up as described above, giving 0.85 g of a semisolid which contained 90% 1-bromobicyclo[2.2.2]octane and 10% 1-iodobicyclo-[2.2.2]octane.

1,4-Diiodobicyclo[2.2.2]octane-*2,2,3,3-d*$_4$. To a solution of 25 g (0.1 mol) of 1,2,3,4-tetrachlorobicyclo[2.2.2]oct-2-ene[16] in 150 mL of ethanol-*d* were added 41 g of dry triethylamine and 1.0 g of 10% palladium on carbon. The solution was reduced by deuterium by using a Parr apparatus (15 h). The solvent was removed by distillation under reduced pressure. The residue was diluted with 500 mL of methylene chloride, filtered through Celite, and washed with water, 10% hydrochloric acid, saturated sodium bisulfite, and brine. The solution was dried over sodium sulfate and concentrated, giving brown crystals. Recrystallization from ethanol gave 16.8 g (92%) of 1,4-dichlorobicyclo[2.2.2]octane-*2,2,3,3-d*$_4$. Mass spectral analysis indicated 86% d_4 and 14% d_3. The dichloride was converted to the diiodide as previously described.[10]

Reacton of 1,4-Diiodobicyclo[2.2.2]octane with Bromine. A solution of 3.5 g (9.7 mmol) of 1,4-diiodobicyclo[2.2.2]octane in 100 mL of methylene chloride was treated with a solution of 3.3 g (21 mmol) of bromine in 25 mL of methylene chloride. After 1.25 h at room temperature, the reaction mixture was worked up as described above, giving 2.5 g (96%) of 1,4-dibromobicyclo-[2.2.2]octane, mp 252-254 °C.[11]

Reaction of 1,4-Diiodobicyclo[2.2.2]octane-*d*$_4$ with *tert*-Butyllithium. A solution of 0.72 g (1.96 mmol) of the diiodide in 64 mL of dry pentane-ether (3:1) was cooled to -77 °C and treated with 1.26 mL (2.1 mmol) of 1.7 M *tert*-butyllithium with stirring. After 14 min, the stirring was stopped, and the solid matter was allowed to settle. A portion of the solution was studied at -21 °C by ^{2}H NMR at 41.4 MHz. The spectrum contained bands of the starting material and those of the two deuterium-labeled isomers of 1,4-dimethylenecyclohexane.

Acknowledgment. This investigation was supported by National Science Foundation Grant No. CHE-78-24880. We also acknowledge the support of the NSF Northeast Regional NMR Facility at Yale University which is funded by Grant No. CHE-79-16210 from the Chemistry Division of the NSF. We thank Dr. Kauer for his assistance in effecting the Diels-Alder reaction between tetrachloro-α-pyrone and ethylene.

Registry No. 1, 70279-05-9; 2, 930-80-3; 3, 931-98-6; 4, 74725-75-0; 5, 81389-50-6; 6, 10364-05-3; 4-*d*$_4$, 81389-51-7; 7, 4982-20-1; 7-*d*$_4$, 81389-52-8; 8, 81389-53-9; cyclohexane, 110-82-7; 1-bromobicyclo-[2.1.1]hexane, 77379-00-1; 7-bromonorbornane, 13237-88-2; 1-bromonorbornane, 13474-70-9; 1-bromobicyclo[2.2.2]octane, 7697-09-8; 1,2,3,4-tetrachlorobicyclo[2.2.2]oct-2-ene, 1197-74-6; 1,4-diiodobicyclo[2.2.2]octane-*d*$_4$, 10364-05-3.

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Mechanism of Asymmetric Hydrogenation. Rhodium Complexes Formed by Unsaturated Carboxylic Acids, Carboxylates, and Carboxamides

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α,β-Unsaturated acids displace solvent from (*RR*)-[4,5-bis[(diphenylphosphino)methyl]-2,2-dimethyldioxolan]bis(methanol)rhodium cation, forming chelate complexes in which olefin and carboxylate are bound to the metal. The strength of complexation is enhanced in basic media and propenoic or 2-methylpropenoic acid form a different type of species with 2:1 stoichiometry in the absence of base. α,β- and β,γ-unsaturated amides likewise form complexes in which olefin and carboxamide oxygen are bound to rhodium. The ratio of diastereomers observed by ^{31}P NMR does not correlate with optical yields in hydrogenation of these precursors. In related experiments with (*RR*)-[1,2-bis(*o*-anisylphenylphosphino)ethane]bis(methanol)rhodium cation, 2-methylenesuccinic acid and its methyl esters gave a variety of complexes, including tridentate species where both carboxyl groups and olefin were concomitantly bound.

As a general rule, asymmetric hydrogenation is rarely used other than in the synthesis of amino acids and very closely related species.[1] Its extension will require new types of catalyst and perhaps a better understanding of reaction mechanism to assist their design. For this latter reason we have studied the complexes formed by representative α,β-unsaturated carboxylic acids and their congeners with bis(phosphine)rhodium(I) procatalysts, employing ^{31}P NMR in the manner of earlier work.[2-5] Four distinct types of complexes have been observed, depending on the system, shown as A-D in Chart I.[6] Each of these is associated with a characteristic set of PRh and PP coupling constants. Much of the survey was conducted

Chart I. Types of Rhodium Bis(phosphine) Complex Formed by Carboxylic Acids and Carboxamides

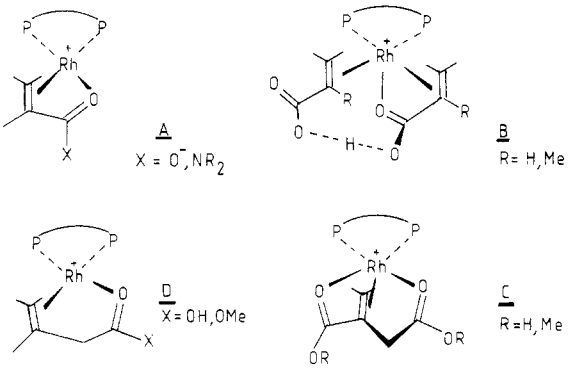

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Table I. Phosphorus-31 NMR Spectral Data of Carboxylate Complexes in Methanol[a,b]

entry	bis(phosphine) complex	substrate	temp, K	diastereomer ratio[c]	$\delta(P_1)$	$\delta(P_2)$	J_{RhP_1}	J_{RhP_2}	$J_{P_1P_2}$
1	4	2	230	3:1	35.3	15.1	176	170	52
					41.3	12.7	176	168	52
2	4	3a	235	3:2	35.5	13.6	173	168	50
		NEt_3			39.3	10.6	173	170	50
3	4	3b	252	5:4	35.5	13.7	171	168	50
					39.4	10.6	173	170	50
4	4	6	303	3:2	31.8	16.0	178	171	50
		NEt_3			35.6	11.6	178	170	51
5	7	6	303		57.7	13.3	179	166	53
		NEt_3							
6	4	10a	252	4:1	37.1	14.7	173	172	53
		NEt_3			42.0	10.2	170	172	52
7	4	5	295	1:1	38.4	11.6	178	166	52
					33.3	15.4	178	170	52

[a] Chemical shifts are recorded in parts per million downfield from H_3PO_4. [b] [Rh] = 0.03 M, substrate/Rh = 6:1; triethylamine where added was in comparable concentration to substrate. [c] Major species first.

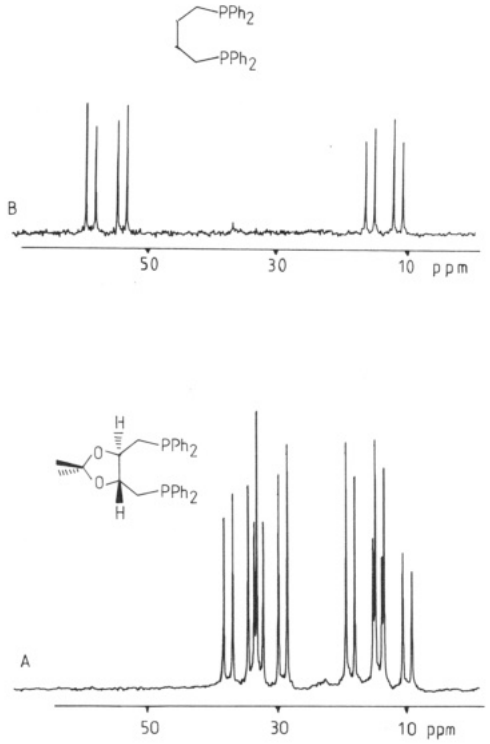
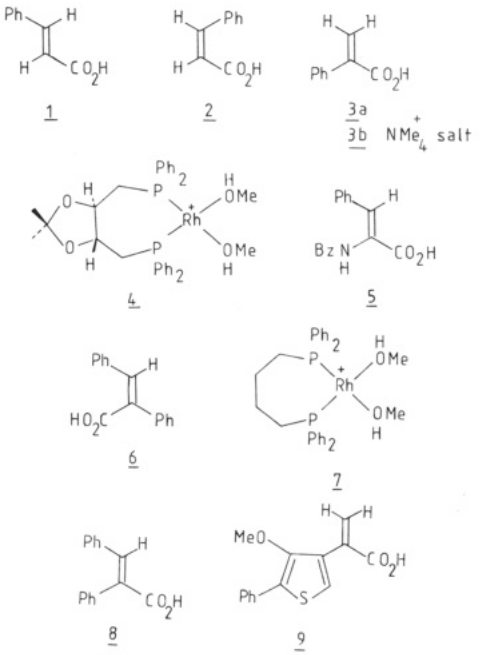


Figure 1. Phosphorus-31 NMR spectra of (a) the (diop)Rh complex derived from (*Z*)-2-phenylcinnamic acid and (b) the (dppb)Rh complex derived from (*Z*)-2-phenylcinnamic acid.

with (*RR*)-4,5-bis[(diphenylphosphino)methyl]-2,2-dimethyldioxolan (diop) and (*RR*)-1,2-bis(*o*-anisylphenylphosphino)ethane, (dipanp) the two most commonly employed ligands in asymmetric hydrogenation.

Complexes Derived from α,β-Carboxylates and Carboxamides

In the course of examining (diop)Rh complexes of dehydro amino acids, we studied *trans*-cinnamic acid (**1**) as a model compound and observed that it bound very weakly, thereby demonstrating the importance of the amide function in the former case.[7] More recent experiments with *cis*-cinnamic acid (**2**) or with atropic acid (**3a**) give a very different result. When an excess of **2** in methanol was mixed with the (diop)Rh solvate **4**, the resulting red solution showed a 16-line ^{31}P NMR spectrum which was sharp below room temperature and little affected by added triethylamine. This was interpreted as two diastereomeric species of similar structure, and their proportions varied such that one became dominant at low temperature (Table I). Identical spectra were obtained at substrate/rhodium ratios of 5:1 and 1.3:1 so that the stoichiometry of the two species is the same. Atropic acid (**3a**) behaved similarly, although the ^{31}P NMR spectrum was exchange broadened to an appreciable extent even at 260 K. This was much less apparent in the presence of triethylamine, and the spectrum derived from preformed tetramethylammonium atropate (**3b**) is sharp at room temperature. The most likely line-broadening mechanism is intermolecular exchange between free and bound substrate which makes the phosphorus nuclei equivalent without vitiating the Rh–P coupling. With a 10:1 excess of acid **3a** in the presence of triethylamine the observed spectrum was sharp at 290 K, whereas with a 5:1 excess it was appreciably broadened at this temperature ($\omega_{1/2}$ = 7 Hz).



The spectra obtained are remarkably similar to those observed for (*E*)-benzamidocinnamic acid (**5**) when complexed to solvate **4**.[7] In this case, ^{13}C NMR studies have demonstrated that the olefin and carboxylate (but not the amide) are bound to rhodium, and a similar structure is indicated here. The two diastereomers are related by binding of the opposite prochiral faces of olefin to rhodium,

(7) Brown, J. M.; Chaloner, P. A. *Chem. Commun.* **1978**, 321–2.

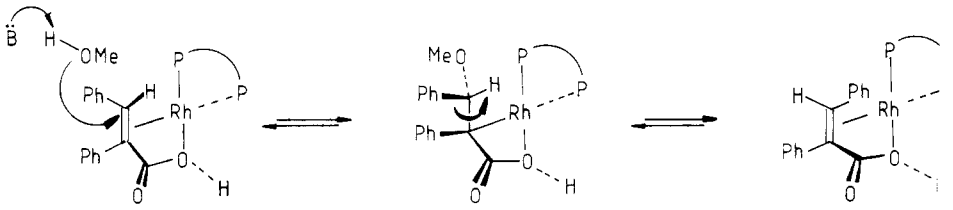


Figure 2. A mechanistic pathway for olefin isomerization in base.

Table II. Phosphorus-31 NMR Spectral Data of Carboxamide Complexes in Methanol[a]

entry	bis(phosphine) complex	substrate[b]	temp, K	diastereomer ratio[c]	$\delta(P_1)$	$\delta(P_2)$	J_{RhP_1}	J_{RhP_2}	$J_{P_1P_2}$
1	4	11a	236	3:2	39.3	14.1	173	168	53
					35.9	10.3	174	170	53
2	4	11b	228	5:4	43.3	6.7	163	162	52
					36.9	12.4	172	168	51
3	4	10b	252	3:1	37.3	13.4	171	168	52
					41.2	9.2	171	167	53
4	13	11a							
5	4	propenamide	222		49.1	2.4	156	159	50
6	4	*N,N*-dimethyl-propenamide	262		45.3	5.7	162	162	53
7	4	2,*N,N*-trimethyl-propenamide	228	3:1	44.1	6.9	165	163	53
					37.3	11.5	172	168	54

[a] [Rh] = 0.03 M; substrate/Rh = 6:1. [b] **11b** is atropamide, **10b** is *N,N*-dimethyl-2-(*o*-methoxyphenyl)propenamide. [c] Major species first.

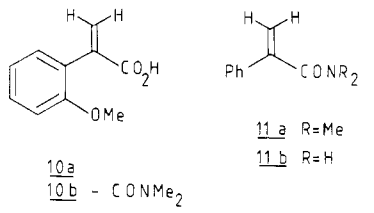
Table III. Asymmetric Hydrogenation of α,β-Unsaturated Acids and Amides in Methanol Solution[a]

entry	procatalyst	substrate	enantiomer excess,[d] %
1	4	3a, NEt_3	67 *S*
2	4	3b	67 *S*
3	18	3b	5 *R*
4	4	10a, NEt_3	36 *S*
5	18	10a	18 *R*[b]
6	4	11a	14 *R*
7	4	11a, NEt_3	34 *S*
8	4	11b	30 *S*
9	4	11b, NEt_3	5 *R*
10	4	10b	14 *R*
11	4	10b, NEt_3	51 *S*[c]

[a] [Rh] = 0.004 M; catalyst/substrate = 1:50; [Et_3N] = 0.012 M, where added. [b] Unaffected by added NEt_3. [c] The same result was obtained employing $EtN(i\text{-}Pr)_2$ or *N*-methylephedrine. [d] Measured by rotation[23] (entries 8, 9) or by shift reagent analysis of the dimethyl amide (see text). The configuration of the products of reduction of *o*-methoxyatropic acid is based on the assumption that they have the same sign of rotation as corresponding reduction products of atropic acid.[23]

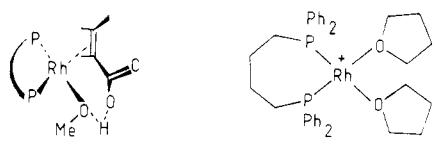
since (*Z*)-1-phenylcinnamic acid (**6**) gives the expected two eight-line multiplets on reaction with **4** in the presence of triethylamine but only one eight-line multiplet in the corresponding experiment with achiral solvate **7** derived from 1,4-bis(diphenylphosphino)butane (dppb) (Figure 1). The corresponding *E* isomer of 1-phenylcinnamic acid (**8**) does not complex with **4**, but in the presence of triethylamine a rapid catalytic isomerization (proved by ^1H NMR and TLC of isolated product) to an 80:20 mixture of **6** and **8** occurs. Both complex **4** and triethylamine are required for isomerization, and after 2 h at room temperature the ^{31}P NMR spectrum of a sample derived from **4** and the pure *E* isomer contains only the complex derived from the *Z* isomer. A probable mechanism for the isomerization is outlined in Figure 2, the key step being nucleophilic attack of methanol at the coordinated ethylene with general-base participation of triethylamine.

The highest optical yield recorded in reduction of an α,β unsaturated carboxylic acid is 88%, for hydrogenation of **9**.[8] The methoxy group ortho to the unsaturated acid may play a part in this reaction and accordingly the simple model compound, 1-(*o*-methoxyphenyl)propenoic acid (**10**) was synthesized. The ^{31}P spectra obtained from mixtures of **10**, NEt_3, and the (diop)Rh solvate **4** were very similar to those derived from atropic acid (**3**) under similar conditions, although the diastereomer ratio was quite different with the major species present to 78% of total complex at 280 K. It seems clear that the methoxy group does not participate, at least in formation of the carboxylate complex, although we cannot rule out its involvement at a later stage of hydrogenation.



10a
10b - $CONMe_2$

11a R=Me
11b R=H



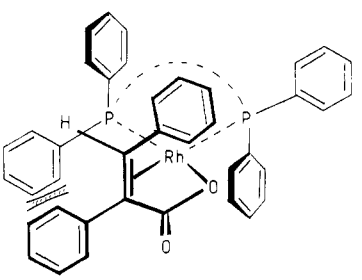
12 13

Very little work has been carried out on asymmetric hydrogenation of α,β unsaturated amides, although the amide group does seem to possess exceptionally strong basicity toward rhodium(I) cations. In accordance with this, *N,N*-dimethylatropamide (**11a**) complexed strongly with the diop solvate **4**, and the ^{31}P NMR spectrum of the resulting complex was very closely similar to that derived from tetramethylammonium atropate and solvate **4**. A range of similar samples were prepared (Table II) and the close correspondence of their NMR spectra suggest that they have a common structure, related to that of the carboxylate complexes described earlier. The simplest

(8) Stöll, A. P.; Süess, R. *Helv. Chim. Acta* **1974**, *51*, 2487–92.

structure in accord with observation is A (Chart I), which involves a rather small-ring chelate (formally three and one-half membered) and structure **12** was at least considered as an alternative possibility. This was ruled out by two experiments. Firstly, the spectrum obtained from **11a** and solvate **13** in anhydrous tetrahydrofuran was almost identical with that obtained in methanol. Since complex **12** requires an intramolecular H bond donated from coordinated solvent, and none is available in tetrahydrofuran, it cannot be the structure of the observed species. Furthermore, only two diastereomeric species are observed on reaction of amide **11a** with the analogue of **4** prepared in *rac*-2-butanol. In a complex containing one coordinated prochiral olefin and one chiral solvent molecule there are *four* possible diastereomers. Structure A is thus supported by all available evidence as the preferred complex for a range of unsaturated amides and carboxylates. The small chelate ring involved suggests that a bis(phosphine) with large bite angle will be preferred as counterligand. This is borne out in practice since diop (typical chelate angle 96°)[9] forms strong complexes, whereas the 1,2-bis(diphenylphosphino)ethane analogues dipamp and chiraphos ((*SS*)-2,3-bis(diphenylphosphino)butane) (typical chelate angle 82°)[9] do not form characterizable complexes of type A.

The disposition of substituents on the olefin is critical. *trans*-Cinnamic acid does not react appreciably with **4** even in the presence of base, whereas *cis*-cinnamic acid displaces the solvent from **4** even in the absence of base; atropic acid shows intermediate complexing ability. This can be rationalized if a square-planar carboxylate complex has structure **14** in which intracomplex Ph–Ph repulsions are minimized for an (*E*)-phenyl substituent. This model explains why *E* dehydro amino acids complex less readily than *Z* isomers in related rhodium complexes and suggests that the low optical yield in the former case is brought about by steric inhibition of the pathway, leading to high selectivity. Under conditions where (*E*)-cinnamic acid (**2**) is 94% reduced in the presence of **4** [20 °C, p_{H_2} = 1 atm, catalyst/substrate = 50:1, 15 h], the trans isomer **1** only hydrogenates to the extent of 13%.



14

Hydrogenation of α,β-Unsaturated Acids and Amides

Atropic acid (**3a**) was one of the substrates reduced by (diop)Rh complexes in the original communication of Kagan and Dang.[10] They found that in the presence of base, but not in its absence, a moderate optical yield (61%) of 2-phenylpropionic acid was obtained. Slightly greater selectivity was obtained under our conditions, although reduction of **3a** in the presence of triethylamine proved as effective as reduction of preformed tetramethylammonium atropate (Table III). Optical yields were determined by conversion of the product acid into its *N*,*N*-dimethyl amide and observation of the ^{1}H NMR spectrum of a solution in CCl_4 in the presence of 15–20 mol % of the chiral shift reagent tris(3-(heptafluorobutyryl)-*d*-camphorato)europium(III).[11] Under these conditions the *C*-methyl doublets of *R* and *S* isomers were separated by 0.25 ppm, with *S* at lower field. Reduction of methoxy acid **10** under similar conditions gave a lower optical yield of 36% *S*. In this series, there seems to be little correlation between the diastereomer ratio observed in solution by ^{31}P NMR and the enantiomer excess observed in hydrogenation.

Under these conditions α,β-unsaturated amides reduce readily, in modest optical yield. The most interesting feature is that the stereochemistry of product is sensitive to added base, even when the amide is tertiary. The nature of the base seems unimportant, for triethylamine, *N*,*N*-diisopropylethylamine and *N*-methylephedrine all affect the outcome of reduction of *o*-methoxy-*N*,*N*-dimethylatropamide similarly.

Since the addition of triethylamine does not affect the ^{31}P NMR spectrum of (diop)Rh complexes of unsaturated amides, the role of base presumably comes at a later stage in the catalytic cycle. Optical yields were the same in reduction of **11a** with hydrogen or deuterium but isotopic exchange at the α-position of product (and to a much lesser extent at the β-position) occurred when reaction was carried out with D_2 in CH_3OH or with H_2 in CD_3OD. This was typically of the order of 30% in the absence of triethylamine and 50% in its presence; control experiments demonstrated that it occurred during the catalytic cycle. A mechanism which might account for these observations is outlined in Figure 3. Two diastereomers of coordinated amide are present and they react (at different but unspecified rates) to give transient dihydrides. Intracomplex hydride transfer gives the respective monohydrides. These may (a) interconvert by olefin dissociation, followed by rotation and recombination, (b) undergo reversible proton transfer to external base, and (c) effect a second intracomplex hydride transfer, giving rise to the product of hydrogenation. It is necessary to postulate all of these steps if the initial addition of dihydrogen is irreversible. Step b then causes isotope exchange when the reagent and solvent are isotopically different, and by proper adjustment of the respective rate constant for the competitive steps, it is possible to simulate the observed changes in optical yield on adding base, concomitant with increased exchange. It is notable that exchange must occur with retention of configuration because of the isotopic invariance of optical yield. In the addition of deuterium to propenoic acid catalyzed by **4** in methanol in the absence of triethylamine, isotopic exchange also occurs but with inversion of configuration.[12] Thus it appears that there are two distinct mechanisms by which exchange can occur, depending on pH and the structure of the reactant.

Complexes Derived from Propenoic and 2-Methylpropenoic Acids and Their Amides

In the presence of triethylamine, 2-methylpropenoic acid displaces solvent from complex **4** to form a carboxylate adduct similar to those described earlier. In the absence of triethylamine an entirely different kind of species is formed with reduced coupling constants and a reduced chemical shift separation. Five different acid/rhodium ratios were investigated (1.2:1; 2.3:1; 6:1; 10:1, and 15:1)

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(10) Dang, T. P.; Kagan, H. B. *Chem. Commun.* **1971**, 481.
(11) Frazer, R. R.; Petit, M. A.; Saunders, J. K. *J. Chem. Soc. D* **1971**, 1450–1. Cf. McCreary, M. D.; Lewis, D. W.; Wernick, D. L.; Whitesides, G. M. *J. Am. Chem. Soc.* **1974**, *96*, 1038–54.
(12) Brown, J. M.; Parker, D. *Organometallics* **1982**, in press.

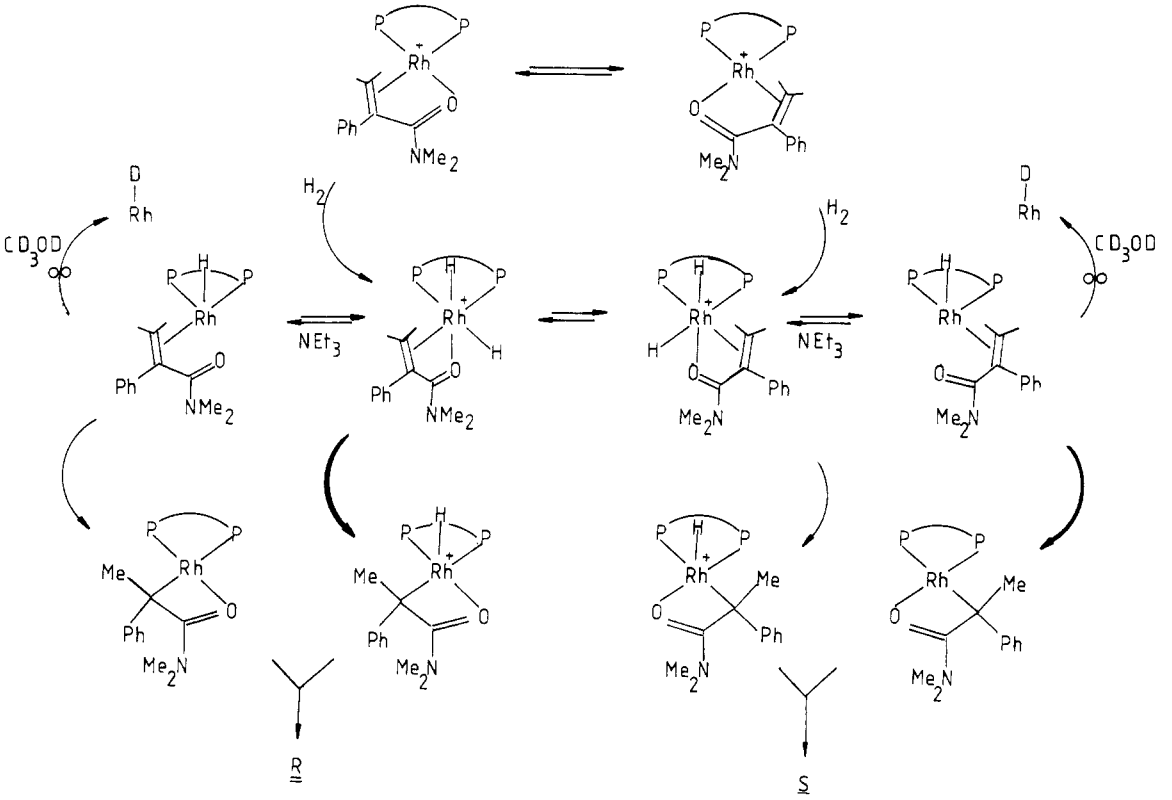


Figure 3. A mechanistic pathway for isotopic exchange and reduction of α,β-unsaturated amides.

Table IV. Phosphorus-31 NMR Data of Complexes Derived from Propenoic and 2-Methylpropenoic Acid[a]

entry	substrate	temp, K	diastereomer ratio	$\delta(P_1)$	$\delta(P_2)$	J_{RhP_1}	J_{RhP_2}	$J_{P_1P_2}$
1	2-methylpropenoic acid,[b] NEt_3	252	1:1	39.4	13.1	170	173	53
				34.6	14.4	171	173	53
2	propenoic acid, NEt_3	228	c	44.5	9.62	170	168	53
3	2-methylpropenoic acid	252	5:1	30.7	29.7	161	137	39
				31.4	17.6	140	134	41
4	propenoic acid	228	6:1	31.5	18.3	140	134	41
				30.5	30.5	161	141	

[a] [Rh] = 0.03 M, substrate/Rh = 6:1; solutions were orange in the presence of Et_3N and pale yellow in its absence. [b] An identical spectrum was obtained from tetramethylammonium propenoate. [c] Only one species was observed.

and the latter three gave almost identical spectra. At lower ratios complexation was slow, and sharp spectra were only obtained after equilibrating for more than 18 h at room temperature (Table IV). There were two eight-line multiplets observed which equilibrated slowly and whose relative proportion was temperature dependent. At the lowest substrate/rhodium ratio 45% of the total ^{31}P signal was due to **4**, although at the higher ratios this was completely absent.

Description of the new species as a mixture of diastereomers of 2:1 adduct B is consistent with this experiment and with related observations on rhodium complexes derived from α-acetamidoacrylic acid and 1,3-bis(diphenylphosphino)propane.[13] The most cogent evidence comes from reaction of solvate **15** with 1.2 equiv of 2-methylenesuccinic acid (**17a**) at 228 K. A single complex is initially observed, consistent with type C structure (vide infra) and with **15** completely absent. After 3 h at or above 280 K the spectrum had changed irreversibly and now revealed a reversion to ca. 50% of **15** and 50% of a new complex whose spectrum closely resembled that of the type B species derived from **4**. This strongly suggests 2:1 stoichiometry and a similar structure to the known bis(methyl acrylate)rhodium(I) acetylacetonate (**16**) whose ^{13}C NMR spectrum reveals at least two diastereomers.[14]

In a recent comprehensive paper on asymmetric catalysis by **15** and related proline-derived bis(phosphine) catalysts, Ojima and co-workers observed a single complex in the presence of a large excess of 2-methylenesuccinic acid.[15] Inspection of the data presented indicates that it has a very similar structure to those of type B quoted here and is unlikely to be the resting state of the catalyst under turnover conditions when hydrogen is present to intercept the 1:1 complex formed initially. We expect that type B addends are irrelevant to catalysis and will inhibit reaction if formed. Coordinatively saturated rhodium(I) complexes are normally very pale in color, and the appearance of solutions of 2:1 complexes is in accord with this.

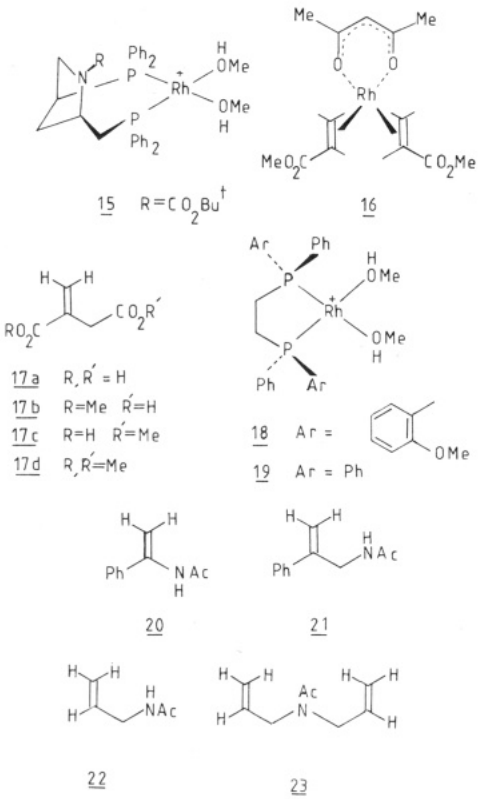
Complexes Derived from 2-Methylenesuccinic Acid Derivatives

Generally speaking, asymmetric hydrogenation of 2-methylenesuccinic acid with rhodium catalysts has been

(13) Brown, J. M.; Chaloner, P. A. *J. Chem. Soc., Perkin Trans. 2*, in press.

(14) Parker, D.; Part II Thesis, Oxford University, Oxford, 1978. Cf. Herberhold, M.; Krester, C. G.; Wiedersatz, G. O. *J. Organomet. Chem.* **1976**, *120*, 103–30.

(15) Ojima, I.; Kogure, T.; Yoda, N. *J. Org. Chem.* **1980**, *45*, 4728–41. A full discussion of the complexes formed by proline-derived ligands is in ref 16.



much more successful than that of other carboxylic acids, both five-membered-ring and seven-membered-ring chelates giving good results.[5] The presence of a second carboxylic acid moiety complicates matters, and the types of complex formed under hydrogenation conditions are of some interest.

We first examined the complexes formed between solvate **4** and itaconic acid or its methyl esters in methanol. The only sharp characterizable spectrum was found with **17c** in the presence of triethylamine and its similarity to other type A complexes in spectral parameters (Table V) makes it clear that only the olefin and α-carboxylate are bound. Two diastereomers are formed in comparable amount, and hydrogenation of **17c** in the presence of a catalytic amount of **4** proceeds in low optical yield, with 9% excess of the *S* enantiomer of product.

The range of complexes formed by solvate **15** with itaconates has been discussed elsewhere.[16] Like the proline-derived bis(phosphines), dipamp has been shown to be an effective procatalyst in the asymmetric hydrogenation of **17**. Since five-membered-ring chelate bis(phosphines) can show very different complexation behavior from their seven-membered-ring counterparts, it was of some interest to examine the species formed by solvate 18 in the presence of itaconates. A further stimulus was provided by the report of Christopfel and Vineyard that itaconates **17** are reduced in high optical yield with (dipamp)Rh catalysts, with the added subtlety in the parent case that the optical yield is strongly dependent on substrate concentration.

Reaction of itaconic acid (**17a**) at high concentrations with solvate **18** gave a complex whose ^{31}P NMR is radically different from those previously described (Table V). Its main characteristic is a very low P–P coupling constant of 22 Hz and this coupled with the very pale yellow color leads us to propose a five-coordinate structure C carrying two bound carbonyl groups. When the initial observation

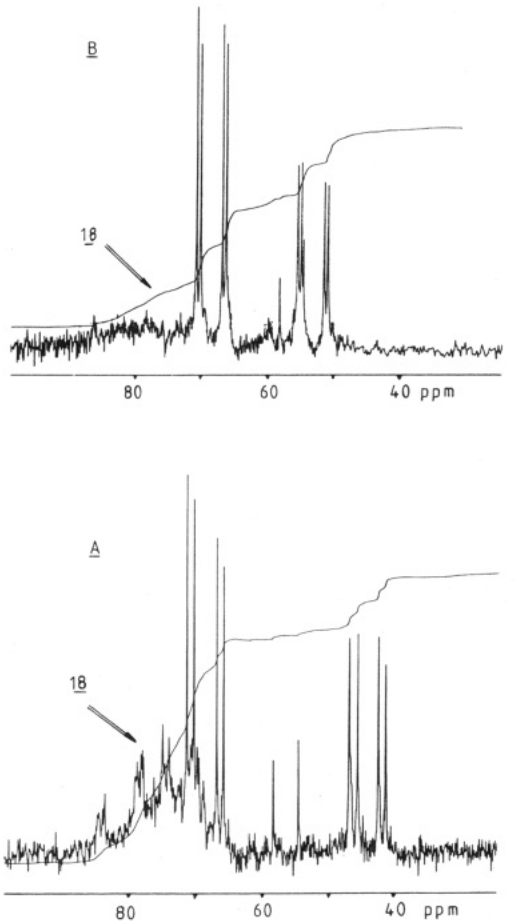


Figure 4. Phosphorus-31 NMR spectra of the (dipamp)Rh complex derived from 2-methylenesuccinic acid: (a) initial spectrum at low temperature and (b) spectrum after solution allowed to stand after at ambient temperature and recooled to –65 °C.

is made at low temperature and a minimal excess of **17a** employed, then an orange solution is obtained with a completely different NMR spectrum (Figure 4). This is typical of a bidentate complex with bound olefin and carboxylate but fails to distinguish between two possible structures with α- and β-acids respectively coordinated. When this solution is warmed, an irreversible change to the type C complex (Figure 4) occurs, and since only 1.2 molar excess of **17a** is employed, the initial and final complexes must have the same stoichiometry.

Both α-methyl (**17b**) and β-methyl (**17c**) esters of itaconic acid form similar tridentate complexes. In the former case an intermediate bidentate species was observed at 228 K even in the presence of a tenfold excess of reactant. The latter forms two diastereomeric tridentate complexes in ratio 4:1 but behaves very differently in the presence of triethylamine. Then two diastereomeric complexes are formed which are very clearly of type A, with characteristically large rhodium couplings to both phosphorus nuclei. This implies that all other bidentate complexes produced in this series involve coordination of the olefin and β-carboxyl group, closely modelling enamide, and of type D in Chart I. The diversity of complex types in this series contrasts with the uniformity of optical yield (55–88% *R*) of (**17a–d**) in asymmetric hydrogenation although their reactivities fall into two categories. The diester **17d** and α-ester **17b** are most reactive with diacid **17a** hydrogenating much more slowly and β-ester **17c** still less reactive. Substrate **17d** forms only a type D complex and substrate **17b** forms a type D complex transiently en

(16) Achiwa, K.; Chaloner, P. A.; Parker, D. *J. Organomet. Chem.* **1981**, *218*, 249–60.

Table V. Phosphorus-31 NMR Spectral Data of Complexes Derived from Itaconic Acid and Its Esters[a]

entry	bis(phosphine) complex	substrate	temp and conditions	diastereomer ratio	$\delta(P_1)$	$\delta(P_2)$	J_{RhP_1}	J_{RhP_2}	$J_{P_1P_2}$
1	4	17c, NEt_3	251 K, 6:1	1:1	40.8	15.8	168	167	54
					35.1	12.0	175	169	56
2	18	17a	228 K, 1.2:1	c	68.5	43.6	171	157	41
3	18	17a	303 K, 10:1	7:2	67.9	52.2	147	154	22
					70.2	52.4	151	153	22
4	18	17a, NEt_3	228 K	c	66.8	43.2	162	165	41
5a	18	17b	228 K, 10:1	c	68.6	44.2	172	156	41
5b	18	17b	303 K, 10:1	c	77.1	64.0	136	157	21
6	18	17c	303 K, 6:1	4:1	68.2	51.0	150	153	22
					66.6	50.8	148	151	21
7	18	17c, NEt_3	252 K, 6:1	2:1	76.5	51.9	175	175	38
					76.9	51.6	173	172	38
8	18	17d	228 K, 12:1	c	69.9	49.1	174	152	40
9a	19	17a	228 K, 1.3:1		74.2	57.3	164	150	35
9b	19	17a	228 K, 3:1		60.9	56.9	146	128	25

[a] [Rh] = 0.03 M, major species first. [b] The ratio of substrate to rhodium is quoted in each case. [c] Only diastereomer observed. [d] Spectrum unchanged in the presence of trichloroacetic acid.

Table VI. Phosphorus-31 NMR Spectral Data of Rhodium Complexes Derived from Allylic Amides[a]

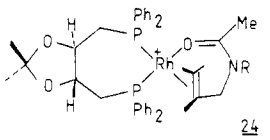
entry	bis(phosphine) complex	substrate	temp K	diastereomer ratio[b]	$\delta(P_1)$	$\delta(P_2)$	J_{RhP_1}	J_{RhP_2}	$J_{P_1P_2}$
1	4	21	228	3:2	38.9	12.6	174	155	50
					40.5	10.5	171	154	49
2	4	22	252	1:1	41.6	12.1	179	153	48
					42.0	10.5	179	153	49
3	4	23	252	3:1	40.3	11.5	174	154	47
					42.4	9.5	176	153	47

[a] Methanol solution [Rh] = 0.03 M, [substrate] = 0.18 M. Sharp spectra were observed up to 280 K. [b] Major species first.

route to the tridentate species. With a large excess of itaconic acid itself, only the tridentate species is seen. We consider that the species involved in the catalytic cycle is D and find support in the comparability of reaction rates between **17d** and (*Z*)-α-acetamidocinnamic acid. For reasons which are now moderately well understood,[4] there seems little correlation between diastereomer ratios in complexation and enantiomer excess in reduction. It is notable that no 2:1 complexes are formed under any circumstances and also that complexes derived from 1,2-bis(diphenylphosphino)ethane solvate **19** with **17a** appear very similar to the dipamp complexes.

Complexes Derived from Allylic Amides

In view of the report that **20** is reduced in moderate optical yield by (diop)Rh complexes, we throught it of some interest to examine the analogue **21** and related amides **22** and **23**. Spectra of solutions containing a 6:1 excess of amide over solvate **4** showed strong complexation in all cases and sharp ^{31}P signals below room temperature. All the spectra were quite similar and showed large P_1Rh_1 and substantial P_2Rh and P_1P_2 coupling constants consistent with a bidentate 1:1 complex (**24**; (Table VI). It is interesting that diallylacetamide forms this type of complex (compare entries 2 and 3) since diallyl ethers and thioethers form chelate rhodium bisolefin complexes.[17]

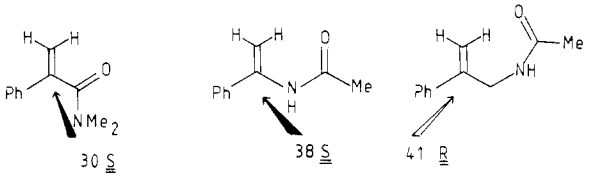


24

Hydrogenation of **21** catalyzed by **4** in the presence or absence of triethylamine gave product which was 40% *R*

(17) Grigg, R.; Kongathip, B.; King, T. J. *J. Chem. Soc., Dalton Trans.* **1978**, 333–8.

Chart II. Optical Efficiency in Reduction of α-Styryl Derivatives by (diop)Rh Complexes



(±2%). The optical purity was determined by hydrolysis of the product (HBr/H_2O) and measurement of the rotation in ethanol. This result completes a series of reactants (Chart II) where the chelate ring size in the intermediate complex varies from four to five to six, and the optical yield is reasonably constant although the stereochemical course changes on going from **20** to **21**. Clearly the steric bulk of the phenyl group is an important factor in stereochemical control.

Summary and Conclusions

Unsaturated acids and amides are capable of forming a range of cationic bis(phosphine)rhodium complexes, although structural changes in the counterligand are critical in deciding which type is formed and the strength of complexation. With seven-membered-ring chelates, exemplified by diop, carboxylate complexes A are formed preferentially in the presence of base and where the substrate is sufficiently bulky (atropic or (*E*)-cinnamic acids) they are the only species formed. Unhindered acids, namely propenoic and 2-methylpropenoic acid, likewise form carboxylate complexes in the presence of base but otherwise produce a complex of 2:1 stoichiometry, B, which is formed relatively slowly. Itaconic acid and its esters form a range of (dipamp)Rh complexes in which either (A, D) or both (C) carboxylate groups are metal bound. Our confidence in the respective structures is gained by the

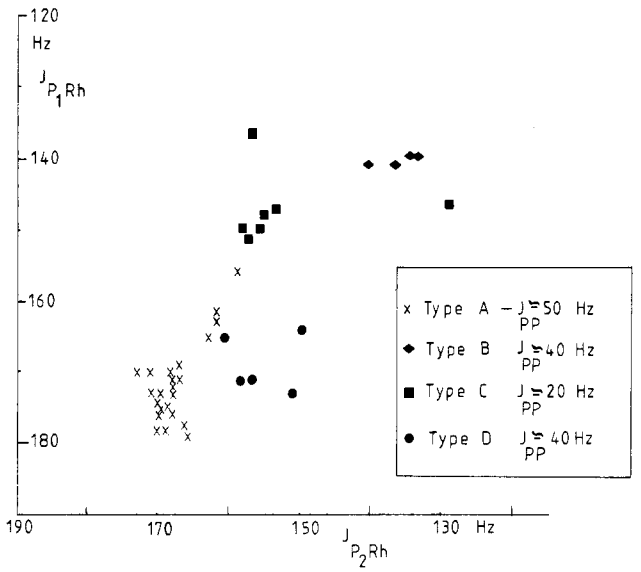


Figure 5. Phosphorus–rhodium and phosphorus–phosphorus coupling constants in the various types of carboxylate complex.

characteristic patterns of ^{31}P NMR coupling which prevail in the different series of complexes. These seem remarkably independent of the phosphine, so much so that they may be used for structural prediction, as demonstrated in Figure 5.

There seems little resemblance between the structure of complexes, diastereomer ratios and ultimate optical yield, although those cases where a five-membered-ring chelate is accessible and the substrate is bidentate are associated with highest reactivity. It is well-known that carboxylic acids hydrogenate more rapidly and with higher optical selectivity in the presence of base, which implies that the carboxylate complexes described here are the true catalytic intermediate. It is not obvious why such carboxylate complexes generally lead to lower optical efficiency (cf. also *E* enamides[18]) than do *Z* enamides, but it may be that a less rigid chelate structure is formed at subsequent stages of the reaction. Effective asymmetric catalysis requires a very subtle combination of competitive reactivities in the separate stages of reaction, and only enamides or very closely related species fit the requirements of present procedures.

Experimental Section

Phosphorus-31 NMR spectra were recorded on a Bruker WH-90 spectrometer operating at 36.43 MHz and chemical shifts are reported in parts per million relative to external 85% H_3PO_4. Organometallic reactions and the preparation of samples was carried out on a vacuum line under an argon atmosphere, with argon purified by sequential passage through concentrated H_2SO_4, KOH pellets, and glass wool. Solutions for NMR were transferred under positive argon pressure into 8-mm NMR tubes which were thoroughly degassed, sealed under argon, and inserted into 10-mm tubes containing D_2O (room temperature) or CD_3OD (low temperature) in the interannular space to maintain spectrometer lock. Preparation of samples followed previous methods.

Preparations. Commercial solvents were distilled from an appropriate drying agent before use according to standard procedures. Diethyl ether was distilled from phosphorus pentaoxide and then sodium benzophenone ketyl; dioxan and tetrahydrofuran were first filtered through activated alumina and then successively distilled from calcium hydride and sodium benzophenone ketyl. Atropic acid was prepared by a standard procedure,[19] as were the three methyl esters of itaconic acid.[20,16] (*E*)- and (*Z*)-2-phenylcinnamic acid were provided by Dr. D. Sinou (Lyon). Amides of 2-phenylpropenoic acid and of 2-(2-methoxyphenyl)-propenoic acid were prepared via the respective acid chlorides ($RCO_2H + (COCl)_2$).

2-(2-Methoxyphenyl)propenoic Acid. A solution of diethyl oxalate (11.9 g, 0.082 mol) and ethyl 2-(2-methoxyphenyl)acetate (9.75 g, 0.051 mol) in ether (25 mL) was added over 15 min to a suspension of sodium methoxide (4.3 g, 0.065 mol) in dry ether (100 mL). The mixture was refluxed for 15 h when it was cooled to 0 °C, washed with HCl solution (2 M, 2 × 50 mL) and saturated aqueous sodium chloride solution (2 × 50 mL), dried (anhydrous $MgSO_4$), and evaporated to dryness. The residue was suspended in water (100 mL), and in the presence of a trace of hydroquinone, formaldehyde solution (0.12 mol, 10 mL) was added dropwise with stirring. Potassium carbonate (8.1 g, 0.058 mol) was added in portions and the mixture stirred at 20 °C for 3 h. The reaction mixture was extracted with Et_2O (3 × 50 mL), the combined extracts were washed with water and dried over anhydrous $MgSO_4$, and the solvent was removed in vacuo to give a colorless liquid which was distilled to give **ethyl 2-(2-methoxyphenyl)-propenoate**: bp 75–77 °C (0.08 mm), 8.4 g, 80%. ^1H NMR ($CDCl_3$) δ 1.23 (3 H, t, CH_3CH_2), 3.76 (3 H, s, OCH_3), 4.22 (2 H, q, CH_3CH_2), 5.71 (1 H, s, H_Z), 6.25 (1 H, s, H_E), 7.20 (4 H, m, Ar); UV (EtOH) λ_{max} 282 nm (ε 17 000); IR ($CHCl_3$) 1715 (vs), 1623 (w), 1600 (m), 1490 (s), 1460 (s), 1435 (m), 1370 (w), 1320 (s), 1284 (s), 1244 (s), 1194 (s), 1120 (m). Anal. Calcd for $C_{12}H_{14}O_3$: C, 70.0; H, 6.80. Found: C, 70.2; H, 6.79.

Potassium hydroxide solution (0.33 M, 70 mL) was added to the product (2.06 g, 0.01 mol) in THF (100 mL) and the solution stirred for 48 h at 20 °C. Solvent was removed in vacuo and HCl (1.0 M, 50 mL) added at 0 °C. The acid was extracted with dichloromethane (3 × 50 mL), the extract was washed with saturated aqueous NaCl (2 × 25 mL) and water (2 × 25 mL) and dried ($MgSO_4$), and then the solvent was removed under reduced pressure to give a colorless solid, 1.60 g (88%). Recrystallization from CH_2Cl_2/30–40% petroleum ether gave colorless needles of 2-(2-methoxyphenyl)propenoic acid, mp 142–144 °C; ^1H NMR ($CDCl_3$) δ 3.78 (3 H, s, OMe), 5.80 (1 H, s, H_E), 6.40 (1 H, s, H_Z), 6.86 (1 H, dd, Ph 3-H), 6.91 (1 H, dt, Ph 5-H), 7.09 (1 H, dd, Ph 6-H), 7.31 (1 H, dt, Ph 6-H), 12.60 (1 H, s, COH); UV (EtOH) λ_{max} 282 mm (ε 26 000); mass spectrum, *m/e* (relative intensity) 178 (90), 133 (64), 103 (80), 91 (100), 77 (53), 63 (32).

***N*-Acetyl-2-phenyl-2-propenamine.** *N*-Bromosuccinimide (50 g, 0.3 mol) and 2-phenyl-1-propene (1215 mL) in carbon tetrachloride (50 mL) were heated to reflux for 1 h in the presence of azobis(isobutyronitrile) (0.2 g). After the mixture was cooled to 0 °C, *n*-pentane (100 mL) was added and succinimide removed by filtration. Excess reactant was removed by distillation in vacuo and addition of further pentane (50 mL) caused precipitation of more succinimide, which was removed by filtration. Distillation of the residue gave a 3:1 mixture of **3-bromo-2-phenyl-1-propene** and **(*E*)-1-bromo-2-phenyl-1-propene**: bp 105–110 °C (14 mmHg).[21] A small sample was purified by chromatography of Florisil (pentane) to give **3-bromo-2-phenyl-1-propene**: UV (EtOH) λ_{max} 245 nm (ε 8700); ^1H NMR ($CDCl_3$) δ 4.32 (2 H, br s, CH), 5.45 (1 H, s, H_E), 5.50 (1 H, d, H_Z), 7.26 (5 H, m, Ar).

To 3-bromo-2-phenyl-1-propene (8.25 g, 0.037 mol, crude distilled product) was added potassium phthalimide (7.40 g, 0.04 mol) and the mixture was stirred for 1 h. Chloroform (40 mL) was then added and the mixture was poured into iced water (100 mL); then the aqueous phase was separated and extracted with chloroform (2 × 15 mL). The combined extracts were washed with aqueous NaOH (0.2 M, 20 mL) and water (2 × 20 mL) and dried ($MgSO_4$). After removal of solvent under reduced pressure the crude product was triturated with ether to give a voluminous white solid: 6.8 g (70%), mp 127–129 °C; ^1H NMR ($CDCl_3$) δ 2.88

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(23) Aaron, C.; Dull, D.; Schmiegel, J. L.; Jaeger, D.; Ohashi, Y.; Mosher, H. S. *J. Org. Chem.* **1967**, *32*, 2797–2803.

(2 H, br s, NCH_2), 5.17 (1 H, s, H_Z), 5.42 (1 H, br s, H_E), 7.2–8.0 (9 H, br m, Ar); mass spectrum, *m/e* 263 (100), 243 (24), 160 (26), 103 (30), 77 (33), 76 (17). Anal. Calcd for $C_{17}H_{13}NO_2$: C, 77.5; H, 4.95; N, 5.34. Found: C, 77.7; H, 4.90; N, 5.51. To the ***N*-phthalimido-2-phenyl-1-propen-3-amine** thus obtained (3.95 g, 0.015 mol) in refluxing methanol was added hydrazine (85% in H_2O, 1.8 mL, 0.03 mol) and the mixture was refluxed for 1 h. The reaction mixture was cooled, 6 M HCl (25 mL) was added, and reflux was reestablished and continued for a further 30 min. After the solution was cooled in an ice bath, it was filtered and concentrated to 40 mL. Further standing at −10 °C precipitated the hydrochloride, which was collected and recrystallized from absolute ethanol, giving 1.8 g (70%), mp 172–173 °C, ^1H NMR (CD_3OD) δ 4.08 (2 H, br s, NCH), 5.47 (1 H, br s, H_E), 5.68 (1 H, s, H_Z), 7.45 (5 H, m, Ar). Anal. Calcd for $C_9H_{12}ClN$: C, 63.5; H, 7.06; N, 8.23; Cl, 20.9. Found: C, 63.3; H, 7.21; N, 8.50; Cl, 21.0. The free amine **2-phenyl-1-propen-3-amine** was liberated by addition of aqueous base: ^1H NMR ($CDCl_3$) δ 2.20 (2 H, br s, NH_2), 3.68 (2 H, s, CH_2), 5.20, 5.31 (2 H, s + s, $=CH_2$), 7.27 (5 H, m, Ar). To this product (1.25 g, 0.0097 mol) in CH_2Cl_2 (25 mL) were aded pyridine (0.79 g, 0.01 mol) and $(CH_3CO)_2O$ (1.02 g, 0.01 mol) at 0 °C and the solution was stirred for 1 h. After the solution was filtered, washed with saturated aqueous $NaHCO_3$ (15 mL) and water (15 mL), and dried ($MgSO_4$), the solvent was removed under reduced pressure to leave a colorless solid residue of ***N*-acetyl-2-phenylprop-2-enamine**: 1.34 g (80%), mp 41–43 °C; ^1H NMR ($CDCl_3$) δ 1.92 (3 H, s, CH_3), 4.25 (2 H, d, CH_2N, $J_{H,NH}$ = 7 Hz), 5.19 (1 H, br s, H_E), 5.41 (1 H, s, H_Z), 6.10 (1 H, br d, NH), 7.32 (5 H, br s, Ar); IR ($CHCl_3$) 3446 (s), 3006 (s), 1666 (vs), 1572 (s), 1372 (w), 1264 (w), 906 (m); mass spectrum, *m/e* 175 (59), 133 (100), 132 (47), 79 (62), 52 (43), 43 (75). Anal. Calcd for $C_{11}H_{13}NO$: C, 75.5; H, 7.55; N, 8.00. Found: C, 75.7; H, 7.78; N, 7.82.

Hydrogenation Procedures. a. Tetramethylammonium 2-Phenylpropenoate. To a solution of the salt (0.22 g, 0.001 mol) in dry methanol (5 mL) was added (bicyclo[2.2.1]heptadiene)-[(*R*)-*trans*-4,5-bis[(diphenylphosphino)methyl)]-2,2-dimethyldioxolan]rhodium(I) tetrafluoroborate (0.0156 g, 20 μmol) in a Schlenk tube. The solution was degassed by three freeze–thaw cycles under argon. Hydrogen was admitted to the evacuated system, which was then equilibrated (20 °C, P_{H_2} = 1 atm). The red solution was stirred until the original yellow color due to the solvent adduct had been regenerated. Solvent was removed in vacuo and the product was taken up in water (10 mL) and treated with cationic ion-exchange resin (1.5 equiv, Dowex 50 W). After extraction with Et_2O (3 × 10 mL) the organic phase was washed with aqueous NH_4Cl (1 M, 10 mL) and water (10 mL) and dried over $MgSO_4$, and the solvent was removed in vacuo. To a solution of approximately half of this product in CH_2Cl_2 was added oxalyl chloride (0.25 g, 0.002 mol) with stirring. After an hour the solution was evaporated in vacuo and redissolved in CH_2Cl_2 (5 mL) and the solvent was again removed. The residue was redissolved in dry CH_2Cl_2 (10 mL) and aqueous dimethylamine (2.5 mL, 70%) added slowly at 0 °C with stirring. After 5 min the organic layer was washed with aqueous NaCl (saturated 2 × 5 mL) and water (2 × 5 mL) and dried over K_2CO_3 and the solvent was removed in vacuo. The proton NMR spectrum of a portion of the residue (CCl_4, 90 MHz) was recorded in the presence of tris[3-(heptafluorobutyryl)-*d*-camphorato]europium(III) (20 mol %), and the optical purity was determined by measuring the area of the α-Me doublets of the diastereomeric amide complexes ($\Delta\delta$ = 0.25 ppm; weighed average of four traces).

b. *N*-Acetyl-2-phenylprop-2-enamine. (Bicyclo[2.2.1]heptadiene) [(*R*)-*trans*-4,5-bis[(diphenylphosphino)methyl]-2,2-dimethyldioxolan]rhodium(I) tetrafluoroborate (0.0156 g, 20 μmol) was added to a solution of *N*-acetyl-2-phenylprop-2-enamine (0.0175 g, 0.001 mol) in dry methanol (5 mL) contained in a Schlenk tube. The solution was degassed by three freeze–thaw cycles under argon. Hydrogen was admitted to the evacuated system, which was then equilibrated (20 °C, P_{H_2} = 1 atm). Complete hydrogenation was observed after 12 h of stirring. Methanol was removed and the crude amide taken up in water and refluxed for 18 h with aqueous HBr (2.5 mL, 40%). Removal of water under reduced pressure gave the crude salt, which was washed with CH_2Cl_2 (3 × 5 mL) and dried in vacuo. Aqueous NaOH (5 mL, 1 M) was added to the product at 0 °C and the resulting amine extracted into ether (5 × 4 mL), washed with water (2 × 5 mL), and dried (anhydrous $MgSO_4$) followed by removal of solvent in vacuo at 10 °C. The residue was distilled (50 °C bath, 0.1 mm) to give **2-phenylpropanamine**: 0.117 g, 85%; $[\alpha]^{20}_D$ +14.1 (*c* 1, EtOH); 41% *S* lit.[22] $[\alpha]^{20}_D$ 34.0 (*c* 1, EtOH). An identical result was obtained in the presence of NEt_3, and with deuterium rather than hydrogen *N*-acetyl-2-phenyl[2,3-$^2H_2$]-propanamine was the only product obtained.

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Registry No. **2**, 102-94-3; **3a**, 492-38-6; **3b**, 81616-74-2; **4**, 71264-75-0; **5**, 57427-85-7; **6**, 91-47-4; **7**, 71264-74-9; **10a**, 81616-75-3; **10a** ethyl ester, 81616-76-4; **10b**, 81616-77-5; **11a**, 81616-78-6; **11b**, 14485-09-7; **13**, 81625-49-2; **17a**, 97-65-4; **17b**, 3377-31-9; **17c**, 7338-27-4; **17d**, 617-52-7; **18**, 75397-15-8; **19**, 68811-68-7; **21**, 25957-50-0; **22**, 692-33-1; **23**, 6296-61-3; ethyl 2-(2-methoxyphenyl)acetate, 6056-23-1; 2-phenyl-1-propene, 98-83-9; 3-bromo-2-phenyl-1-propene, 3360-54-1; (*E*)-1-bromo-2-phenyl-1-propene, 16917-35-4; potassium phthalimide, 1074-82-4; *N*-phthalimido-2-phenyl-1-propen-3-amine, 81616-79-7; 2-phenyl-1-propen-3-amine hydrochloride, 56132-76-4; 2-phenyl-1-propen-3-amine, 28144-67-4; (bicyclo[2.2.1]heptadiene)[(*R*)-*trans*-4,5-bis[(diphenylphosphino)methyl)]-2,2-dimethyldioxolan]rhodium-(I) tetrafluoroborate, 60584-05-6; (*S*)-2-phenylpropanamine, 51-64-9; propenamide, 79-06-1; *N*,*N*-dimethylpropenamide, 2680-03-7; 2,*N*,-*N*-trimethylpropenamide, 6976-91-6; (*S*)-2-phenylpropanoic acid, 7782-24-3; (*R*)-2-phenylpropanoic acid, 7782-26-5; (*S*)-2-(2-methoxyphenyl)propanoic acid, 81616-80-0; (*R*)-2-(2-methoxyphenyl)-propanoic acid, 81616-81-1; (*R*)-*N*,*N*-dimethyl-2-phenylpropanamide, 81616-82-2; (*S*)-*N*,*N*-dimethyl-2-phenylpropanamide, 81616-83-3; (*S*)-2-phenylpropanamide, 13490-74-9; (*R*)-2-phenylpropanamide, 14182-57-1; (*R*)-*N*,*N*-dimethyl-2-(2-methoxyphenyl)propanamide, 81616-84-4; (*S*)-*N*,*N*-dimethyl-2-(2-methoxyphenyl)propanamide, 81616-85-5; 2-methylpropenoic acid, 79-41-4; propenoic acid, 79-10-7.