*
8	Cu(I)[b]	C_6H_6	72	22	1*S*,6*R*
9	Rh(II)[c]	CH_2Cl_2	58	6	

[a] Copper semicorrin complexes.[8] [b] Chiral salicylaldimine copper complexes.[20] [c] $Rh_2(5S\text{-MEPY})_4$.[6]

Table 4. Cyclopropanation of Diazo Ketone 26



26 27

			27		
entry	catalyst	solvent	yield (%)	ee (%)	
1	(*M*)-**2**	*n*-C_5H_{12}	99	76	1*R*,5*S*
2	(*M*)-**2**	CH_2Cl_2	99	68	1*R*,5*S*
3	(*M*)-**7**	*n*-C_5H_{12}	99	80	1*R*,5*S*
4	(*M*)-**7**	CH_2Cl_2	99	52	1*R*,5*S*
5	(*M*)-**8**	*n*-C_5H_{12}	99	70	1*R*,5*S*
6	(*M*)-**8**	CH_2Cl_2	99	58	1*R*,5*S*
7	(*M*)-**12**	CH_2Cl_2	99	46	1*R*,5*S*
8	Cu(I)[a]	$(ClCH_2)_2$	58	85	1*S*,5*R*
9	Cu(I)[b]	$(ClCH_2)_2$	51	63	
10	Rh(II)[c]	CH_2Cl_2	80	27	
11	Ru(II)[d]	$CHCl_3$	91	75	1*R*,5*S*

[a] Copper semicorrin complexes.[8] [b] Biferrocene-based bis(oxazoline) copper complex.[10] [c] $Rh_2(4S\text{-MEOX})_4$.[6] [d] Ru(II) with chiral (diphenylphosphino)(oxazolinyl)quinoline ligands.[9]

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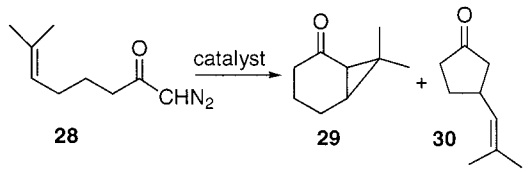
Table 5. Cyclopropanation of Diazo Ketone 28



				29			30	
entry	catalyst	yield (%)	solvent	yield (%)	ee (%)		yield (%)	ee (%)
1	(*M*)-**2**	99	*n*-C_5H_{12}	91	55	1*S*,6*R*	9	83
2	(*M*)-**2**	99	CH_2Cl_2	50	20	1*S*,6*R*	50	80
3	(*M*)-**7**	87	*n*-C_5H_{12}	93	80	1*S*,6*R*	7	91
4	(*M*)-**7**	74	CH_2Cl_2	67	63	1*S*,6*R*	33	93
5	(*M*)-**8**	92	*n*-C_5H_{12}	69	80	1*S*,6*R*	31	94
6	(*M*)-**8**	93	CH_2Cl_2	51	63	1*S*,6*R*	49	92
7	Cu(I)[a]	50	$(ClCH_2)_2$	50	14			
8	Cu(I)[b]	12	$(ClCH_2)_2$	12	64			
9	Rh(II)[c]	67	CH_2Cl_2	76	17		24	1

[a] Copper semicorrin complexes.[8] [b] Biferrocene-based bis(oxazoline) copper complex.[10] [c] Rh_2(5*S*-MEPY)$_4$.[6]

Results

Synthesis of Dirhodium(II) Complexes. Rh(II) complexes of the general formula $Rh_2(O_2CR)_2(pc)_2$ (**1**−**13**) were prepared by a modified method first published by Cotton et al.[11] These compounds are inherently chiral and are obtained as a racemic mixture of the *P* and *M* enantiomers (Figure 1). The racemic mixture of the $Rh_2(O_2CCH_3)_2(pc)_2$ compounds was transformed into two diastereoisomers by replacement of the acetate groups for the chiral carboxylate protons (protosH = *N*-((4-methylphenyl)sulfonyl)-L-proline). Both proline derivatives were separated by column chromatography, and the pure enantiomers of compounds **1**−**13** were obtained via ligand exchange with the corresponding carboxylic acid (Scheme 1). The enantiomer arising from the first eluted diastereoisomer was the dextrorotatory isomer in all the compounds, and it was assigned the *M* configuration by correlation of the sign of the rotation of polarized light with the known structure of **(*M*)-1**. Not only these compounds but also some proline derivatives (**14**−**21**; Figure 1) were used in the following catalytic studies.

Asymmetric Catalysis. The diazo compounds **22**, **24**, **26**, and **28** were prepared from the corresponding acid by reaction with methyl chloroformate, followed by treatment with freshly prepared diazomethane.[15]

Catalytic reactions were performed by addition of a solution containing the diazo species to a solution of the dirhodium(II) complex in the same solvent (diazo:Rh = 100:1, the reaction time and temperature are indicated in the tables). The solution was filtered through a short plug silica gel to remove the catalyst, the solvent was evaporated under reduced pressure, and the crude product was analyzed by ^{1}H and ^{13}C NMR. The products were separated by HPLC chromatography, and the ee values were based on GC analysis with a 2,3-di-*O*-acetyl-6-*O*-(*tert*-butyldimethylsilyl)−beta-CDX column.

The cyclization of the diazo compound **22** in refluxing dichloromethane was used as the pattern reaction to study the influence of the phosphine and carboxylate catalyst ligands on the enantiocontrol of the process. All the tested catalysts $Rh_2(O_2CR)_2(pc)_2$ (**1**−**21**) afforded ketone **23** in high yield (80−99%) (see Table 1). The highest ee values (ca. 65%) were obtained with catalysts possessing trifluoroacetate as the carboxylate ligands (catalysts **7**, **8**, and **10**). Comparison of the catalysts **2**, **7**, **8**, and **10**−**13** with the same carboxylate, trifluoroacetate, but different phosphines revealed the low influence of the electronic and steric nature of the phosphine, except in the case of catalyst **11** with tris(*p*-*tert*-butylphenyl)phosphine. Catalysts with carboxylates bulkier than trifluoroacetate or acetate, such as pivalate and triphenylacetate, led to a low enantiocontrol (27% ee for **4**, 24% ee for **5**). On the other hand, enantiomerically pure $Rh_2(protos)_2(pc)_2$ compounds **14**−**21** were also tested in this reaction, but they provided low ee values (<40%). Both *P* series of dirhodium catalysts **1**−**13** and prolinate derivatives yielded the compound (1*S*,5*R*)-**23** as the predominant enantiomer.

To optimize the conditions for enantioselective cyclopropanation, we explored the effect of temperature and solvent, polar and nonpolar, on the enantiocontrol using the cyclization of diazo compound **22** as the pattern reaction. The temperature had a low influence (entries 6−10, Table 2). A high yield of cyclopropanation with the best asymmetry induction was obtained in refluxing dry pentane (entry 5, Table 2); lower temperatures did not improve the enantiocontrol.[16]

Therefore, trifluoroacetate-derived dirhodium(II) catalysts, which were shown to be the most selective for the cyclopropanation of diazo compound **22**, were further used to study the influence of the substrate structure on enantioselectivity. Reactions were performed in both refluxing dichloromethane and pentane. Again, pentane led to cyclization with the highest enantiocontrol (Tables 3 and 4).

In the cyclization of diazo ketone **28**, two products were obtained: the cyclopropanation product with a six-membered ring, **29**, and the allylic insertion product with a five-membered ring, **30** (Table 5). Cyclopropanation was the predominant reaction, mainly in pentane. Interestingly, while solvents affected the asymmetry induction in the cyclopropanation reaction, the C−H insertion product was obtained with high ee values in both dichloromethane and pentane. Several authors[17] have observed solvent-dependent enantiocontrol in the Rh(II)-catalyzed cyclization of diazo compounds. Depending on the Rh(II) complex, the increasing solvent polarity improved or decreased the asymmetry induction level.[18] However, it appeared that, for the Rh(II) catalysts with ortho-metalated arylphosphines as ligands,

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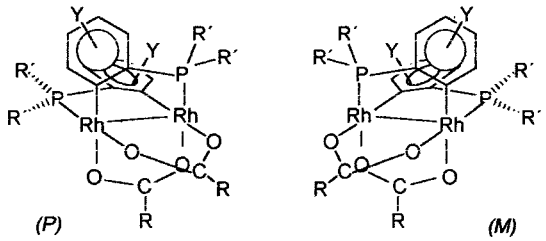
(18) It has been suggested that solvent can influence the alignment of the ligands on chiral Rh(II) complexes and affect the enantioselectivity; thus, rigid chiral Rh(II) carboxamides can prevent similar solvent effects.[17f]



Rh	Phosphine	RCOO	R′	Y
1	$(C_6H_5)_3P$	CH_3COO	C_6H_5	H
2	$(C_6H_5)_3P$	CF_3COO	C_6H_5	H
3	$(C_6H_5)_3P$	C_3F_7COO	C_6H_5	H
4	$(C_6H_5)_3P$	$(CH_3)_3CCOO$	C_6H_5	H
5	$(C_6H_5)_3P$	$(C_6H_5)_3CCOO$	C_6H_5	H
6	$(p\text{-}CH_3C_6H_4)_3P$	CH_3COO	$p\text{-}CH_3C_6H_4$	CH_3
7	$(p\text{-}CH_3C_6H_4)_3P$	CF_3COO	$p\text{-}CH_3C_6H_4$	CH_3
8	$(m\text{-}CH_3C_6H_4)_3P$	CF_3COO	$m\text{-}CH_3C_6H_4$	CH_3
9	$[3,5\text{-}(CH_3)_2C_6H_3]_2(C_6H_5)P$	CH_3COO	$3,5\text{-}(CH_3)_2C_6H_3$	H
10	$[3,5\text{-}(CH_3)_2C_6H_3]_2(C_6H_5)P$	CF_3COO	$3,5\text{-}(CH_3)_2C_6H_3$	H
11	$\{p\text{-}[C(CH_3)_3]C_6H_4\}_3P$	CF_3COO	$p\text{-}[C(CH_3)_3]C_6H_4$	$C(CH_3)_3$
12	$(p\text{-}FC_6H_4)_3P$	CF_3COO	C_6H_5	F
13	$(CH_3)_2(C_6H_4)P$	CF_3COO	C_6H_5	H
(P)-14, (M)-15	$(C_6H_5)_3P$	protos	C_6H_5	H
(P)-16, (M)-17	$(p\text{-}CH_3C_6H_4)_3P$	protos	$p\text{-}CH_3C_6H_4$	CH_3
(P)-18, (M)-19	$[3,5\text{-}(CH_3)_2C_6H_3]_2(C_6H_5)P$	protos	$3,5\text{-}(CH_3)_2C_6H_3$	H
(P)-20, (M)-21	$\{p\text{-}[C(CH_3)_3]C_6H_4\}_3P$	protos	$p\text{-}[C(CH_3)_3]C_6H_4$	$C(CH_3)_3$

Figure 1. List of Rh(II) catalysts with ortho-metalated arylphosphine ligands.

the ability of the solvent to influence the enantiocontrol depended on the type of reaction performed. We have previously described the intermolecular cyclopropanation of styrenes with ethyl diazoacetate catalyzed by these types of compounds.[19] Due to the above results, we decided to investigate the influence of solvents on the enantiocontrol of the cyclopropanation of styrene. The results obtained, shown in Table 6, demonstrated that both the yield of cyclopropanation and the asymmetry induction improved in pentane, the less polar solvent.

Furthermore, enantioselectivity values obtained in the intramolecular cyclopropanation of the tested diazo ketones with our Rh(II) complexes compared favorably with those reported for other chiral catalysts (see Tables 1−5), and access to both enantiomers of **23**, **25**, **27**, **29**, and **30** can be achieved with the use of the *P* or *M* forms of the catalyst. For the same type of catalysts (either *P* or *M* series) cyclopentanones **23** and **27** were obtained with an absolute configuration opposite that of their homologous cyclohexanones **25** and **29**, respectively.

Discussion

The high ee values and the sense of asymmetric induction we observed can be tentatively rationalized on the basis of the model previously used to explain the results in intramolecular C−H insertions promoted by this type of catalyst.[13a] Compound **(*P*)-1**, viewed down the rhodium−rhodium axis, reveals that the four quadrants around the metal atom have different steric congestion. In particular, two quadrants are more sterically hindered due the to aryl groups attached to P which protrude into the region where the carbene transfer takes place (Scheme 2). Thus, the ketone chain

(19) Barberis, M.; Lahuerta, P.; Pérez-Prieto, J.; Sanaú, M. *Chem. Commun.* **2001**, 439.

Scheme 1

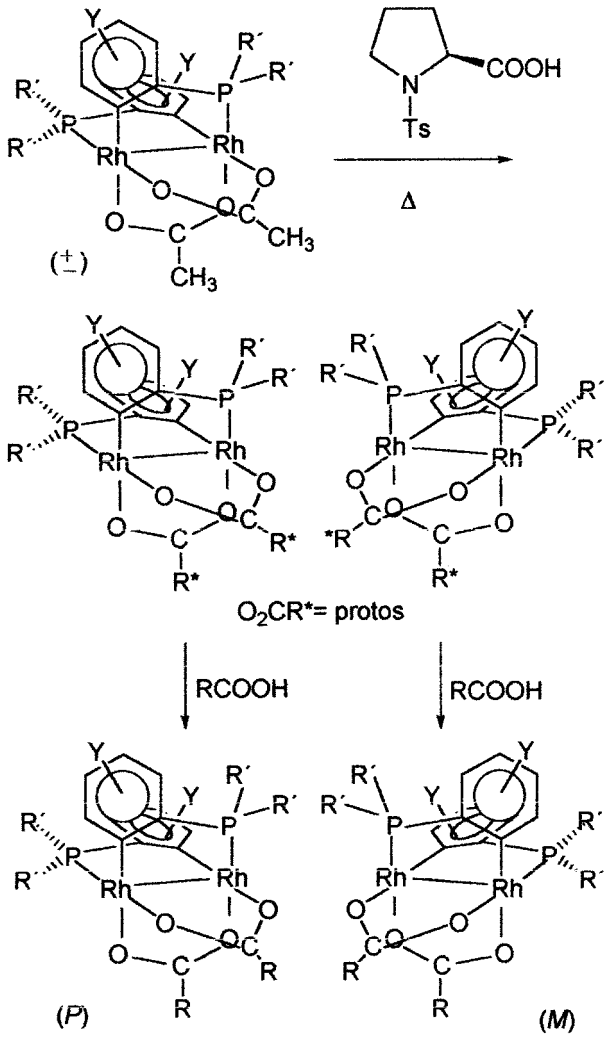
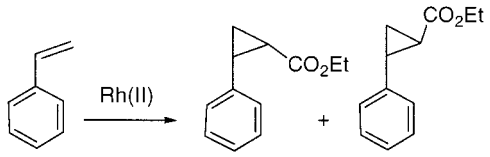


Table 6. Asymmetric Cyclopropanation of Styrene Catalyzed by the (*M*)-Rh(II) Enantiomer



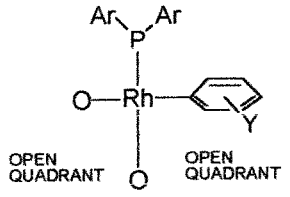
31 32 33

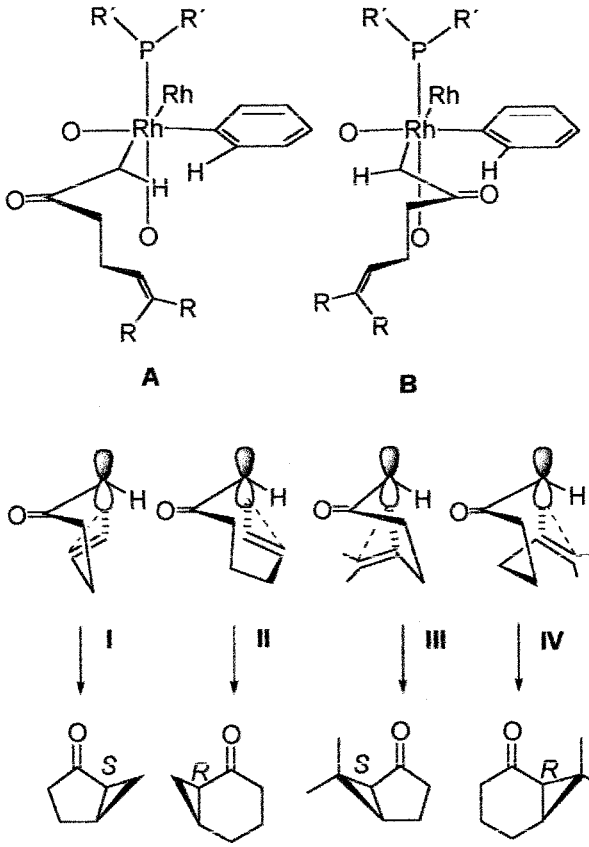
				ee (%)	
Rh	yield (%)[c]	solvent	**32**/**33**[a]	**32**[b]	**33**[b]
2	55	CH_2Cl_2	48/52	91	87
2	62	*n*-C_5H_{12}	42/58	93	94
7	40	CH_2Cl_2	61/39	87	75
7	57	*n*-C_5H_{12}	57/43	95	84
8	36	CH_2Cl_2	51/49	88	81
8	60	*n*-C_5H_{12}	44/56	95	92

[a] Determined by GC analysis. [b] ee values were based on GC analysis with a 2,3-di-*O*-acetyl-6-*O*-(*tert*-butyldimethylsilyl)−beta-CDX colum. [c] Cyclopropanation yield based on ethyl diazoacetate.

occupies one of the two open quadrants with the carbonyl group "syn" to the metal carbene bond (**A** and **B**, Scheme 2). We have previously suggested that the repulsive interaction between the keto group and the metaled aryl group might be the origin of the lower stability of transition state **B**, leaving transition state **A** as the preferred one.

Scheme 2





Results obtained with our catalysts demonstrated that, for the same catalyst, there is a reversal in the preferred configuration of the five-membered-ring and six-membered-ring ketones, **23** and **25**, respectively (entry 2, Table 1 vs entry 1, Table 3). From the transition state **A**, the observed sense of induction for the cyclopropanation is consistent with the alkenes approaching as depicted in **I** and **II** (Scheme 2). In these representations the carbon−carbon double bond approaches the carbene by the more nucleophilic terminal carbon, with the hydrogen substituents oriented toward the catalyst. The different ring sizes might originate conformational differences in both transition states, which could explain the reversal of configuration. Dauben et al.[20] have published similar findings in the asymmetry induction of diazo compounds **22** and **24** promoted by chiral Cu catalysts (entry 24 in Table 1 vs entry 8 in Table 3).

Furthermore, in the case of the cyclopropanation of the substituted analogues **26** and **28** with our catalysts,

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the same reversal in their absolute configuration is observed (compare entries 1 in Tables 4 and 5). The sense of induction for the cyclopropanation is consistent with the transition states depicted in **III** and **IV** (Scheme 2). In this representation the C=C double bond approaches the carbene by the less substituted (more nucleophilic) carbon, with the methyl groups pointing away from the catalyst. This behavior of substituted and nonsubstituted olefins has precedents. Thus, Park et al.[9] also reported the formation of cyclopentanones **23** and **27** with the same absolute configuration by using chiral Ru catalysts in the cyclopropanation of **22** and **26**; they reported that in this case the olefin approach to the carbene carbon for both types of olefins must be different as well.[21]

Finally, increasing the bulk of the carboxylate ligands (pivalate, triphenylacetate, protos) or the bulk of the Y substituent on the metaled aryl group should cause a greater hindrance in the preferred area for the carbene transfer and a decreased enantiocontrol of the process.

Conclusion

A family of chiral dirhodium(II) catalysts with ortho-metalated arylphosphine ligands has been synthesized, and its use in the enantioselective cyclopropanation of α-diazo ketones has been explored. *M* and *P* forms of each catalyst induced identical enantiocontrol in the cyclization of α-diazo ketones, but with opposite sense. The highest enantiocontrol was obtained using pentane as solvent. Most of the dirhodium catalysts tested in this paper gave higher enantioselectivities than dirhodium(II) catalysts with chiral carboxamidate or carboxylate ligands. Until now, dirhodium(II) complexes with ortho-metalated arylphosphine ligands have proven to be the most effective catalysts in the enantioselective cyclopropanation of α-diazo ketones.

Experimental Section

Commercially available $Rh_2(O_2CCH_3)_4$·2MeOH was purchased from Pressure Chemical Co. The synthesis of the following Rh(II) catalysts has been previously described: racemic, **1**,[12] **3**,[12] **4**,[12] **6**,[12] **9**;[13a] enantiomerically pure, **2**,[13a] **7**,[13a] **8**,[13a] **10**,[13a] **11**,[13a] **12**,[13a] **13**,[13a] **(*P*)-14**,[13a] **(*M*)-15**,[13a] **(*P*)-16**,[13a] **(*M*)-17**,[13a] **(*P*)-18**,[13a] **(*M*)-19**,[13a] **(*P*)-20**,[13a] **(*M*)-21**.[13a] The diazo compounds 1-diazo-5-hexen-2-one,[22] 1-diazo-6-hepten-2-one,[20] 1-diazo-6-methyl-5-hepten-2-one,[23] and 1-diazo-7-methyl-6-octen-2-one[24] were prepared according to literature procedures, and the analytical data were coincident with those previously reported. ^{1}H, ^{19}F, ^{13}C, and ^{31}P NMR spectra were recorded on a Bruker AC-300 FT spectrometer as solutions in $CDCl_3$ unless specified otherwise. Chemical shifts are reported in ppm. The coupling constants (*J*) are in Hertz (Hz). All Rh(II) compounds show ^{31}P NMR spectra corresponding to an AA′XX′ system. The Centro Microanálisis Elemental, Universidad Complutense de Madrid, provided analysis. Column chromatography was performed on silica gel (70−230 mesh). Solvent mixtures are volume/volume mixtures. Organic chemicals were purchased from Aldrich Chemical Co. All reactions were carried out in flame-dried glassware under an argon atmosphere. CH_2Cl_2 was distilled from CaH_2 under argon immediately before use. Optical rotations were measured on a Perkin-Elmer 241 polarimeter at the Na D line in 10 cm quartz cuvettes. The ee values were based on GC analysis with a 2,3-di-*O*-acetyl-6-*O*-(*tert*-butyldimethylsilyl)−beta-CDX column using hydrogen as the gas carrier.

General Procedure for the Synthesis of Enantiomerically Pure Rh(II) Complexes with Ortho-Metalated Arylphosphines. To a solution of racemic $Rh_2(O_2CCH_3)_2(pc)_2$·$2HO_2CCH_3$ (pc = ortho-metalated arylphosphine) was added *N*-((4-methylphenyl)sulfonyl)-L-proline (protosH; 8 equiv), and the mixture was refluxed for 2 h using a Soxhlet apparatus with a sodium carbonate trap. The crude product was dissolved in acetone with sodium carbonate to eliminate the excess of protosH, and the two diastereoisomers were separated using standard conditions.[13a] Then, the corresponding carboxylic acid (10 equiv) was added to a dichloromethane (30 mL) solution of each diastereisomer, and the mixture was stirred for $^1/_2$ h. The solution was concentrated, transferred to a column, and eluted with dichloromethane/hexane (10/10) and 1% of the carboxylic acid to afford a complete exchange of the protos groups.

(*M*)-$Rh_2[(C_6H_4)P(C_6H_5)_2]_2(O_2CCH_3)_2$ ((*M*)-1). Yield: 85%. $[\alpha]^{20}_D = -75$ (*c* 0.05, $CHCl_3$).

(*M*)-$Rh_2[(C_6H_4)P(C_6H_5)_2]_2(O_2CC_3F_7)_2$ ((*M*)-3). Yield: 95%. $[\alpha]^{20}_D = -120$ (*c* 0.05, $CHCl_3$).

(*P*)-$Rh_2[(C_6H_4)P(C_6H_5)_2]_2[O_2CC(CH_3)_3]_2$ ((*P*)-4). Yield: 87%. $[\alpha]^{20}_D = +25$ (*c* 0.05, $CHCl_3$).

(*P*)-$Rh_2[(C_6H_4)P(C_6H_5)_2]_2[O_2CC(C_6H_5)_3]_2$ ((*P*)-5). Yield: 90%. ^{31}P{^{1}H} NMR: δ 14.7. ^{1}H NMR: δ 6.39 (m, 2 H), 6.60−7.20 (aromatic signals, 54 H), 7.93 (m, 2 H). ^{13}C{^{1}H} NMR: δ 121.7−138.9 (aromatic signals), 145.1, 163.0 (m), 182.9. $[\alpha]^{20}_D = +60$ (*c* 0.05, $CHCl_3$).

(*M*)-$Rh_2[(p\text{-}CH_3C_6H_3)P(p\text{-}CH_3C_6H_4)_2]_2(O_2CCH_3)_2$ ((M)-6). Yield: 80%. $[\alpha]^{20}_D = -48$ (*c* 0.05, $CHCl_3$).

(*P*)-$Rh_2[(C_6H_4)P(m\text{-xylyl})_2]_2(O_2CCH_3)_2$ ((*P*)-9). Yield: 75%. $[\alpha]^{20}_D = +43$ (*c* 0.05, $CHCl_3$).

Intramolecular Cyclopropanation. All the catalytic reactions were performed by dissolving the catalyst in dry solvent (30 mL) under an argon atmosphere and adding a solution of the corresponding diazo compound (35 mg, [substrate]/[Rh(II) complex] = 100). The mixture was stirred until complete transformation of the diazo compound (the reaction was monitored by TLC). The solvent was trap-to-trap evaporated, and the crude product was filtered in a short chromatography column to eliminate the catalyst. The yield of the reaction was calculated by proton NMR, the cyclization product was purified by HPLC, and the enantiomeric excesses were calculated by chiral gas chromatography.

Bicyclo[3.1.0]hexan-2-one (23)[26] was purified by HPLC using a hexane/ethyl acetate mixture (10/1) as eluent: flow rate 4 mL/min, t_R = 12.0 min. The enantiopurity of the product was determined by chiral GC analysis (oven temperature 100 °C for 2 min, then 5 °C/min to 180 °C). t_R: 1*R*,5*S*, 6.92 min; 1*S*,5*R*, 8.18 min.

Bicyclo[4.1.0]heptan-2-one (25)[26] was purified by HPLC using a hexane/ethyl acetate mixture (10/1) as eluent, flow rate 4 mL/min, t_R = 13.0 min. The enantiopurity of the product was determined by chiral GC analysis (oven temperature 100 °C for 2 min, then 5 °C/min to 180 °C). t_R: 1*R*,6*S*, 11.71 min; 1*S*,6*R*, 12.73 min.

(21) It should be noted that cyclopentanones **23** and **27**, obtained from the same rhodium enantiomer, have different spatial configurations. However, the absolute configurations assigned to them are the same, due to the priority rules of the groups around the stereocenters: (a) Cahn, R. S.; Ingold, C. K.; Prelog, V. *Angew. Chem., Int. Ed. Engl.* **1966**, *5*, 385. (b) Prelog, V.; Helmchen, G. *Angew. Chem., Int. Ed. Engl.* **1982**, *21*, 567.

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6,6-Dimethylbicyclo[3.1.0]hexan-2-one (27)[24,27b] was purified by HPLC using a hexane/ethyl acetate (10/1) mixture as eluent: flow rate 4 mL/min, $t_R = 8.27$ min. The enantiopurity of the product was determined by chiral GC analysis (oven temperature 90 °C for 2 min, then 5 °C/min to 180 °C). t_R: 1*R*,5*S*, 9.41 min; 1*S*,5*R*, 9.63 min.

7,7-Dimethylbicyclo[4.1.0]heptan-2-one (29)[24,27] was purified by HPLC using a hexane/ethyl acetate mixture (10/1) as eluent: flow rate 4 mL/min, $t_R = 13.93$ min. The enantiopurity of the product was determined by chiral GC analysis (oven temperature 100 °C for 2 min, then 5 °C/min to 180 °C). t_R: 1*S*,6*R*, 6.76 min; 1*R*,6*S*, 7.16 min.

3-(2-Methyl-1-propenyl)cyclopentanone (30)[6] was purified by HPLC using a hexane/ethyl acetate mixture (10/1) as eluent: flow rate 4 mL/min, $t_R = 9.51$ min. The enantiopurity of the product was determined by chiral GC analysis (oven temperature 80 °C for 2 min, then 1 °C/min to 180 °C). t_R: 26.11 and 26.36 min. $^{13}C\{^1H\}$ NMR: δ 17.0, 24.6, 29.3, 35.0, 37.5, 44.5, 126.4, 131.8, 218.7. HRMS (*m*/*z*): calcd for $C_9H_{14}O$, 138.1045; found, 138.1044.

Intermolecular Cyclopropanation. A solution of ethyl diazoacetate (17 mg, 0.15 mol) in pentane or dichloromethane (5 mL) was added, via a syringe pump (1 mL/h), to a refluxing solution of the catalyst (1.5 mg) and styrene (156 mg, 1.5 mol) in the corresponding solvent (30 mL). After complete addition, the reaction mixture was stirred at reflux for an additional 4 h and cooled to room temperature. The solvent was evaporated and the crude product filtered in a short chromatography column to eliminate the catalyst. The yield of the reaction was calculated by proton NMR[28] and the enantiopurities of the products were calculated by chiral gas chromatography (oven temperature 70 °C for 10 min, then 1 °C/min to 130 °C). t_R: *cis*-1*S*,2*R*, 58.13 min; *cis*-1*R*,2*S*, 58.71 min; *trans*-1*S*,2*S*, 68.89 min; *trans*-1*R*,2*R*, 69.34 min.

Acknowledgment. We thank the Dirección General de Investigación Científica y Técnica (DGICYT) (Project PB98-1437) and the EC (Project TMR Network ERBFM-RXCT 60091).

OM0110437

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