gel, eluting the isomerically pure product with 20% acetone–hexane: yield 1.833 g (61%); IR (neat) 1670, 1645 (C=O) cm^{-1}. The compound should be handled as **12a**.

Isomerization of Substituted Allylbenzenes (15a–c). Isomerization on **15a–c** was effected in boiling toluene by using **2** as a catalyst and a substrate to catalyst ratio of 200.

Acknowledgment. The authors wish to thank Dr. A. Eisenstadt for isolating compound **10a** in pure form and for the establishment of the existence of the equilibrium **10** ⇌ **10a**. This research was supported by the National Science Foundation (Grant CHE 77-08349).

Registry No. **1**, 692-33-1; **1a**, 5202-79-9; **1b**, 5202-80-2; **2**, 22493-02-3; **3**, 18284-36-1; **4**, 14778-37-1; **4a**, 65693-80-3; **5**, 73286-67-6; **5a**, 5202-82-4; **8**, 6335-03-1; **8a**, 73286-68-7; **9**, 73286-69-8; **10**, 15936-45-5; **10a**, 20213-82-5; **11**, 21399-13-3; **11a**, 23105-58-0; **12**, 73286-70-1; **12a**, 73286-71-2; **13**, 18513-75-2; **13a**, 19615-27-1; **14**, 13463-40-6; **15a**, 300-57-2; **15b**, 68267-69-6; **15c**, 32704-22-6; **16a**, 637-50-3; **16b**, 73286-72-3; allylamine, 107-11-9; acetic anhydride, 108-24-7; 2-methylallylamine, 2878-14-0; phthalic anhydride, 85-44-9; 3,3-dimethylallylamine hydrochloride, 26728-58-5; 3-methyl-2-buten-1-ol, 556-82-1; 1-bromo-3-methyl-2-butene, 870-63-3; potassium phthalimide, 1074-82-4; 3-pyrroline, 109-96-6; *tert*-butoxycarbonyl azide, 1070-19-5; 1,2,3,6-tetrahydropyridine, 694-05-3; $RhCl_3 \cdot 3H_2O$, 13569-65-8; $HRh(CO)(PPh_3)_3$, 17185-29-4.

Asymmetric Hydroformylation and Hydrocarboxylation of Enamides. Synthesis of Alanine and Proline

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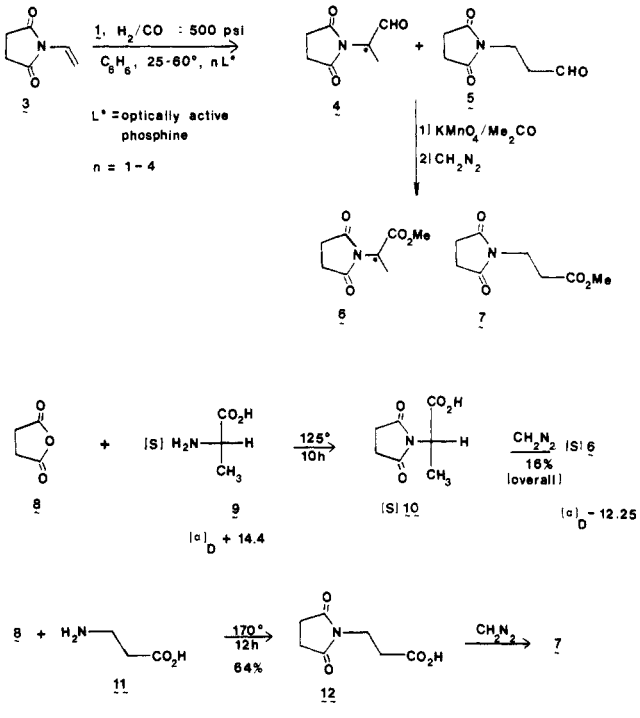
Carbonyltris(triphenylphosphine)hydridorhodium (1) catalyzed the hydroformylation of *N*-vinylimides in the presence of optically active 2,3-*O*-isopropylidene-2,3-dihydroxy-1,4-bis(diphenylphosphino)butane (DIOP) or 2,3-*O*-isopropylidene-2,3-dihydroxy-1,4-bis(5*H*-dibenzophospholyl)butane (DIPHOL) to afford optically active α-amido aldehydes. Linear disubstituted *N*-vinylimides or -amides reacted very sluggishly, while the cyclic *N*-acyl-2-pyrroline (**19**) was very reactive. In the unsubstituted *N*-vinylimides moderate (20–40% ee) asymmetric induction was observed. The optically active α-amido aldehydes were readily converted to the corresponding α-amino acids. Asymmetric hydrocarboxylation of the same substrates in the presence of bis(triphenylphosphine)palladium chloride (**2**) produced α-amido esters in low optical purity.

The rhodium-catalyzed asymmetric hydroformylation has been confined in the past mainly to simple olefins. Generally, low asymmetric induction (up to 27% ee) was observed with DIOP as the chiral phosphine[2] (Figure 1). Higher optical yields (~44% ee) and better selectivity to the branched aldehyde were claimed with DIPHOL as a ligand.[3] The palladium-catalyzed asymmetric hydrocarboxylation of simple olefins afforded high optical yields (up to 60% ee) of branched esters but at relatively high pressures.[4] However, when DIPHOL was used in place of DIOP and the pressure was lowered, the maximum asymmetric induction observed was ~47% ee.[5]

In the rhodium-catalyzed asymmetric hydrogenation of vinylamides, considerably higher optical yields were obtained than with simple olefins as substrates. Recently it was demonstrated[6] that prior coordination of the substrate through the amide group and the double bond takes place, creating a π complex in which the rigidity is responsible for the high stereoselectivities observed.

We had expected the same trend in stereoselectivity in going from simple olefins to vinylamides as substrates for hydroformylation or hydrocarboxylation, provided that a similar type of coordination also takes place in these systems. Limited information on the cobalt-[7a] and rhodium-catalyzed[7b] hydroformylations of vinylamides has been published, but no asymmetric hydroformylation or hydrocarboxylation of these substrates has been reported.

Scheme I



Results and Discussion

1. Hydroformylation. The hydroformylation of vinylamides or -imides generally was carried out under 500 psi of synthesis gas (H_2/CO ratio of 1:1), temperatures in

(1) Present address: Research Department, Plantex-Ikapharm, Netanya, Israel.

(2) (a) Pino, P.; Piancenti, F.; Bianchi, M. *Org. Synth. Met. Carbonyls* **1977**, *2*, 136–61. (b) Pino, P.; Consiglio, C.; Botteghi, C.; Salomon, C. *Adv. Chem. Ser.* **1974**, *No. 132*, 295.

(3) Tanaka, M.; Ikeda, Y.; Ogata, I. *Chem. Lett.* **1975**, 1158.

(4) (a) Consiglio, C. *J. Organomet. Chem.* **1977**, *132*, C26. (b) Consiglio C.; Pino, P. *Chimia* **1976**, *30*, 193.

(5) Hayashi, T.; Tanaka, M.; Ogata, I. *Tetrahedron Lett.* **1978**, 3925.

(6) Brown, J. M.; Chaloner, P. A. *Tetrahedron Lett.* **1978**, 1877.

(7) (a) Sato, S. *Nippon Kagaku Zasshi* **1969**, *90*, 404. (b) Sato, S.; Takesada, M.; Wakamatsu, H. *Nippon Kagaku Zasshi* **1969**, *90*, 579; *Chem. Abstr.* **1969**, *71*, 49178.

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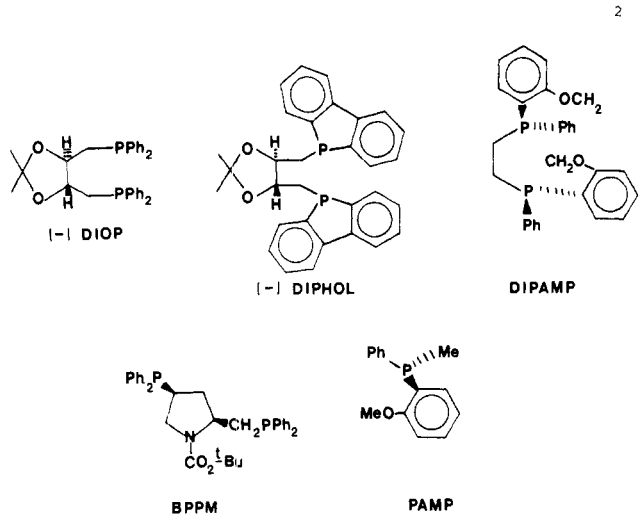


Figure 1. Optically active phosphine ligands used in the present study.

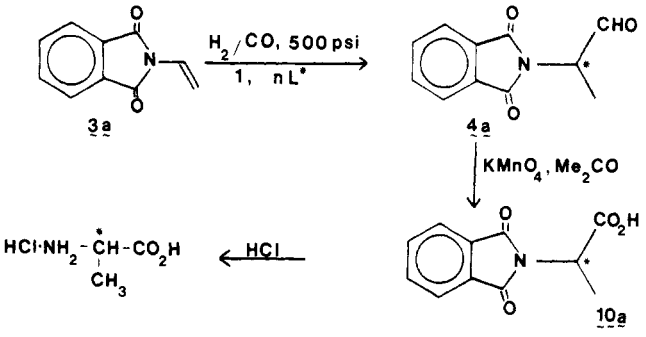
the range of 45–60 °C, and substrate to catalyst ratios of 100–200. Typical solvents used were either benzene or 2-butanone (MEK). In order to induce optical activity in the products, we added optically active phosphines (Figure 1) to the system. As model substrates, commerically available *N*-vinylsuccinimide (**3**) and *N*-vinylphthalimide (**3a**) were chosen.

***N*-Vinylsuccinimide (3).** After hydroformylation of **3** in benzene for several days, the oily reaction mixture obtained was analyzed directly by NMR and then subjected to an oxidation–esterification sequence (Scheme I). The resulting ester mixture was separated by column chromatography, and the optical activity of the isolated branched isomer **6** was determined. Since the intermediates **4** and **6** were liquids, no enantiomeric enrichment could occur during isolation. As a basis for the determination of the optical purity of branched product **6**, (*S*)-**6** was independently synthesized by condensing (*S*)-alanine (**9**) and succinic anhydride (**8**). During the condensation some racemization[8] could have been taking place, but only to a small extent (vide infra). The acid (*S*)-**10** was esterified to yield (*S*)-**6** in 16% overall yield. The structure of the linear product **7** was similarly confirmed by condensing β-alanine (**11**) with **8**.

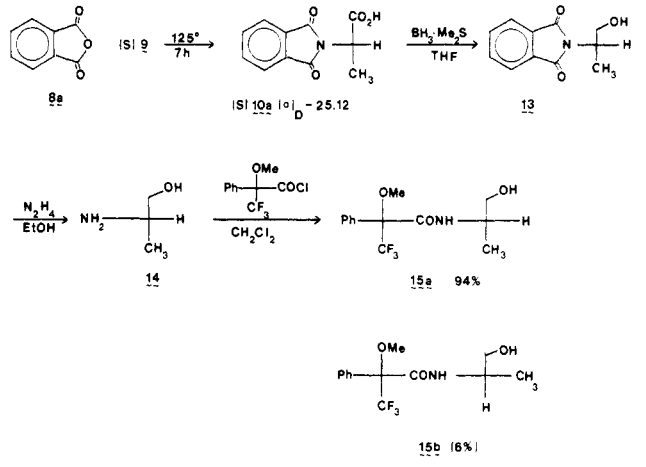
The results are summarized in Table I. Since the absolute rotation of (*S*)-**6** was not determined, the optical purities given should be considered as upper limits. When the reaction was carried out in the presence of **1** alone, high selectivity and good conversion to the branched isomer **4** was observed (runs 1 and 2). Addition of DIOP (run 3) lowered the selectivity and gave low optical yields. An increase in the DIOP/Rh ratio (run 4) had no effect on the optical yield. In both cases addition of DIOP lowered the activity of the catalyst. This effect was very pronounced when DIPAMP was added (run 5). When DIPHOL was used as a chiral ligand, excellent selectivities to the desired branched isomer **6** were observed (runs 6–10). The optical yields varied widely. In one run a 72.5% ee was obtained, but this result could not be duplicated and may be ascribed to the tendency of aldehyde **4** to racemize under the reaction conditions. Interestingly, the same configuration of **4** was observed when either DIOP or DIPHOL was used, in contrast to the observation with simple olefins.[5]

(8) Adriaens, P.; Meesschaert, B.; Hanssen, G.; Dumon, L.; Eyssen, H. *Recl. Trav. Chim. Pays-Bas* **1978**, *97*, 260 and references cited therein.

Scheme II



Scheme III



***N*-Vinylphthalimide (3a).** Since the studies on **3** indicated that DIPHOL had much better selectivity to the desired branched isomer **4** than DIOP, the former was chosen as the preferred chiral ligand in the hydroformylation of **3a**. The reaction was conducted under the same conditions as those employed for **3**, and the resulting solid reaction mixture obtained by removal of the solvent was directly oxidized (Scheme II). Careful acidic workup afforded the pure acid **10a** as a white crystalline material. The linear acid was not present in the product in significant amounts, according to NMR and TLC analyses.

The optical purity of **10a** was determined on the basis of the extrapolated absolute specific rotation of optically pure **10a** (Scheme III). Fusion of phthalic anhydride with (*S*)-alanine yielded the acid **10a**[9] ($[\alpha]_D$ −25.12°) which was reduced to the alcohol **13**. Cleavage of **13** by hydrazine afforded (*S*)-alaninol **14**. The optical purity of the latter was determined through its conversion to the diastereomeric Mosher amides **15a,b**.[10] NMR analysis indicated that the isomeric composition of this mixture was 94:6. A control experiment based on racemic **14** gave an isomeric ratio of **15a** to **15b** of 1:1. Hence, no kinetic resolution took place during this reaction. Since the chiral center remained intact during these transformations, the optical purity of **10a** was 88%, and therefore its extrapolated absolute specific rotation should be 28.5 ± 1°.

The degree of asymmetric induction in the carbonylation reaction was not established directly on the aldehyde **4a** but on its derivative **10a**. The absence of racemization during oxidation of **4a** to **10a** was demonstrated as follows.

(9) Fischer, E. *Ber. Dtsch. Chem. Ges.* **1907**, 40, 489; clearly the author used an impure sample of L-alanine and not the D isomer as incorrectly assigned in this early work. The reported $[\alpha]_D$ in this paper is −17.84° (*c* 9.8%, EtOH).

(10) Dale, J. A.; Dull, D. L.; Mosher, H. S. *J. Org. Chem.* **1969**, *34*, 2543.

Table I. Hydroformylation of *N*-Vinylimides

run	catalyst system	reactant/ catalyst	solvent	time, days	temp, °C	conversion	config	optical purity, % ee
			(a) *N*-Vinylsuccinimide[b]					
1	$HRh(CO)(PPh_3)_3$ (1)	200	C_6H_6	1	43	72		
2	1	100	C_6H_6	3	65	100		
3	(+)-DIOP/1 = 2	100	C_6H_6	6	57	66[a]	*R*	19.8
4	(−)-DIOP/1 = 4.2	100	C_6H_6	2	48	27	*R*	18.4
5	DIPAMP/1 = 4	100	C_6H_6	4	68	3.8		
6	(−)-DIPHOL/1 = 2	100	C_6H_6	3	50	45	*R*	11.6
7	(−)-DIPHOL/1 = 4	100	C_6H_6	6	25	6		
8	(+)-DIPHOL/1 = 4	100	C_6H_6	6	60	45	*S*	8.6
9	(+)-DIPHOL/1 = 4	100	C_6H_6	8	54	33	*S*	27.4
10	(−)-DIPHOL/1 = 4	100	C_6H_6	7	46	32.4	*R*	41
			(b) *N*-Vinylphthalimide[b]					
11	(−)-DIPHOL/1 = 4	100	C_6H_6	6	50–56	69	*R*	34.1
12	(+)-DIPHOL/1 = 4	100	C_6H_6	12	40–50	55	*S*	31.3
13	(+)-DIPHOL/1 = 4	100	C_6H_6	14	45	64	*S*	28.3
14	(+)-DIPHOL/PPh_3/18, 1:1:1	100	C_6H_6	8	50	60.5	*S*	3.5
15	(+)-DIPHOL/18 = 2	100	C_6H_6	5	45	59	*S*	16.4
16	(+)-DIPHOL/18 = 3	100	C_6H_6	5	45	65	*S*	18.4
17	LiCl/(+)-DIPHOL/1, 20:1:1	100	DME	3.75	48–51	84	*S* (−2.04)	7.1
18	(−)-DIOP/1 = 1	100	DME	2	48	51		
19	(−)-DIPHOL/1 = 1	100	C_6H_6/EtOH[c]	3.7	48	79	*R*	12.8
20	(−)-DIPHOL/1 = 2	100	MEK	3	48	52	*R*	27.3
21	(−)-DIPHOL/1 = 3	100	MEK	4	48	35	*R*	38.3
22	(−)-DIPHOL/1 = 3	100	MEK	14	25	25	*R*	2.1
23	$HRh(CO)(PPh_3)$(DIPAMP)	100	MEK	2.75	48	77		
24	BPPM/1 = 2	100	MEK	3.5	46	45	*R*	4.2

[a] Branched/normal ratio of 83/17. In other examples nearly exclusive branched product was obtained. [b] All reactions carried out at 500 psi of CO/H_2 (1:1). [c] In a ratio of C_6H_6/EtOH of 9:1.

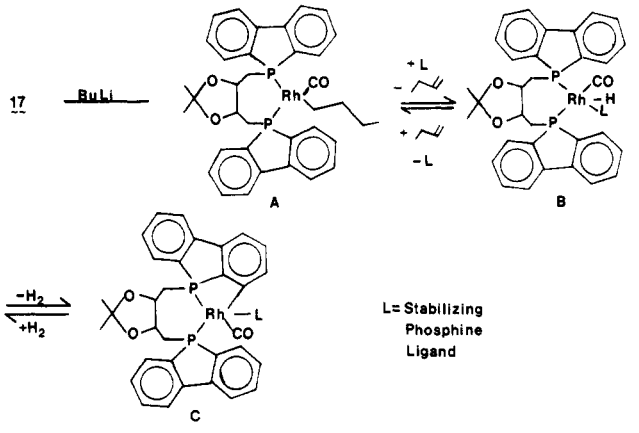
A portion of a sample of optically active **4a** was reduced directly to the alcohol **13**. This transformation does not affect the chiral center in **4a**.[11] Oxidation of part of the above sample of **4a** to **10a** followed by reduction gave the alcohol **13** with a rotation identical with that of the alcohol derived directly from **4a**. Under asymmetric hydroformylation conditions aldehyde **4a** racemized slowly, losing 8% of its original activity after 5 days (see Experimental Section). Similar loss of activity was observed when **4a** was passed through a silica gel column.

Within a range of 45–60 °C (Table I) the extent of asymmetric induction is approximately 30% (runs 11–13). Longer reaction times did not improve the conversion significantly, while a drop of ~17% in the optical activity of the product was observed. This effect is very likely due to the slow racemization of **4a** under the reaction conditions, and hence the initial asymmetric induction probably is higher.

The presence of free triphenylphosphine in the system decreases the optical yield, as demonstrated with a catalyst system generated by the reaction of equivalent amounts of DIPHOL and $[Rh(CO)_2Cl]_2$ (**16**) to afford the yellow carbonyl complex **17** [L = phosphine ligand; "Rh catalyst" (**18**)]. Complex **17** was treated with butyllithium at −78

$$2\text{DIPHOL} + \underset{\mathbf{16}}{[Rh(CO)_2Cl]_2} \xrightarrow[80\ ^\circ C]{C_6H_6} \underset{\mathbf{17}}{2(\text{DIPHOL})Rh(CO)Cl} \xrightarrow[THF]{BuLi,\ L}$$

°C in the presence of a phosphine ligand and then allowed to warm to room temperature. A relatively air-stable red solid which was difficult to purify was obtained. NMR analysis revealed the presence of coordinated DIPHOL, and the IR spectrum exhibited a strong band at 1960 cm^{-1}. No RH–H bond was detected in either the NMR or IR spectrum. The following scheme is consistent with the spectral properties of the product. Alkylation of **17** with butyllithium leads to the alkyl complex A in equilibrium with hydride B.[12] Ortho metalation[13] followed by reductive elimination of dihydrogen yields the carbonyl species C.[14] Under a synthesis-gas atmosphere C can revert[15] to B, which is probably the active catalyst. Regardless of the exact structure of catalyst **18**, it is a very reactive homogeneous hydroformylation catalyst. Run 14 (Table I) shows that **18**, in the presence of equivalent amounts of triphenylphosphine (L), gives a high conversion to the branched aldehyde **4a**, but with very poor stereoselectivity. Replacing triphenylphosphine with DIPHOL (runs 15 and 16 in Table I) results in a sixfold increase in the optical activity of the product, although the net



(11) Poindexter, G. S.; Meyers, A. I. *Tetrahedron Lett.* **1977**, 3527.

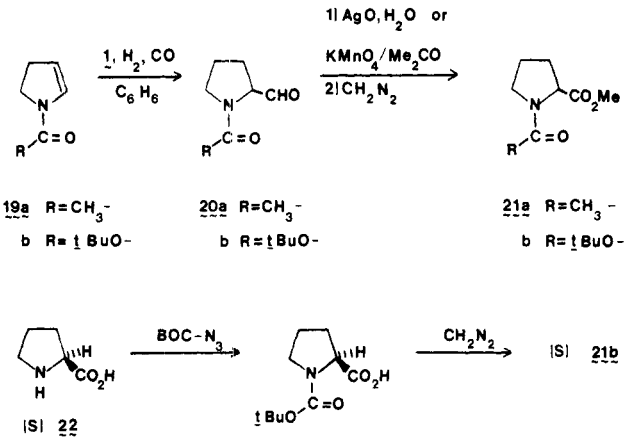
(12) Hegedus, L. S.; Kendal, P. M.; Lo, S. M.; Seats, J. R. *J. Am. Chem. Soc.* **1975**, *97*, 5448.

(13) Keim, W. *J. Organomet. Chem.* **1968**, *14*, 179; *Ibid.*, **1969**, *19*, 161.

(14) Gregorio, G.; Montrasi, G.; Tampieri, M.; Covalieri d'Oro, P.; Pagani, G.; Andreetta, A. *Symp. Rhodium Homogeneous Catal.* [*Proc.*] **1978**, 121; *Chem. Abstr.* **1978**, *90*, 38251.

(15) Chini, P.; Martinego, S.; Garlaschelli, G. *J. Chem. Soc., Chem. Commun.* **1972**, 709.

Scheme IV

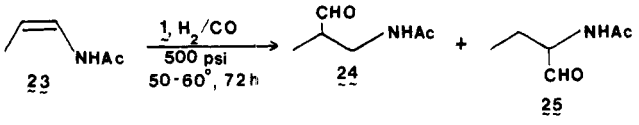


asymmetric induction is lower than those in the other typical runs (e.g., runs 11–13, Table I).

Solvent Effect. The use of more polar solvents such as dimethoxyethane (DME) (runs 17 and 18, Table I) or the addition of alcohol (run 19) caused a sharp drop in the optical yield. On the other hand, 2-butanone (MEK) improved the optical yield up to 38.3% (run 21) with a lower ratio of DIPHOL to rhodium than in run 11. The optical yield in this solvent is very sensitive to temperature (compare runs 22 and 21). With MEK as solvent, the phosphine ligand was changed (runs 23 and 24), but the results were disappointing. In run 23 the catalyst was obtained from the reaction of a hot (80 °C) mixture of DIPAMP and 1. This catalyst gave much higher conversion than when an excess of DIPAMP was deliberately added to 1 (run 5).

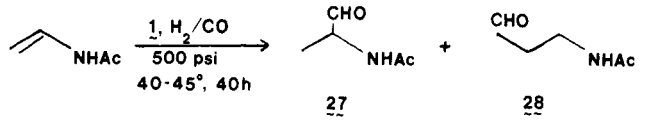
***N*-Acyl-2-pyrrolines.** Hydroformylation of *N*-acyl-2-pyrrolines **19a,b** under the standard conditions afforded exclusively the α-amido aldehydes **20a,b**. The aldehydes were converted by the usual oxidation–esterification sequence to the corresponding esters. The spectral properties (NMR, IR) and TLC analyses of these compounds clearly showed that no formylation took place on the carbon β to nitrogen (Scheme IV). When the hydroformylation of **19b** was carried out in the presence of (–)-DIPHOL and 1 (DIPHOL/Rh ratio of 4), complete conversion to **20b** was observed. After permanganate oxidation, the *R* ester **21b** was isolated, with an optical yield of only 0.35% ee. The pure enantiomer (*S*)-**21b** was prepared by conventional method (Scheme IV).

Other Substrates. Whereas the cyclic enamides **19a,b** proved to be very reactive substrates for 1, linear disubstituted enamides reacted very sluggishly. Thus, **23** was transformed in ca. 10% conversion to a 1:1 mixture of the α- and β-amido aldehydes **24** and **25**. The trisubstituted



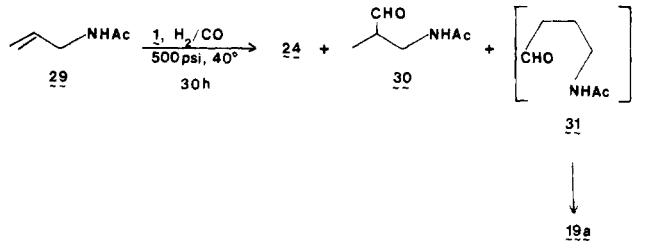
enamides *N*-(2-methylpropenyl)acetamide and *N*-(2-methylpropenyl)phthalimide were completely unreactive. These results are in agreement with the behavior of simple substituted olefins.[16]

The low regioselectivity observed in the hydroformylation of **23** is consistant with the results obtained for the parent compound, *N*-vinylacetamide (**26**). Hydroformylation of **26** afforded a mixture of **27** and **28** in



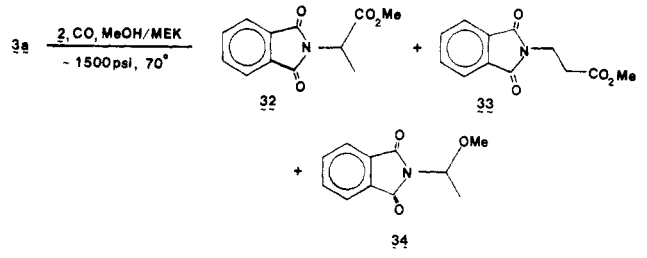
a ratio of 55:46, respectively. This observation is in contrast to the high selectivity obtained with the imides **3** and **3a**. Clearly, the polarization of the double bond in **26** is greater than in **3** or **3a** where electron density on nitrogen is reduced by two carbonyl groups. Thus, in **26** the contribution of cannonical form b is expected to be higher than in **3a,b**, and, consequently, a lower regioselectivity of Rh–H addition was observed.

Hydroformylation of *N*-allylacetamide (**29**) in the presence of 1 yielded a 54:46 ratio of **30** and **19a**, respectively. The linear aldehyde **31** cyclized readily under the



mild reaction conditions to give **19a**. This sequence may prove to be a more convenient route to proline from readily available starting materials.

2. Hydrocarboxylation. As a model substrate for hydrocarboxylation, *N*-vinylphthalimide (**3a**) was selected. The reaction was carried out at 70 °C under ~100 atm in the presence of 10^{-2} mol of $(Ph_3P)_2PdCl_2$ (**2**)/mol of **3a**.



The solvent used was MEK, and the hydrogen donor was methanol. As in the case of the rhodium-catalyzed hydroformylation of **3a**, good selectivities to the branched ester **32** were observed, but the reaction rates were considerably higher (Table II, runs 1 and 2). In addition to the expected product **32**, a side product **34** was isolated in low yield. This product was clearly the result of acid-catalyzed addition of methanol across the reactive double bond of **3a**.[17] When a chelating phosphine was added to 1, the selectivity and activity of the catalyst was considerably lowered (Table II, runs 3 and 4), and negligible asymmetric induction was obtained. Surprisingly, the DIPHOL-based catalyst was completely unreactive (Table II, run 5). Other ligands such as PAMP or DIPAMP behaved very disappointingly, with no reaction being observed (runs 6 and 7, Table II).

Methanol addition becomes the major reaction pathway when a more reactive enamide is subjected to the hydrocarboxylation conditions. Thus, **19b** afforded exclusively

(16) Brown, C. K.; Wilkinson, G. *J. Chem. Soc. A* **1970**, 2753.

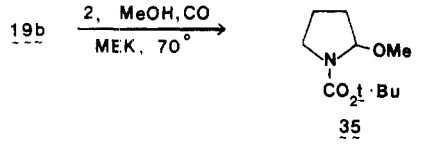
(17) Kato, Kyoshi *Kogyo Kagaku Zasshi* **1957**, *60*, 421; *Chem. Abstr.* **1957**, *53*, 9133*g*.

Table II. Hydrocarboxylation of *N*-Vinylphthalimide

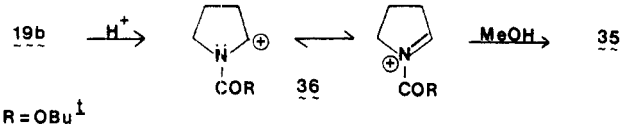
run	catalyst system	reactant/ substrate	CO pressure, psi	temp, °C	time, h	% branched	% normal	mmol MeOH added	% conversion[d]
1	$PdCl_2(PPh_3)_2$ (2)	100	1430	70	21	84		7.3	47.7
2	2	100	1375	70	27	82		12.5	70.8
3	$PdCl_2 \cdot Ph_3$ (−)-DIOP	100	1470	70	43	33[c]	50	8	48
4	$PdCl_2$-(−)-DIOP	100	1500	72	43	23	41	11.5	32
5	$PdCl_2$-(−)-DIPHOL[a,b]	48	1300	71	46		no reaction		
6	$PdCl_2$ (PAMP)$_2$[a]	100	1520	72	36		no reaction		
7	$PdCl_2$ (DIPAMP)	53	1500	72	46		no reaction		

[a] Addition of 10 equiv of LiCl did not change the results. [b] Use of the catalyst $PdCl_2(PhCN)_2$-(−)-DIPHOL did not change the results. [c] The ee was ~1%. [d] Isolated yields.

N-(*tert*-butoxycarbonyl)-2-methoxypyrrolidine (**35**),[18] with no hydrocarboxylation product being observed.



Attempts to suppress formation of **35** by the addition of potassium carbonate were not effective. It seems that protonation of **19b** under the reaction conditions to form the stabilized cation **36** competes effectively with addition



of Pd–H across the double bond. The electron density on nitrogen in **3a** is lower than in **19b**, and therefore the competing reaction pathways are reversed.

Experimental Section

General Procedure for Hydroformylation of Enamides. The enamide (10 mmol) was dissolved in degassed benzene or MEK (10 mL) containing 1 (0.05 mmol), and the resulting solution was placed in a glass sleeve in a high-pressure Parr reactor. The reactor was flushed with nitrogen and then charged with synthesis gas (CO/H_2 ratio of 1:1) to 50 psi. The pressure was slowly released, and after two more charging–discharging cycles the pressure was eventually raised to 500 psi. The reactor was heated in a regulated oil bath to the desired temperature (see Table I) for several days. The reactor was then placed for 0.5 h in an ice bath, and at the end of this period the pressure was slowly released. Typical procedures for workup of the crude reaction product are given in the following examples.

Hydroformylation of *N*-Vinylsuccinimide (3). This compound (1.3 g, 10 mmol) was hydroformylated at 45 °C in benzene (10 mL) in the presence of 1 (46 mg, 0.05 mmol) for 27 h. NMR analysis indicated the presence of 3 and 4 in 72% conversion. NMR of **3**: ($CDCl_3$) δ 5.14 (=CH, d, J = 8 Hz), 6.1 (=CH, d, J = 16 Hz), 6.74 (>NCH=, dd, J = 8, 16 Hz), 2.9 ($COCH_2CH_2CO$, s). NMR of **4**: ($CDCl_3$) δ 1.6 (CH_3, d, J = 8 Hz), 4.45 (>NCH, q, J = 8 Hz), 2.82 ($COCH_2CH_2CO$, s), 9.38 (CHO, s).

The reaction mixture was dissolved in acetone (100 mL) containing magnesium sulfate (1.26 g, 10.5 mmol), and with stirring, potassium permanganate (1.106 g, 7 mmol) was added in small portions over 2 h. The mixture was stirred for an additional 30 min at 25 °C, and then the solvent was removed under reduced pressure. The brown residue was extracted with hot water (3 × 20 mL). The extract was filtered, and the filtrate was decolorized with sodium sulfite and then washed with chloroform (3 × 30 mL). The aqueous phase was concentrated in vacuo to ~30 mL, acidified to pH ~2 (concentrated HCl), and then extracted with chloroform (3 × 50 mL). The organic phase was dried ($MgSO_4$) and concentrated to dryness in vacuo, and the residue was distilled in a Kugelrohr apparatus at 160 °C (20 μm) to afford 1.048 g (87.5% yield from **4**) of (*R,S*)-**10**: NMR ($CDCl_3$) δ 1.52 (CH_3, d, J = 8 Hz), 4.8 (>NCH, q, J = 8 Hz), 2.72 ($COCH_2CH_2CO$, s), 10.4 (COOH, s).

When asymmetric hydroformylation was carried out, the crude acid was not distilled but was dissolved in dry methanol and esterified with etheral diazomethane. The crude methyl *N*-succinylalaninate, **6**, was purified by chromatography (silica gel, 30% acetone–petroleum ether) and obtained as colorless viscous oil, homogeneous by TLC: NMR ($CDCl_3$) δ 1.52 (CH_3, d, J = 8 Hz), 3.7 ($COOCH_3$, s), 4.74 (>NCH, q, J = 8 Hz), 2.7 ($COCH_2CH_2CO$, s). When (−)-DIOP was used as a chiral auxiliary ligand (Table I, run 3), **7** was eluted also: NMR ($CDCl_3$) δ 2.6 (CH_2COOCH_3, t, J = 7 Hz), 3.65 ($COOCH_3$, s), 3.78 (>NCH_2, t, J = 7 Hz), 2.7 ($COCH_2CH_2CO$, s). Optical activity of **6** was measured in a 10-cm cell in chloroform.

***N*-Vinylphthalimide (3a).** This substrate (1.73 g, 10 mmol) was dissolved in benzene (13 mL) containing **1** (92 mg, 0.1 mmol) and (−)-DIPHOL (197.2 mg, 0.4 mmol) and then hydroformylated under 500 psi of pressure at 50–56 °C for 6 days. An orange solid residue was obtained. To 114.9 mg of this material was added 27 μL of phenylacetylene. The resulting mixture was dissolved in 0.4 mL of chloroform and analyzed by NMR to show 69% of **4a** and 31% of **3a**. The material balance indicated that no starting material was lost by polymerization. NMR of **3a** ($CDCl_3$): δ 4.95 (=CH, d, J = 10 Hz), 5.95 (=CH, d, J = 16 Hz), 6.8 (>NCH=, dd, J = 10, 16 Hz), 7.75 (aromatic, 4 H, m). NMR of **4a**: δ 1.59 (CH_3, d, J = 7 Hz), 4.8 (>NCH, q, J = 7 Hz), 7.7 (aromatic, 4 H, m), 9.54 (CHO, s). The crude reaction mixture was oxidized by the usual method to afford the acid as a white crystalline solid. After the solid was dried in vacuo, there was obtained 889.4 mg of **10a** (59% from **4a**): $[\alpha]^{25}_D$ +9.73° (*c* 8.19, EtOH); NMR ($CHCl_3$) δ 1.65 (CH_3, d, J = 8 Hz), 4.96 (>NCH, q, J = 8 Hz), 7.7 (aromatic, 4 H, m), 10.6 (COOH, s).

Independent Syntheses of Intermediates. (*S*)-(−)-Methyl *N*-Succinylalaninate ((*S*)-6). Succinic anhydride (**8**; 2.0 g, 20 mmol) and (*S*)-alanine [1.625 g, 18.23 mmol; $[\alpha]^{25}_D$ +14.42 (*c* 10, 6 N HCl)] were crushed in a mortar and then heated in an oil bath to 125 °C for 10 h. The oily product was extracted with hot chloroform and concentrated, and then ether was added. The oil was separated, and the mother liquor was decanted, filtered, and finally concentrated to a thick oil. The oil was dissolved in absolute methanol followed by addition of ethereal diazomethane. The resulting mixture was purified on a silica gel column (eluent, 30% acetone–hexane) to afford 487 mg (16%) of pure (*S*)-**6**, $[\alpha]^{25}_D$ −12.25 ± 0.03° (*c* 3.1, $CHCl_3$). Anal. Calcd for $C_8H_{11}NO_4$: C, 51.87; H, 5.95; N, 7.56. Found: C, 51.31; H, 5.91; N, 7.63.

Methyl *N*-Succinyl-β-alaninate (7). Fussion of **8** (2.0 g, 20 mmol) with **11** (1.63 g, 18.3 mmol) was carried out at 170 °C for 12 h. The resulting solid was recrystallized from chloroform to yield white needles: 1.758 g (64%), mp 120–121 °C. The acid was esterified with diazomethane, and the product was distilled in a Kugelrohr apparatus at 150–155 °C, (0.01 mmHg). Colorless viscous oil was obtained: IR (neat) 1780, 1745, 1720 (C=O) cm^{-1}. Anal. Calcd for $C_8H_{11}NO_4$: C, 51.89; H, 5.95; N, 7.56. Found: C, 51.81; H, 5.97; N, 7.59.

(*S*)-(−)-*N*-Phthalylalanine ((*S*)-10a). Phthalic anhydride (**8a**; 9.0 g, 60.7 mmol) and (*S*)-alanine [5.0 g, 56.1 mmol; $[\alpha]^{25}_D$ +14.42° (*c* 10, 6 N HCl)] were fused at 120–125 °C for 7 h. The product was heated in 20 mL of water, cooled to 25 °C, and filtered. The crude product (14.1 g) was twice recrystallized from

(18) Analogous *N*-acyl-2-methoxypyrrolines have been reported: Warning, K.; Mitzlaff, M.; Jensen, H. *Justus Liebigs Ann. Chem.* **1978**, 1707 and references la,b cited therein.

hot water (200 mL). The colorless dry needles had a melting point of 150–151 °C (lit.[9] 150–151 °C) and $[\alpha]^{25}_D$ −25.12° (c 8.12, EtOH). When the experiment was repeated with (R)-alanine [$[\alpha]^{25}_D$ −14.19 (c 10, 6 N HCl)], (R)-**10a** was obtained; $[\alpha]^{25}_D$ +24.5° (c 8.27, EtOH).

Hydrolysis of (*R*)-(+)-*N*-Phthalylalanine ((*R*)-10a). (R)-**10a** (220 mg, 1.0 mmol; $[\alpha]^{25}_D$ +9.73) was heated with stirring in 2.0 mL of 20% aqueous HCl for 2 h. After being cooled to 0 °C for several hours, the mixture was filtered. The mother liquor was concentrated in vacuo, and the residue was extracted with 2 mL of ice-cold water. Two drops of concentrated HCl were added, and the solution was kept for several hours at 0 °C. After filtration of the mixture, this process was repeated twice more, and eventually concentration of the solution gave an oil which solidified on standing. The crude alanine hydrochloride (99 mg) was dissolved in 3 mL of ethanol containing 1 drop of ethanolic HCl. Upon addition of ether, alanine hydrochloride separated as colorless needles. After the product was dried over calcium chloride in vacuo, the yield was 80.5 mg: $[\alpha]^{25}_D$ −3.89° (c 8.05, H_2O); 37.2% ee (based on $[\alpha]^{25}_D$ +10.3 for the pure hydrochloride).

(*S*)-(+)-*N*-Phthalylalaninol (13). A sample of (S)-**10a** (5.0 g, 22.83 mmol; $[\alpha]^{25}_D$ −25.12°) in 80 mL of dry tetrahydrofuran was cooled to 0 °C. Boron hydride–dimethyl sulfide complex (26 mmol, 2.6 mL) was added with stirring, and the mixture was stirred under nitrogen at 25 °C for 48 h. Water (60 mL) was carefully added. The aqueous layer was extracted with chloroform, dried ($MgSO_4$), and concentrated. The white crystalline residue was purified on a silica gel column (10% acetone–petroleum ether) to afford (S)-**13** in 60% yield: mp 86–87 °C (from acetone–hexane); $[\alpha]^{25}_D$ +13.7° (c 4.2, $CHCl_3$); IR (KBr) 3480 (OH), 1760, 1675 (C=O) cm^{-1}; NMR ($CHCl_3$) δ 1.47 (CH_3, d, J = 6 Hz), 3.2 (OH, br s), 3.9 (CH_2O, m), 4.4 (>NCH, m), 7.72 (aromatic, 4 H, m). Anal. Calcd for $C_{11}H_{11}NO_3$: C, 64.39; H, 5.37; N, 6.83. Found: C, 64.46; H, 5.45; N, 6.80.

(*S*)-Alaninol (14). (S)-**13** (1.0 g, 4.88 mmol) was dissolved in 10 mL of ethanol. Hydrazine hydrate (85%, 0.28 g, 4.88 mmol) was added, and the mixture was stirred at 60 °C for 1.25 h. A copious white gelatinous mass was formed. Concentrated HCl (1 mL) was added, and heating at 60 °C was continued for 1 h. The resulting mixture was filtered, the filtrate was concentrated to dryness, and the residue was dissolved in 2 mL of water. One drop of concentrated HCl was added, and the mixture was kept overnight at ~0 °C. The resulting precipitate was filtered, the solvent was removed in vacuo, and this process was repeated twice. The resulting syrup contained traces of phthalhydrazide (NMR analysis in D_2O) together with the desired product. The crude alaninol hydrochloride was dissolved in 1 mL water, one sodium hydroxide pellet was added to give a strongly basic solution, and the solvent was removed in vacuo. The residue was extracted with methylene chloride (the product is only partially soluble in this solvent). After removal of the solvent in vacuo, there was obtained a viscous oil (94 mg) which was purified by distillation in a Kugelrohr apparatus at 135 °C (7 mm Hg) to yield 49 mg of the pure product as a colorless oil.

(*R,S*)-Alaninol. (R,S)-Alanine (8.9 g, 0.1 mol) was suspended in tetrahydrofuran (60 mL), and boron trifluoride etherate (13.8 mL, 0.12 mol) was added. The mixture was heated to a gentle reflux, and after 30 min an almost homogeneous solution was obtained. External heating was removed, and boron hydride–dimethyl sulfide complex (12 mL, 0.12 mol) was very slowly added to maintain a gentle reflux (**Caution**: a very exothermic reaction is observed). At the end of the addition the reflux was maintained for 2.5 h. The cautious addition of 10 mL of tetrahydrofuran–water (1:1) was followed by 58 mL of 6 N sodium hydroxide. The aqueous phase was concentrated in vacuo, and the resulting syrup was distilled at 80 °C (15 mmHg) in a Kugelrohr apparatus. The colorless oil contained alaninol in >90% purity (NMR analysis).

Preparation of Mosher's Amides 15a,b. (S)-Alaninol (**14**; 49 mg, 0.65 mmol) was mixed with methylene chloride (4 mL), and Mosher's acid chloride[10] (82 mg, 0.33 mmol) was added in 4 mL of methylene chloride. The mixture was stirred at 25 °C overnight. Alaninol hydrochloride precipitated. The mother liquor was decanted, and the solvent was removed under reduced pressure. The resulting solid was purified by passage through a short silica gel column (30% acetone–hexane). The amide was obtained in quantitative yield: NMR (acetone-d_6, 90-MHz JEOL FT NMR spectrometer) for **15a** (94%): δ 1.099 (CH_3, d, J = 6.7 Hz), 3.06 (CH_2OH, br s), 3.506 (OCH_3, q, J = 1.7 Hz), 4.08 (>NCH, m), 7.45 (aromatic, 4 H, m); for **15b** (6%): δ 1.205 (CH_3, d, J = 6.7 Hz), 3.06 (CH_2OH, br s), 3.435 (OCH_3, q, J = 1.58 Hz), 4.08 (HCH, m), 7.45 (aromatic, 4 H, m).

When the experiment was repeated by starting from (R,S)-alaninol, an amide was obtained. The NMR in the methyl region (acetone-d_6) exhibited a 1:2:1 triplet, indicative of 1:1 mixture of **15a** and **15b**.

Absence of Racemization during Oxidation of 4a. Aldehyde **4a** (3.4 mmol, 690 mg) containing unreacted **3a** was reduced in tetrahydrofuran (20 mL) with boron hydride–dimethyl sulfide complex (0.35 mL, 3.5 mmol) under the same conditions as those described for **13**. Chromatography on a silica gel column (30% acetone–hexane) yielded a small amount of *N*-ethylphthalimide as colorless crystals: NMR ($CHCl_3$) δ 1.35 (CH_3 t, J = 6 Hz), 3.7 (>NCH_2, q, J = 6 Hz), 7.65 (aromatic, 4 H, m). Continued elution with the same solvent system yielded alcohol **13** (420.5 mg). Recrystallization from methylene chloride–hexane yielded colorless needles, $[\alpha]^{25}_D$ +5.7° (c 4.21, $CHCl_3$). Another identical sample of **4a** was oxidized by the usual procedure to the acid, $[\alpha]^{25}_D$ −8.91° (c 8.14, EtOH). The acid (467.8 mg, 2.14 mmol) was reduced in tetrahydrofuran with boron hydride–dimethyl sulfide complex (0.3 mL, 3 mmol) by the usual procedure to afford alcohol **13**: 262.4 mg (60% yield); $[\alpha]^{25}_D$ +5.7° (c 4.41, $CHCl_3$).

Stability of 4a. A sample of **4a** was divided into two batches. The first batch was oxidized to the acid, $[\alpha]^{25}_D$ −8.07° (c 4.805, EtOH) (28.3% ee). The second batch of **4a** was purified by chromatography on a silica gel column (10% acetone–hexane as eluent). After unreacted **3a** was eluted, **4a** was obtained as white crystals. A small portion of this material was recrystallized from acetone–hexane to afford needles: mp 112–113 °C; $[\alpha]^{25}_D$ −8.9° (c 2.76, C_6H_6). The major fraction of **4a** was oxidized directly to the acid **10a**, $[\alpha]^{25}_D$ −5.7 (20% ee), which corresponds to an 8.3% loss of optical activity during chromatography. A third portion of purified **4a** (250 mg, 1.23 mmol) was dissolved in benzene (2.5 mL) containing **1** (11.3 mg, 0.0124 mmol) and (+)-DIPHOL (24.4 mg). The mixture was kept at 45 °C for 5 days under 500 psi of CO/H_2 (1:1). Oxidation of that mixture afforded 177 mg of the acid **10a**, $[\alpha]^{25}_D$ −5.25° (c 8.85, EtOH) (18.4% ee). Hence, the aldehyde **4a** suffered an 8% loss of its original activity under hydroformylation conditions.

Hydroformylation of *N*-Vinylacetamide (26). A mixture of *N*-vinylacetamide (400 mg, 4.88 mmol) and **1** (30 mg, 0.033 mmol) in benzene (10 mL) was hydroformylated under 500 psi of 1:1 CO/H_2 at 40–45 °C for 40 h. The resulting yellow oil (446 mg) was distilled in a Kugelrohr oven at 128 °C (30 mmHg) to yield 399.4 mg of a clear, colorless oil, consisting of a mixture of branched (55%) and linear (45%) aldehydes: NMR of **27** ($CDCl_3$) δ 1.45 (CH_3, d, J = 7 Hz), 2.15 (CH_3CO, s), 4.45 (>NCH, q, J = 7 Hz), 6.3 (NH, br s), 9.5 (CHO, s); NMR of **28** ($CDCl_3$) δ 2.05 (CH_3CO, s), 2.8 (CH_2, t, J = 6 Hz), 3.6 (>NCH_2, t, J = 6 Hz), 6.3 (NH, br s), 9.70 (CHO, s).

Hydroformylation of *N*-Acetyl-2-pyrroline (19a). A mixture of *N*-acetyl-2-pyrroline (**19a**; 818.5 mg, 7.37 mmol) and **1** (68 mg, 0.074 mmol) in benzene (10 mL) was hydroformylated under 500 psi of CO/H_2 at 60 °C for 3 days. NMR analysis indicated complete conversion: NMR of **20a** ($CDCl_3$) δ 2.1 (CH_2CH_2, m), 2.14 (CH_3, s), 3.55 (>NCH_2, m), 4.4 (NCHCHO, m), 9.4 (CHO, d, J ≃ 2 Hz). The crude product was dissolved in tetrahydrofuran–water (9:1, 50 mL), and silver oxide[19] (3.35 g, 29.5 mmol) was added. The mixture was stirred at 25 °C for 13 h and filtered, the solids were washed with tetrahydrofuran, and the combined washings and filtrates were concentrated under reduced pressure: NMR of *N*-acetylproline ($CDCl_3$) δ 2.15 (CH_2CH_2, m), 2.2 (CH_3, s), 3.55 (>NCH_2, m), 4.45 (>NCHCOO, m), 6.4 (COOH, s). The residue was extracted with methanol, filtered, and esterified with etheral diazomethane. Removal of the solvent afforded 360 mg of viscous oil (**21a**), homogeneous by TLC: NMR ($CDCl_3$) δ 2.05 (CH_2CH_2, m), 2.12 (CH_3, s), 3.60 ($CH_2N<$, m), 3.7 ($COOCH_3$, s), 4.35 (>NCHCOO, m).

Hydroformylation of *N*-(*tert*-Butoxycarbonyl)-2-pyrroline (19b). Hydroformylation of **19b** (0.5 g, 3.0 mmol) in

(19) Hammer, R. N.; Kleinberg, J. *Inorg. Synth.* **1953**, *4*, 12.

benzene (15 mL) in the presence of 1 (55.2 mg, 0.06 mmol) and (–)-DIPHOL (118.6 mg, 0.24 mmol) was carried out at 52 °C for 8 days under 500 psi of CO/H_2. NMR revealed complete conversion to **20b**: ($CDCl_3$) δ 1.5 (($CH_3)_3C$, s), 2.0 (CH_2CH_2, m), 3.5 (>NCH_2, m), 4.1 (>NCHCHO, m), 9.52 (CHO, d, $J \simeq 2$ Hz). Oxidation by $KMnO_4/Me_2CO/MgSO_4$ yielded the corresponding acid (720 mg, 6 mmol): NMR ($CDCl_3$) δ 1.4 (($CH_3)_3C$, s), 2.05 (CH_2CH_2, m), 3.4 (>NCH_2, m), 4.2 (>NCHCOOH, m), 8.7 (COOH, br s). Esterification with etheral diazomethane afforded the ester **21b** as a colorless, viscous oil: NMR ($CDCl_3$) δ 1.3 (($CH_3)_3C$, s), 1.9 (CH_2CH_2, m), 3.65 (CH_3OCO, s), 4.2 (>$NCHCOOCH_3$, m); yield 379.7 mg (56% from **19b**); $[\alpha]^{25}_D$ +0.19° (0.35% ee).

(*S*)-(–)-*N*-(*tert*-Butoxycarbonyl)proline ((*S*)-21b). (*S*)-Proline (1.15 g, 10 mmol) and triethylamine (2.1 mL, 15 mmol) were dissolved in dioxane (10 mL). Water (6 mL) and BOC-ON[20] (*t*-BuOCOONC(CN)Ph, 2.71 g, 11 mmol) were added, and after the mixture was stirred at 25 °C for 2.5 h, the homogeneous clear yellow solution was diluted with water (15 mL) and ethyl acetate (20 mL). The aqueous layer was separated, extracted with ethyl acetate (2 × 10 mL), and then acidified with 1 N HCl. The resulting emulsion was extracted with ethyl acetate (3 × 30 mL), dried ($MgSO_4$), and concentrated to afford a colorless oil which solidified on standing. (*tert*-Butoxycarbonyl)proline was obtained as a low-melting solid. Esterification with etheral diazomethane followed by column chromatography on silica gel (10% acetone–hexane) gave (*S*)-**21b** as a colorless oil which was purified by distillation in a Kugelrohr oven (130 °C, 30 μm), $[\alpha]^{25}_D$ –54.54° (*c* 10.04, $CHCl_3$).

Hydroformylation of *N*-Allylacetamide (29). A mixture of **29** (5.0 mL) and **1** (99.6 mg) in benzene (10 mL) was hydroformylated under 500 psi of CO/H_2 (1:1) at 40 °C for 30 h. NMR and TLC analyses showed only a mixture of aldehydes. The crude mixture was fractionated at 0.1 mmHg. Two fractions were collected: I, bp 74–78 °C, 1.973 g (mainly starting material); II, bp 88–94 °C, 2.177 g. This fraction contained no starting material and consisted of **30** and **19a** in 54:46 ratio, respectively. Oxidation of this mixture with potassium permanganate–acetone yielded an acid which was esterified with diazomethane. The product, methyl 2-methyl-3-acetamidopropionate, was purified on a GLC column [10 ft × $^3/_8$ in. 20% Carbowax 20-M, Chromosorb W (60/80)] at 225 °C and was obtained as a colorless oil: NMR ($CDCl_3$) δ 1.15 (CH_3, d, J = 8 Hz), 1.92 ($COCH_3$, s), 2.7 (CH_2N<, m), 3.4 (CHCOOMe, m), 3.7 ($COOCH_3$, s), 5.9 (NH, br s).

Preparation of Catalyst 18. (+)-DIPHOL [$[\alpha]^{25}_D$ +66° (*c* 1.93, C_6H_6); 300 mg, 0.6 mmol] and $[Rh(CO)_2Cl]_2$ (108.8 mg, 0.28 mmol) were heated to reflux temperature in benzene under nitrogen for 5.5 h. The yellow precipitate was collected and dried to yield 342.2 mg (93%) of product, IR (KBr) 1975 (C=O) cm^{-1}. This complex (**17**; 100 mg, 0.15 mmol) was suspended in THF (10 mL) under nitrogen, and a phosphine ligand was added. The suspension was stirred and cooled to –78 °C whereupon a red coloration was observed. *n*-Butyllithium in hexane (120 μL, 0.3 mmol, 2.56 M) was added, and the reaction mixture was allowed to warm to 25 °C. After 3 h a red homogeneous solution was obtained. The solvent was removed in vacuo, and a dark red solid was obtained; IR (KBr) 1960 (C=O) cm^{-1}. The solid was dissolved in benzene (4 mL) under nitrogen. The resulting red solution was washed with water (4 × 5 mL) until the washings were neutral and then dried ($MgSO_4$). This solution was used directly as a catalyst for hydroformylation.

General Procedure for Hydroesterification. The substrate was dissolved in 2-butanone, the solvent was flushed with nitrogen, and the catalyst was then added. The reaction mixture was placed in a high-pressure reactor. The unit was charged with carbon monoxide up to 1500 psi and maintained at 70 °C. The reaction mixture was stirred at this temperature for 1 or 2 days and then cooled to 0 °C. The pressure was slowly released, and the mixture was filtered. The filtrate was concentrated to dryness. When **3a** was the substrate, a semisolid was obtained which was directly analyzed by NMR. The isolation of the products was effected by chromatography on a silica gel column with acetone–petroleum ether as eluent (Table II).

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Registry No. **1**, 17185-29-4; **2**, 13965-03-2; **3**, 2372-96-5; **3a**, 3485-84-5; **4**, 53531-15-0; **4a**, 73365-03-4; (*S*)-**6**, 73365-04-5; **7**, 39267-22-6; **8**, 108-30-5; **8a**, 85-44-9; (*R*)-**9**, 338-69-2; (*R*)-**9**·HCl, 16428-74-3; (*R,S*)-**9**, 302-72-7; (*S*)-**9**, 56-41-7; (*R,S*)-**10**, 73323-90-7; (*S*)-**10**, 73365-05-6; (*R*)-**10a**, 29588-83-8; (*S*)-**10a**, 4192-28-3; **11**, 107-95-9; **12**, 5724-76-5; (*R*)-**13**, 73323-91-8; (*S*)-**13**, 70058-19-4; (*R,S*)-**14**, 6168-72-5; (*S*)-**14**, 2749-11-3; **15a**, 73323-92-9; **15b**, 73323-93-0; **16**, 14523-22-9; **17**, 73333-86-5; **19a**, 23105-58-0; **19b**, 73286-71-2; **20a**, 73323-64-5; (*R*)-**20b**, 73365-02-3; **21a**, 27460-51-1; (*R*)-**21b**, 73323-65-6; (*S*)-**21b**, 59936-29-7; **22**, 7005-20-1; **23**, 65693-79-0; **24**, 24431-53-6; **25**, 73323-66-7; **26**, 5202-78-8; **27**, 73323-67-8; **28**, 73323-68-9; **29**, 692-33-1; **32**, 33745-25-4; **34**, 22156-23-6; α-methoxy-α-(trifluoromethyl)-benzeneacetyl chloride, 20445-33-4; *N*-ethylphthalimide, 5022-29-7; *N*-acetylproline, 68-95-1; 1-*tert*-butyl (*R*)-1,2-pyrrolidinedicarboxylate, 37784-17-1; *t*-BOC-proline, 15761-39-4; methyl 2-methyl-3-acetamidopropionate, 73323-69-0; (+)-DIOP, 37002-48-5; (–)-DIOP, 32305-98-9; (–)-DIPHOL, 57221-96-2; (+)-DIPHOL, 73323-70-3; BPPM, 61478-28-2.

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Syntheses with Halogen Derivatives of Thiophene and Benzothiophene

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Pyrolysis of octachlorotetrahydrothiophene 1,1-dioxide provides a practical synthesis of octachlorocyclobutane. 1,2-Dichlorohexafluorotetrahydrothiophene 1,1-dioxide also yields a cyclobutane. Treatment of these sulfones with potassium hydroxide forms perhalogenated 3-butenesulfonates. From octachloro-2,3-dihydrobenzothiophene 1,1-dioxide, octachlorostyrene is produced by pyrolysis and hexachlorobenzothiophene 1,1-dioxide by treatment with sodium iodide. Hexachlorobenzothiophene has been prepared from octachloro-2,3-dihydrobenzothiophene and oxidized with chromium trioxide to a thiolactone (**17**). Hydrolysis of the latter gives a 2*H*-benzothiete (**18**). Oxidation of tetrachlorothiophene forms the thiolactone tetrachloro-2,3-dihydrothiophen-2-one (**19**). Octachlorodibenzothiophene can be made by direct chlorination.

Pyrolysis of Octahalotetrahydrothiophene 1,1-Dioxides. Octachlorocyclobutane has previously been made in 5% yield by treatment of octachloro-2-butene with aluminum chloride.[2] This preparation was the source of

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