peak), 105, 91. Diastereoisomer *Z*: ^{1}H NMR ($CDCl_3$, 200 MHz) δ 7.4–7.25 (m, 5 H), 4.25 (d, J = 4.6 Hz, 1 H), 3.83 (d, J = 4.6 Hz), 3.55 (s, 3 H). Diastereoisomer *E*: ^{1}H NMR ($CDCl_3$, 200 MHz) δ 7.4–7.25 (m, 5 H), 4.1 (d, J = 1.8 Hz, 1 H), 3.82 (s, 3 H), 3.52 (d, J = 1.8 Hz, 1 H).

Methyl 3-(1,1-dimethylethyl)-2-oxiranecarboxylate:[41] GC analysis, two diastereoisomers, isolated in pure form; MS 141 (M – 17), 115, 101, 70, 55 (base peak). Diastereoisomer *Z*: ^{1}H NMR ($CDCl_3$, 200 MHz), δ 3.78 (s, 3 H), 3.47 (d, J = 4.7 Hz, 1 H), 2.95 (d, J = 4.7 Hz, 1 H), 0.97 (s, 9 H). Diastereoisomer *E*: ^{1}H NMR ($CDCl_3$, 200 MHz), δ 3.78 (s, 3 H), 3.32 (d, J = 1.9 Hz, 1 H), 2.98 (d, J = 1.9 Hz, 1 H), 0.97 (s, 9 H).

(41) Mulzer, J.; Lammer, O. *Chem. Ber.* **1986**, *119*, 2178.

Methyl 3-(1-methylethyl)-2-oxiranecarboxylate:[41] GC analysis, two diastereoisomers, isolated as a mixture; ^{1}H NMR ($CDCl_3$, 200 MHz) δ 3.80 (s, 3 H_Z), 3.78 (s, 3 H_E), 3.56 (d, J = 4.6 Hz, 1 H_Z), 3.28 (d, J = 1.9 Hz, 1 H_E), 2.98 (dd, J = 1.9 and 7 Hz, 1 H_E), 2.86 (dd, J = 4.6 and 9.2 Hz, 1 H_Z), 1.70–1.53 (m, 1 H), 1.15–0.9 (m, 6 H); MS 127 (M – 17), 113, 101, 85 (base peak).

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Supplementary Material Available: ^{1}H NMR spectra of all compounds described (24 pages). Ordering information is given on any current masthead page.

New Synthesis of Nitrogen Heterocycles through Amide-Directed Hydrocarbonylation of Alkenamides Catalyzed by Rhodium Complexes

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Amide-directed hydrocarbonylation of 3-butenamide (**1**) catalyzed by rhodium complexes such as $RhCl(PPh_3)_3$, $RhCl(CO)(PPh_3)_2$, $HRh(CO)(PPh_3)_3$, and $Rh_4(CO)_{12}$ gives a mixture of 3,4-dihydro-2-pyridone (**2**), 4-methyl-3-pyrrolin-2-one (**3**), and a unique heterodimer, 6-(4-methyl-2-oxo-3-pyrrolin-1-yl)-2-piperidone (**4**). Dihydropyridone (**2**) is obtained in 88% yield with 98% selectivity by using $HRh(CO)(PPh)_3$–dppb (2 equiv) catalyst system while **4** is yielded in 90% yield with 94% selectivity with the use of $RhCl(PPh_3)_3$–$P(OPh)_3$ (10 equiv) as the catalyst. Control experiments revealed that this crossed coupling only proceeds in the copresence of rhodium catalyst, carbon monoxide, and hydrogen. The reactions of *N*-benzyl-3-butenamide (**1a**) gives a mixture of 1-benzyldihydropyridone (**2a**), 1-benzyl-4-methylpyrrolinone (**3a**), and 1-benzyl-6-formyl-3,4-dihydropyridone (**5**) and its 5-formyl isomer (**6**). The formation of **5** and **6** is suppressed by the addition of PPh_3, and **2a** is selectively isolated (72%) in the reaction using $RhCl(CO)(PPh_3)_2$–PPh_3 (20 equiv) as the catalyst. The hydroformylation of **2a** catalyzed by $RhCl(PPh_3)_3$ gives **5** in 80% isolated yield. The reaction of *N-tert*-butyl-3-butenamide (**1b**) gives a nearly 1:1 mixture of 1-*tert*-butyl-4-methylpyrrolinone (**3b**) and uncyclized *N-tert*-butyl-4-formylbutanamide (**7**) accompanied by a small amount of 1-*tert*-butyldihydropyridone (**2b**). In the reaction of *N*-trityl-3-butenamide (**1c**), no dihydropyridone (**2c**) was formed, and a mixture of 1-trityl-4-methylpyrrolinone (**3c**) (major) and *N*-trityl-4-formylbutanamide (**8**) (minor) is yielded. The reaction of 4-pentenamide gives 4-methyl-3,4-dihydro-2-pyridone (**9**) exclusively regardless of the structure of the rhodium catalysts used. Possible mechanisms for these reactions are discussed.

Dihydro-2-pyridone and 2-pyrrolinone skeletons are among the important nitrogen heterocycles for pharmaceutical and agrochemical agents.[2] Dihydro-2-pyridones and 2-pyrrolinones also serve as key intermediates for the syntheses of biologically active alkaloids.[2] Simple dihydro-2-pyridones have been synthesized by the direct reaction of 2,4-pentadienoic acid or sorbic acid with ammonia[3] and by the sodium borohydride reduction of glutarimide.[4] The former reaction gives a mixture of 3,6-dihydro- and 5,6-dihydro-2-pyridones, while the latter yields 3,4-dihydro-2-pyridones selectively. Substituted 3,4-dihydro-2-pyridones and 5,6-dihydro-2-pyridones have been synthesized selectively, for example, through hetero-Diels–Alder cycloaddition of 1-aza-1,3-butadienes with ketenes[5] and cyclocondensation of vinylketene silyl acetals with imines promoted by Lewis acids,[6] respectively. 2-Pyrrolinones have been synthesized in 25–30% yields by oxidation of the corresponding pyrroles with hydrogen peroxide in water,[7] by dehydration of 4-hydroxypyrolidin-2-one,[8] by the condensation of furan with diazoformate,[9] or by alkaline hydrolysis of 4-(chloromethyl)azetidin-2-one[10] by ferrous sulfate promoted rearrangement of bicyclic oxaziridines which were obtained through photolysis of 2*H*-pyrroles.[11]

In the course of our study on chelation-controlled regio- and stereoselective carbonylations in organic syntheses, we have found that amide function can serve as a strong "directing group" in regioselective hydrocarbonylations[12,13]

(1) Postdoctoral Research Associate, 1988–1990, on leave from the Institute of Organic Chemistry, Polish Academy of Sciences, ul Kasprzaka 44, 01-224 Warsaw, Poland.

(2) (a) E.g.: Jones, R. A.; Bean, G. P. In *The Chemistry of Pyrroles*; Academic Press: London, 1977; pp 209–238. (b) Coutts, R. T.; Casy, A. F. Pyridines and Reduced Pyridines of Pharmacological Interests. In *Heterocyclic Compounds. Pyridine and Its Derivatives*; Abramovitch, R. A., Ed.; John Wiley Interscience: New York, 1975; pp 445–524.

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(9) Bordner, J.; Rapoport, H. *J. Org. Chem.* **1965**, *30*, 3824.

(10) Clauss, K. *Tetrahedron Lett.* **1974**, 1271.

(11) Black, D. S. C.; Blackman, N. A. *Aust. J. Chem.* **1979**, *32*, 2035, 2041.

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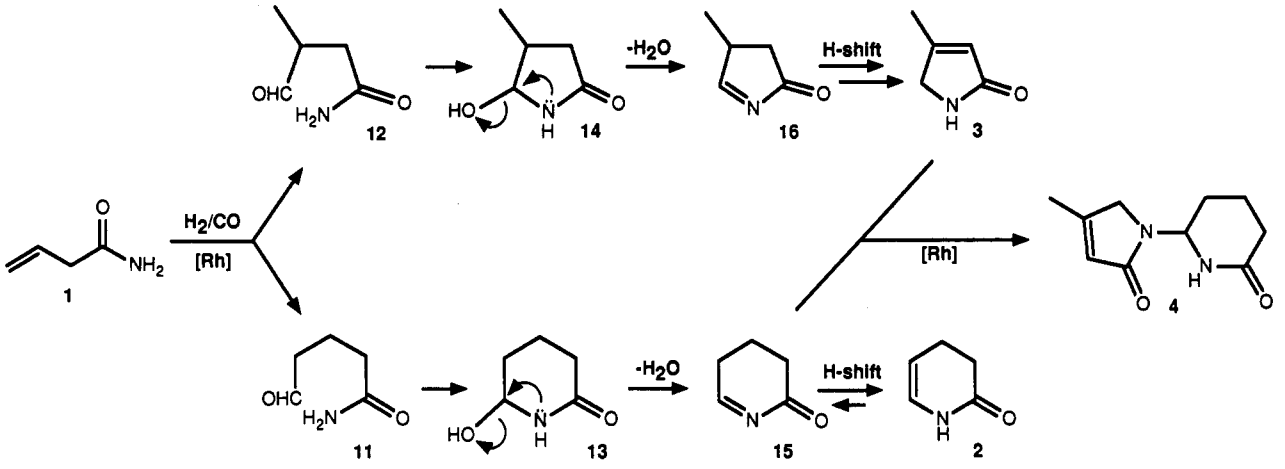
Table I. Amide-Directed Hydrocarbonylation of 3-Butenamide (1)[a]

entry	catalyst	CO (psi)[b]	H_2 (psi)[b]	temp (°C)	time (h)	yield[c] (%)	product ratio (%)[d] 2	3	4
1	$RhCl(PPh_3)_3$	900	300	80	9	88	53[e]	41[e]	6
2	$RhCl(PPh_3)_3$	900	300	80	18	92	13	19	78[f]
3	$RhCl(PPh_3)_3$/10 PPh_3	900	300	80	40	90	57	17	26
4	$RhCl(PPh_3)_3$/20 PPh_3	900	300	80	40	88	92[g]	8	–
5	$RhCl(PPh_3)_3$/10 $P(OPh)_3$	900	300	80	40	90	3	3	94
6	$PhCl(PPh_3)_3$/dppb	600	600	100	40	88	73	27	–
7	$RhCl(PPh_3)_3$/2 dppb	600	600	100	40	85	89	11	–
8	$RhCl(CO)(PPh_3)_2$	600	600	100	5	87	53[h]	47[h]	–
9	$RhCl(CO)(PPh_3)_2$	600	600	100	18	89	18	10	72[i]
10	$RhCl(CO)(PPh_3)_2$/10 PPh_3	600	600	100	40	92	47	6	47
11	$RhCl(CO)(PPh_3)_2$/20 PPh_3	600	600	100	40	86	74	9	17
12	$RhCl(CO)(PPh_3)_2$/2 dppb	600	600	100	40	90	67	24	9
13	$RhCl(CO)(PPh_3)_2$/2 dppe	600	600	100	40	91	48	43	9
14	$HRh(CO)(PPh_3)_3$	900	300	80	18	83	12	13	75
15	$HRh(CO)(PPh_3)_3$/20 PPh_3	900	300	80	40	82	96	4	–
16	$HRh(CO)(PPh_3)_3$/2 dppb	900	300	80	40	88	98[j]	2	–
17	$HRh(CO)(PPh_3)_3$/2 dppe	900	300	80	40	90	45	44	11
18	$Rh_4(CO)_{12}$	600	600	80	18	98	25	22	53

[a] All reactions were run with 3-butenamide (1) (1.50 mmol) and a rhodium catalyst (0.015 mmol) in THF (3.6 mL) in a stainless steel autoclave (300 mL) using a Pyrex reaction vessel (50 mL) with magnetic stirring. Conversion was 100% for every case. [b] Initial pressure at 25 °C. [c] Determined by GLC analysis. [d] Determined by GLC and ^1H NMR analyses. [e] 2 and 3 were isolated in 39% and 30% yields, respectively. [f] 4 was isolated in 68% yield. [g] 2 was isolated in 66% yield. [h] 2 and 3 were isolated in 41% and 31% yields, respectively. [i] 4 was isolated in 65% yield. [j] 2 was isolated in 68% yield.

Scheme I



and have been investigating the amide-directed reactions of *N*-alkenylamides[12a,13] and alkenamides[12b,13] catalyzed by rhodium and cobalt complexes. We describe here a full account of our work on new routes to 3,4-dihydro-2-pyridones and 2-pyrrolinones through amide-directed hydrocarbonylation, i.e., intramolecular amidocarbonylation,[14] of alkenamides as well as a novel crossed coupling reaction giving 6-(4-methyl-2-oxo-3-pyrrolidin-1-yl)-2-piperidone.[15]

Results and Discussion

Amide-Directed Hydrocarbonylation of 3-Butenamide (1). The hydrocarbonylation of 3-butenamide (1) was carried out under typical hydroformylation conditions, i.e., at 80–100 °C and 1200 psi (CO/H_2 = 1 or 3) using common rhodium catalysts such as $RhCl(PPh_3)_3$, $RhCl(CO)(PPh_3)_2$, $HRh(CO)(PPh_3)_3$, or $Rh_4(CO)_{12}$. Results are summarized in Table I. As Table I shows, the reaction under those conditions gave a mixture of 3,4-dihydro-2-pyridone (2), 4-methyl-3-pyrrolin-2-one (3), and a heterodimer, 6-(4-methyl-2-oxo-3-pyrrolin-1-yl)-2-piperidone (4) (eq 1).

It is quite reasonable to assume that 2 and 3 are formed via 5-formylbutanamide (11) and 4-formylbutanamide (12), respectively, whereas 4 is yielded via the crossed coupling of 2 (via 15) and 3 under reaction conditions (see Control Experiments) as shown in Scheme I.[16]

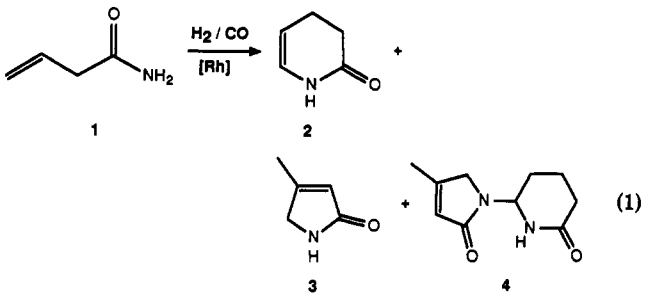
(12) (a) Ojima, I.; Zhang, Z. *J. Org. Chem.* **1988**, *53*, 4422. (b) Ojima, I.; Korda, A. *Tetrahedron Lett.* **1989**, *30*, 6283. For the synthesis of heterocycles through hydrocarbonylation of alkenylamines catalyzed by rhodium complexes, see: (c) Kraft, M. E.; Wilson, L. J. *Tetrahedron Lett.* **1988**, *29*, 6421. (d) Anastasiou, D.; Jackson, W. R. *J. Chem. Soc., Chem. Commun.* **1990**, 1205.

(13) Ojima, I.; Zhang, Z.; Korda, A.; Ingallina, P.; Clos, N. In *New Science in Homogeneous Transition Metal Catalyzed Reactions*; Advances in Chemistry Series; Moser, W. R., Slocum, D. W., Eds.; American Chemical Society: Washington, 1990–1991, in press.

(14) For original $Co_2(CO)_8$-catalyzed amidocarbonylation of aldehydes, see: (a) Wakamatsu, M.; Uda, J.; Yamazaki, N. *J. Chem. Soc., Chem. Commun.* **1971**, 1540. For applications of $Co_2(CO)_8$-catalyzed amidocarbonylations, see: (b) Izawa, K.; Nishi, S.; Asada, S. *J. Mol. Catal.* **1987**, *41*, 135. (c) Izawa, K. *J. Synth. Org. Chem. Jpn.* **1988**, *46*, 218. For other applications of amidocarbonylation, see: (d) Ojima, I. *J. Mol. Catal.* **1986**, *37*, 25. (e) Ojima, I. *Chem. Rev.* **1988**, *88*, 1011 and references cited therein.

(15) For the preliminary communication, see ref 12b. A patent describes a similar reaction giving a mixture of 2 and 3 and their derivatives, but the formation of 4 is not reported at all: Kummar, R.; Fischer, R.; Vagt, U. Ger. Offen. DE 3,630,613; *Chem. Abstr.* **1989**, *109*, 73344u.

(16) Similar *homocoupling promoted by a Lewis acid* was observed for 4-(phenylsulfonyl)azetidin-2-one: Kobayashi, T.; Ishida, N.; Hiraoka, T. *J. Chem. Soc., Chem. Commun.* **1980**, 736. See also ref 4.



(1)

It should be noted that only the crossed coupling product, heterodimer 4, was obtained, and no homocoupling of 2 or 3 was observed at all. In order to look at the reaction profile of this system, we monitored the reaction catalyzed by $RhCl(PPh_3)_3$ under the standard reaction conditions mentioned above. Result is depicted in Figure 1. As Figure 1 shows, the composition of 2, 3, and 4 depends on the reaction time, i.e., 2 and 3 are the predominant products in the early stage of the reaction having a peak at 9–10-h period whereas 4 becomes the predominant product after 15 h. The heterodimer 4 can be isolated in 65–70% yield after 18 h (entries 2, 9, and 14) while 2 and 3 can be isolated in 34–40% and 29–32% yields, respectively, when the reaction is quenched at less than a 10-h period followed by column chromatography on neutral alumina (entries 1 and 8). It should also be noted that cyclization of initially formed aldehydes 11 and 12 should be a very fast process since the formation of 11 and 12 are not detected at all on monitoring the reaction.

Next we examined the effects of phosphine ligands on the regioselectivity, i.e., 2/3 ratio, as well as the monomer/heterodimer selectivity, i.e., (2 + 3)/4 ratio, of the reaction. As Table I shows, addition of 20 equiv of triphenylphosphine to $RhCl(PPh_3)_3$ and $HRh(CO)(PPh_3)_3$ remarkably improves the selectivity in the formation of 2, i.e., 92% and 96%, respectively (entries 4 and 15), and the formation of 4 is completely suppressed. A chelating diphosphine ligand, 1,4-bis(diphenylphosphino)butane (dppb), exhibits even stronger effects, viz., only 2 equiv of dppb is required to achieve similar selectivity to that attained by 20 equiv of triphenylphosphine (entries 7 and 16). The best selectivity is realized by $HRh(CO)(PPh_3)_3$/2dppb catalyst system. In contrast to this, those phosphine ligands turn out to be not so effective in improving the selectivity when $RhCl(CO)(PPh_3)_2$ is used as the catalyst (entries 8–13). Another chelating diphosphine, 1,2-bis(diphenylphosphino)ethane (dppe), however, does not improve the regioselectivity, i.e., 2/3 ratio, although the crossed coupling of 2 and 3 giving 4 is substantially suppressed (entries 13, 17). It should also be noted that the reactions catalyzed by the rhodium complexes modified with excess phosphine ligands are much slower than those catalyzed by the original rhodium complexes by a factor of two.

When 10 equiv of triphenyl phosphite is employed for $RhCl(PPh_3)_3$, the crossed coupling of 2 and 3 is not suppressed, giving 4 with excellent selectivity in high yield (entry 5). As the reaction profile depicted in Figure 2 discloses, the reaction promoted by this catalyst system, $RhCl(PPh_3)_3$/10$P(OPh)_3$ proceeds in a manner quite different from that catalyzed by $RhCl(PPh_3)_3$ (Figure 1), viz., the formation of 4 starts in much earlier stage and the ratio of 2:3:4 is almost 1:1:1 when 3-butenamide is completely consumed at an 18-h period. The heterodimer 4 may serve as a useful intermediate for the synthesis of tricyclic or tetracyclic nitrogen heterocycles.

As for the mechanism of this unique crossed coupling reaction giving 4, we first hypothesized the selective nucleophilic addition of 3 to the reactive acylimine 11 as shown in Scheme I. It is reasonable to assume that (i) the nucleophilic addition of 3 or 2 to 16 is unfavorable because of steric hindrance caused by the 4-methyl group and (ii) nucleophilicity of the amide nitrogen of 3 should be stronger than that of 2 since the cross-conjugation in 3 may reduce the contribution of imidate structure whereas the lone pair on the nitrogen may well be delocalized in enamide structure. Accordingly, the most favorable coupling should take place through the nucleophilic addition of 3 to 11. However, it turned out that this first hypothesis had to be revised when we found the indispensable participation of rhodium catalyst species in this crossed coupling in the following control experiments.

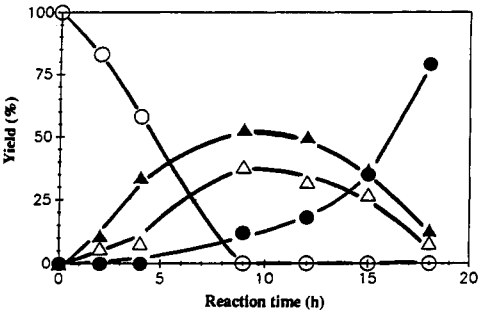


Figure 1. Reaction profile for the hydrocarbonylation of 1 catalyzed by $RhCl(PPh_3)_3$: 1 (○), 2 (▲), 3 (△), and 4 (●).

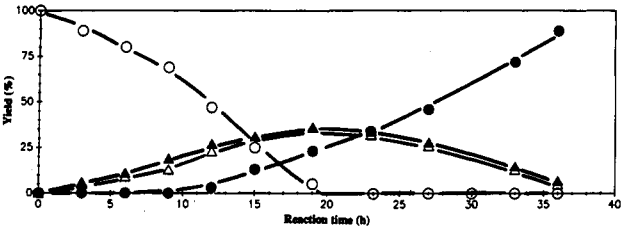


Figure 2. Reaction profile for the hydrocarbonylation of 1 catalyzed by $RhCl(PPh_3)_3$/10 $P(OPh)_3$: 1 (○), 2 (▲), 3 (△), and 4 (●).

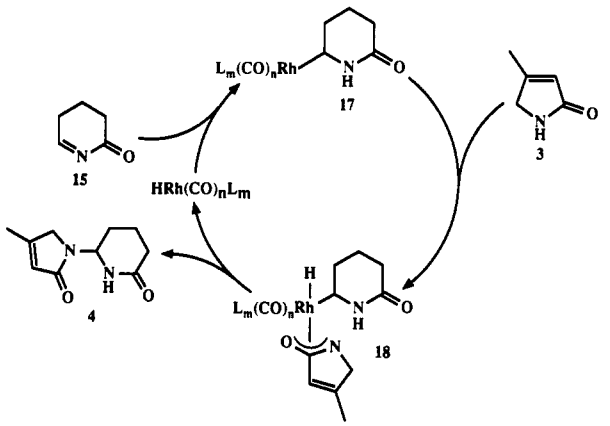
Control Experiments for the Formation of 4 from 2 and 3. In order to examine our hypothesis, coupling between the isolated 2 and 3 was studied. Attempted thermal coupling of 2 and 3 in refluxing THF for 18 h did not take place at all. It was also found that boron trifluoride etherate and *p*-toluenesulfonic acid in refluxing benzene for 18 h did not promote the reaction. These results strongly suggest that the rhodium–phosphine or the rhodium–phosphite complexes are playing a key role for the crossed coupling. Accordingly, a series of control experiments were carried out, i.e., the reactions of 2 and 3 were run in the presence of $HRh(CO)(PPh_3)_3$ at 100 °C for 5 h in THF with (a) both carbon monoxide (600 psi) and hydrogen (600 psi), (b) only carbon monoxide (1200 psi), (c) only hydrogen (1200 psi), and (d) without carbon monoxide and hydrogen in refluxing THF for 18 h. It was found that the reaction under the condition a indeed gave 4 whereas the conditions b, c, and d did not yield 4 at all; no reaction took place under the condition b or d, and only hydrogenation of starting materials occurred under the condition c. Consequently, it is concluded that *this crossed coupling is a catalytic process and the rhodium–phosphine or rhodium–phosphite complexes indeed play a key role for the process*, and the presence of both carbon monoxide and hydrogen is essential to generate active catalyst species. To our best knowledge, *this is the first example for transition metal catalyzed crossed coupling of enamide and amide.* A possible mechanism for the rhodium complex catalyzed crossed coupling of 2 and 3

Table II. Amide-Directed Hydrocarbonylation of *N*-Benzyl-3-butenamide (1a)[a]

entry	catalyst	time (h)	yield[b] (%)	product ratio (%)[c] 2a	3a	5	6
1	$RhCl(PPh_3)_3$	18	88	28	53	16	3
2	$RhCl(PPh_3)_3$/10 PPh_3	40	88	55	37	6	2
3	$RhCl(PPh_3)_3$/20 PPh_3	40	85	78	16	6	–
4	$RhCl(CO)(PPh_3)_2$	18	92	35	49	14	2
5	$RhCl(CO)(PPh_3)_2$/10 PPh_3	40	95	60[d]	40[d]	–	–
6	$RhCl(CO)(PPh_3)_2$/20 PPh_3	40	98	91[e]	9	–	–
7[f]	$Rh_4(CO)_{12}$	18	85	31	51	15	3

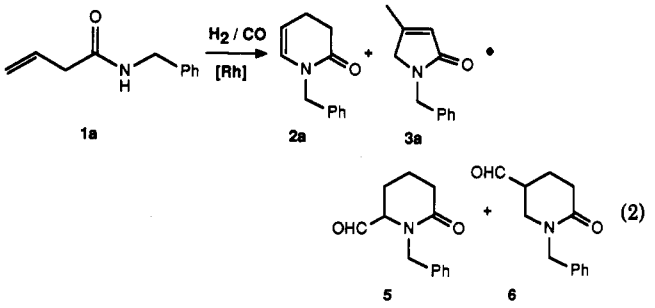
[a] All reactions were run with *N*-benzyl-3-butenamide (1a) (1.50 mmol) and a rhodium catalyst (0.015 mmol) in THF (3.6 mL) in a stainless autoclave (300 mL) using a Pyrex reaction vessel (50 mL) with magnetic stirring at 100 °C and 1200 psi (CO/H_2 = 1; initial pressure at 25 °C) unless otherwise noted. Conversion was 100% for every case. [b] Determined by GLC analysis. [c] Determined by GLC and ^1H NMR analyses. [d] 2a and 3a were isolated in 52% and 36% yields, respectively. [e] 2a was isolated in 72% yield. [f] Reaction was run at 80 °C. The reaction at 100 °C gave substantial amounts of hydrogenated products.

Scheme II



giving 4 is proposed in Scheme II. As Scheme II illustrates, a hydridorhodium carbonyl species is likely to be the active species, which adds to the reactive acylimine 15 to give an intermediate 17. To 17 the amide 3 undergoes oxidative addition to generate an intermediate 18. Then, the subsequent reductive elimination gives the crossed coupling product 4 and regenerates the hydridorhodium carbonyl species.

Reaction of *N*-Benzyl-3-butenamide (1a). Hydrocarbonylation of *N*-benzyl-3-butenamide (1a) under the standard reaction conditions (vide supra) catalyzed by $RhCl(PPh_3)_3$, $RhCl(CO)(PPh_3)_2$, or $Rh_4(CO)_{12}$ gave 1-benzyl-3,4-dihydro-2-pyridone (2a) and 1-benzyl-4-methyl-3-pyrrolin-2-one (3a) as major products accompanied by 6- and 5-formyl-1-benzyl-2-piperidinones, 5 and 6, respectively (eq 2).[17] The aldehydes, 5 and 6, are the

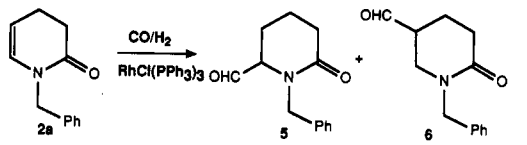


(2)

products of sequential double carbonylation, i.e., the hydroformylation of 2a. Because of the N-benzylation, no formation of heterodimer such as 4 was observed. Addition of phosphine ligands to the rhodium catalysts exerts a marked influence on the selectivity of the reaction as observed for the reaction of 1. Results are listed in Table II.

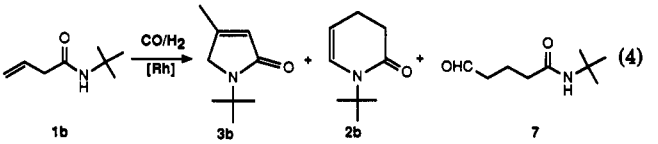
As Table II shows, the overall regioselectivity for the formation of terminal and branched aldehydes in the initial step is approximately 1:1 with all rhodium catalysts examined in the absence of additional phosphine ligands. Addition of excess amounts of triphenylphosphine to the rhodium catalysts suppresses the formation of the secondary reaction products, i.e., 5 and 6, and also favors the formation of 2a over 3, e.g., the reaction catalyzed by $RhCl(CO)(PPh_3)_2$/20 PPh_3 at 100 °C and 1200 psi (CO/H_2 = 1) gave 2a with 91% selectivity in 98% yield like the case of 1 (entry 6, Table II); 2a was isolated in 72% yield by a column chromatography on neutral alumina.

The secondary products, 5 and 6, can be obtained through the hydroformylation of 2a thus obtained, e.g., hydroformylation of 2a catalyzed by $RhCl(PPh_3)_3$ at 100 °C and 1600 psi (CO/H_2 = 4.33) for 40 h cleanly gave 5 as the major and 6 as the minor product (5/6 = 87/13 by GLC), and 5 was isolated in 80% yield through a column chromatography on neutral alumina (eq 3).[18]



(3)

Reactions of *N*-*tert*-Butyl-3-butenamide (1b) and *N*-Trityl-3-butenamide (1c). In order to look at the substituent effect on the regioselectivity of the reaction, 3-butenamides bearing bulky substituents on the amide nitrogen, i.e., *N*-*tert*-butyl-3-butenamide (1b) and *N*-trityl-3-butenamide (1c), were prepared and submitted to hydrocarbonylation (eqs 4 and 5). Results are listed in Table III.

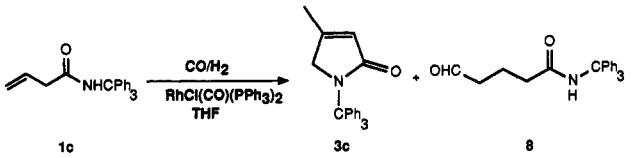


(4)

As Table III shows, the bulkiness of the substituent on the amide nitrogen virtually does not have any effects on the overall regioselectivity, i.e., terminal vs branched ratio,

(17) The amidocarbonylation of 1a catalyzed by $Co_2(CO)_8$ at 100 °C and 1470 psi (CO/H_2 = 1) was reported to give 3-(*N*-benzylcarbamoyl)-2-methylpropanoic acid in 69% yield, viz., no formation of nitrogen heterocycles was observed. See: Nishi, S.; Asada, S.; Izawa, K. 31st Symposium on Organometallic Chemistry, Japan, Oct. 30–31, Tsukuba, Japan, 1984; Abstracts B202.

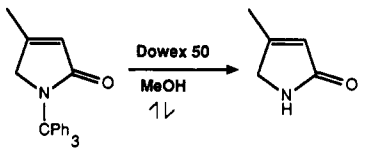
(18) A similar α-selectivity has been observed in the hydroformylation of acyclic *N*-alkenylamides, *N*-acyl-2-pyrrolines, and *N*-vinylimides: (a) Sato, S. *Nippon Kagaku Zasshi* **1969**, *90*, 404. (b) Becker, Y.; Eisenstadt, A.; Stille, J. K. *J. Org. Chem.* **1980**, *45*, 2145. (c) Cavinato, G.; Toniolo, L.; Botteghi, C.; Gladiali, S. *J. Organomet. Chem.* **1982**, *229*, 63. (d) Delogu, G.; Faedda, G.; Gladiali, S. *J. Organomet. Chem.* **1984**, *268*, 167.



(5)

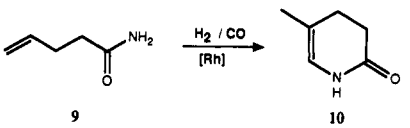
of the reaction, but it exerts a marked effects on the cyclic/acyclic ratio of the products. For instance, 1-*tert*-butyl-4-methyl-3-pyrrolin-2-one (**3b**) was formed in 44% yield whereas 1-*tert*-butyl-3,4-dihydro-2-pyridone (**2b**) was produced only in 7% yield and the rest of the terminal aldehyde (**7**) remained uncyclized (entry 1, Table III). The effect of bulky N-substituent is more pronounced in the case of **1c**, viz., no formation of 1-trityl-3,4-dihydro-2-pyridone (**2c**) was observed and 1-trityl-4-methyl-3-pyrrolin-2-one (**3c**) was obtained as the sole cyclic product (entries 3–5). Considerable solvent effect on the **3**/**8** ratio is observed, thus THF is the best solvent so far for the cyclization (entry 3); **8** is the predominant or exclusive product when toluene, DMF, or dioxane is used as the solvent (entries 4–6). In these cases, the aldehyde **8** consists of terminal and branched isomers. The pyrrolinone **3c** and the aldehydes **8**, were easily separated and isolated through a column chromatography on neutral alumina.

4-Methyl-3-pyrrolin-2-one (**3**) can be obtained by deprotection of **3c**. Thus, **3c** was treated with an ion exchange resin, Dowex 50 X2-400, in refluxing methanol to give **3** in high yield (eq 6).



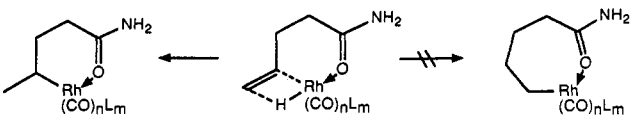
(6)

Reaction of 4-Pentenamide (9). Finally, the hydrocarbonylation of 4-pentenamide (**9**) was carried out using $RhCl(PPh_3)_3$, $RhCl(CO)(PPh_3)_2$, $HRh(CO)(PPh_3)_3$, and $Rh_4(CO)_{12}$ as catalysts at 100 °C and 1200 psi (CO/H_2 = 1) for 18 h. The reactions gave 5-methyl-3,4-dihydro-2-pyridone (**10**) as the sole product in excellent yield (eq 7): $RhCl(PPh_3)_3$, 91%; $RhCl(CO)(PPh_3)_2$, 89%; $HRh(CO)(PPh_3)_3$, 88%; $Rh_4(CO)_{12}$, 92%.

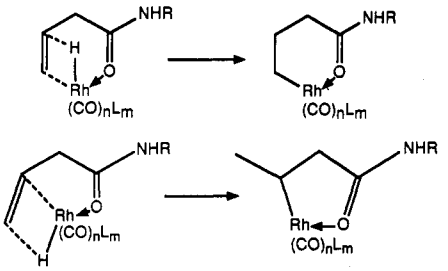


(7)

Although the formation of a seven-membered ring lactam is conceptually possible, such a product was not detected at all even when $RhCl(PPh_3)_3$/20 PPh_3 was used as the catalyst. The result clearly indicates that a "chelation control" is operative in the reaction favoring the formation of branched aldehyde in the initial hydroformylation step.



The results also strongly suggests that a similar "chelation control" is operating in the reactions of **1** and **1a** as well. Accordingly, the effects of a large excess of triphenylphosphine or an excess of dppb cannot simply be accommodated by the blocking (or disruption) of the amide-directed "chelation control", but should be interpreted as the regioselective hydroformylation of **1** (or **1a**) with the coordination of the amide moiety intact, viz., the regiocontrol is caused by phosphine ligands in the coordination sphere of the rhodium catalysts. In the two possible transition states leading to the six-membered ring chelate and the five-membered ring chelate shown below, it is apparent that increased bulk of the rhodium moiety bearing ligands, L_m, would prefer the formation of the six-membered ring chelate through a less congested transition state.



Further mechanistic study on the details of the novel crossed coupling reaction as well as chelation-controlled hydrocarbonylations and applications of the amide-directed hydrocarbonylations to alkaloid synthesis are actively underway. Results will be reported elsewhere.

Experimental Section

General Method. Melting points were measured with a Thomas-Hoover Unimelt apparatus and are uncorrected. ^1H NMR and ^{13}C NMR spectra were recorded on a General Electric QE-300 spectrometer. The IR spectra were measured with a Perkin-Elmer 1600 FT-IR spectrophotometer with a Hewlett-Packard 7470A plotter using samples as solutions in a liquid cell or as KBr disks. Mass spectra (GCMS) were recorded on a Hewlett-Packard 5980A mass spectrometer equipped with a Hewlett-Packard 5710A gas chromatograph and a Hewlett-Packard 5933A data system. High-resolution mass spectra (HRMS) were measured with Kratos MS-80RFA mass spectrometer equipped with Chrompack Carlo Erba/Kratos gas chromatograph and DATA General Eclipse S/120 data station. Analytical gas chromatography was performed with a Hewlett-Packard 5890 gas chromatograph (FID) using a column packed with OV-17. Elemental analyses were performed by M-H-W Laboratories, Phoenix, AZ.

Materials. Tetrahydrofuran was distilled over sodium/benzophenone under nitrogen prior to use. All other solvents were reagent grade and were used as received. Alkenylamides were prepared according to text book procedures from the corresponding alkenoyl acids via the reaction of acid chlorides with ammonia or amines. Wilkinson's catalyst, $RhCl(PPh_3)_3$, was purchased from Aldrich and used as received. Rhodium complexes, $RhCl(CO)(PPh_3)_2$[19] and $HRh(CO)(PPh_3)_3$,[20] were prepared according to the literature method. Triphenylphosphine was purchased from Aldrich and recrystallized from ethanol. 1,4-Bis(diphenylphosphino)butane (dppb) and 1,2-bis(diphenylphosphino)ethane (dppe) were obtained from Strem Chemicals and used as received. Silica gel (MN-Kieselgel 60) and neutral alumina (100–200 mesh) for chromatography were purchased from Brinkmann Instruments, Inc. and Fischer Scientific, respectively.

General Procedure for the Amide-Directed Hydrocarbonylation. In a typical run, an alkenamide (1.50 mmol) and a rhodium catalyst (1.50×10^{-2} mmol) are placed in a 25-mL reaction vessel under nitrogen or argon. When a phosphine ligand is required, an appropriate amount is also added to the reaction vessel. To the reaction vessel is added THF (3.7 mL) via syringe, and the reaction vessel is placed in a 300-mL stainless steel autoclave. The autoclave is charged with desired pressure of carbon monoxide (600–900 psi) and hydrogen (300–600 psi), which is equipped with a magnetic stirrer and a thermostated oil bath.

(19) Evans, D.; Osborn, J. A.; Wilkinson, G. *Inorg. Synth.* **1968**, *11*, 99.
(20) Ahmad, N.; Levison, J. J.; Robinson, S. D.; Uttley, M. F. *Inorg. Synth.* **1974**, *15*, 59.

Table III. Hydrocarbonylation of *N-tert*-Butyl-3-butenamide (1b) and *N*-Trityl-3-butenamide (1c)[a]

entry	substrate	catalyst	solvent	yield[b] (%)	products and product ratio[b]		
1	1b	$HRh(CO)(PPh_3)_3$	THF	90	2b (8)[c]	3b (46)[c]	7 (46)[c]
2	1b	$RhCl(CO)(PPh_3)_2$	THF	78	2b (13)	3b (47)	7 (40)
3	1c	$RhCl(CO)(PPh_3)_2$	THF	79	–	3c (47)[d]	8 (53)[d,e]
4[f]	1c	$RhCl(CO)(PPh_3)_2$	toluene	83	–	3c (17)	8 (83)[g]
5	1c	$RhCl(CO)(PPh_3)_2$	DMF	80	–	3c (12)	8 (88)[h]
6	1c	$RhCl(CO)(PPh_3)_2$	dioxane	75	–	–	8 (100)[i]

[a] All reactions were run with substrate (1b or 1c) (1.50 mmol) and a rhodium catalyst (0.015 mmol) in THF (3.6 mL) in a stainless steel autoclave (300 mL) using a Pyrex reaction vessel (50 mL) with magnetic stirring at 100 °C and 1200 psi (CO/H_2 = 1; initial pressure at 25 °C) for 18 h unless otherwise noted. Conversion was 100% for every case. [b] Determined by ^1H NMR analysis. [c] Determined by GLC and ^1H NMR analyses. [d] 2b, 3b, and 7 (only terminal aldehyde was yielded) were isolated in 5%, 33%, and 17% yields, respectively. [d] 3c and 8 (terminal) were isolated in 29% and 15% yields, respectively. [e] Terminal/branched ratio is 87/13. [f] Reaction was run for 40 h. [g] Terminal/branched ratio is 58/42. [h] Terminal/branched ratio is 67/33. [i] Terminal/branched ratio is 50/50.

The mixture in the autoclave is heated at the given temperature (80–100 °C) for the required time period with stirring. Then, pressure is carefully released and the reaction mixture is submitted to GLC and/or NMR analyses.

Synthesis of 3,4-Dihydro-2-pyridone (2) and 4-Methyl-3-pyrrolin-2-one (3). A 50-mL reaction vessel containing a mixture of 3-butenamide (1) (510 mg, 6.00 mmol) and $RhCl(CO)(PPh_3)_2$ (40 mg, 6.0×10^{-2} mmol) in THF (16 mL) was placed in an 300-mL stainless steel autoclave. The reaction was carried out at 100 °C and 1200 psi (CO/H_2 = 1) for 5 h with stirring. After the gases were released and the solvent was removed from the reaction mixture on a rotary evaporator, a brown oil (525 mg) was obtained, which was redissolved in 25 mL of ethyl acetate. The resulting precipitate was filtered off on a glass filter, and the filtrate was treated with Norit to give a pale yellow oil (497 mg) after removal of the solvent. This crude product was submitted to a column chromatography on silica gel using ethyl acetate as the eluant to give 2 (239 mg, 41% yield) and 3 (179 mg, 31% yield).

2:[4] colorless oil; IR ($CHCl_3$) 3248 (NH), 1666 (CO) cm^{-1}; ^1H NMR ($CDCl_3$) δ 2.31 (m, 2 H), 2.50 (t, J = 8.02 Hz, 2 H), 5.09 (m, 1 H), 6.09 (m, 1 H), 7.00 (bs, 1 H); ^{13}C NMR ($CDCl_3$) δ 19.86, 30.24, 104.60, 124.95, 171.96; MS (m/e) 97 (M^+, 100), 69 (25), 68 (28), 56 (13), 54 (22), 43 (13).

3: white solid; mp 110–111 °C (lit.[10] mp 113°C); IR ($CHCl_3$) 3330 (NH), 1660 (CO) cm^{-1}; ^1H NMR ($CDCl_3$) δ 2.08 (s, 3 H), 3.92 (s, 2 H), 5.85 (s, 1 H), 7.80 (bs, 1 H); ^{13}C NMR ($CDCl_3$) δ 15.19, 51.66, 104.89, 122.38, 176.11; MS (m/e) 97 (M^+, 100), 82 (13), 59 (30), 58 (18), 41 (10).

Synthesis of 6-(4-Methyl-2-oxo-3-pyrrolin-1-yl)-2-piperidone (4). A 50-mL reaction vessel containing 1 (850 mg, 10.0 mmol) and $RhCl(PPh_3)_3$ (90 mg, 0.10 mmol) in THF (20 mL) was placed in a 300-mL stainless steel autoclave. The reaction was carried out at 100 °C and 1200 psi (CO/H_2 = 3) for 18 h with stirring. The gases were released, and the solvent was evaporated from the reaction mixture to give a brown oil, which was redissolved in 30 mL of methanol and treated with Norit to give a yellow oil (927 mg) after removal of the solvent. Treatment of the yellow oil with ethyl acetate resulted in the formation of pale yellow precipitate, which was collected on a glass filter. The precipitate was recrystallized from ethyl acetate to give 4 as colorless crystals (660 mg, 68% yield).

4: mp 151–152 °C; IR (KBr disk) 3230 (NH), 1682 (CO) cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.7–2.1 (m, 2 H), 2.2–2.5 (m, 4 H), 2.10 (s, 3 H), 3.86 (d, J = 18.5 Hz, 1 H), 3.98 (d, J = 18.5 Hz, 1 H), 5.69 (t, J = 4.2 Hz, 1 H), 5.86 (s, 1 H); ^{13}C NMR ($CDCl_3$) δ 15.45, 18.89, 27.11, 31.12, 50.89, 59.55, 122.29, 156.81, 172.19, 172.30. Anal. Calcd for $C_{10}H_{14}N_2O_2$: C, 61.84; H, 7.26; N, 14.42. Found: C, 61.87; H, 7.26; N, 14.36.

Synthesis of 3,4-Dihydro-2-pyridone (2). A 50-mL reaction vessel containing 1 (510 mg, 6.00 mmol), $RhCl(PPh_3)_3$ (55 mg, 6.0×10^{-2} mmol), and PPh_3 (31 mg, 0.12 mmol) in THF (16 mL) was placed in a 300-mL stainless steel autoclave. The reaction was run at 80 °C and 1200 psi (CO/H_2 = 3) for 40 h with stirring. The gases were released, and the solvent was removed from the reaction mixture to give a brown solid (585 mg), which was redissolved in 50 mL of ethyl acetate. Undissolved material was removed by filtration on a glass filter, and the filtrate was treated with Norit to give a pale yellow solid (532 mg) after removal of the solvent. This crude product was subjected to a column chromatography on neutral alumina. Triphenylphosphine was recovered from benzene elute, and 2 was obtained from ethyl acetate elute as a colorless oil (365 mg, 62% yield).

Control Experiments for the Formation of 4 from 2 and 3. A 25-mL reaction vessel containing 2 (24 mg, 0.25 mmol) and 3 (24 mg, 0.25 mmol) and $HRh(CO)(PPh_3)_3$ (4.0 mg, 5.0×10^{-3} mmol) in THF (1.5 mL) was placed in a 300-mL stainless steel autoclave. The reaction was run at 100 °C and 1200 psi (CO/H_2 = 1) for 5 h with stirring. The gases were released, and the solvent was removed from the reaction mixture to give crude product as a brown solid (55 mg). The GLC analysis of the crude product showed that conversion was 62% and 4 was formed with 90.3% selectivity.

When another control reaction was carried out under 1000 psi of carbon monoxide without hydrogen in the same scale and manner as the one described above, no formation of 4 was observed, i.e., 2 and 3 were recovered unchanged.

Another control experiment under 1000 psi of hydrogen without carbon monoxide, in the same scale and manner as the one described above, yielded only hydrogenation products of 2 and 3, i.e., piperidin-2-one and 4-methylpyrrolidin-2-one, respectively, in quantitative yield.

Synthesis of *N*-Benzyl-3,4-dihydro-2-pyridone (2a) and *N*-Benzyl-4-methyl-3-pyrrolin-2-one (3a). A 50-mL reaction vessel containing *N*-benzyl-3-butenamide (1a) (1.760 g, 10.0 mmol), $RhCl(CO)(PPh_3)_2$ (33 mg, 5.0×10^{-2} mmol), and PPh_3 (107 mg, 0.500 mmol) in THF (24 mL) was placed in a 300-mL stainless steel autoclave. The reaction was run at 100 °C and 1200 psi (CO/H_2 = 1) for 40 h with stirring. The gases were released, and the solvent was removed from the reaction mixture to give an oily residue (1.938 g), which was subjected to a column chromatography on neutral alumina. After triphenylphosphine was recovered by using benzene as the eluant, 2a (972 mg, 52% yield) and 3a (671 mg, 36% yield) were isolated from ethyl acetate/hexane (1/1) elutes: 2a was obtained as a pale yellow oil while 3a was first obtained as a colorless oil, but solidified on standing to give a white solid.

2a: IR (CH_2Cl_2) 1668 (CO) cm^{-1}; ^1H NMR ($CDCl_3$) δ 2.33 (m, 2 H), 2.58 (t, J = 8.1 Hz, 2 H), 4.68 (s, 2 H), 5.12 (m, 1 H), 6.00 (d, J = 8.1 Hz, 1 H), 7.3 (m, 5 H); ^{13}C NMR ($CDCl_3$) δ 20.00, 30.98, 48.42, 106.05, 122.20, 127.02, 127.08, 127.52, 143.56, 171.60; MS (m/e) 187 (M^+, 32), 92 (10), 91 (100), 65 (13). Anal. Calcd for $C_{12}H_{13}NO$: C, 76.97; H, 7.01; N, 7.48. Found: C, 76.87; H, 7.01; N, 7.49.

3a: mp 61–62 °C; IR (CH_2Cl_2) 1654 (CO) cm^{-1}; ^1H NMR ($CDCl_3$) δ 2.01 (s, 3 H), 3.72 (s, 2 H), 4.59 (s, 2 H), 5.89 (s, 1 H), 7.3 (m, 5 H); ^{13}C NMR ($CDCl_3$) δ 14.92, 45.52, 54.85. 122.15, 127.24, 127.61, 128.44, 137.02, 155.56, 172.00; MS (m/e) 187 (M^+, 84), 186 (21), 172 (3), 110 (10), 91 (100), 83 (22), 82 (20), 65 (18), 39 (12). Anal. Calcd for $C_{12}H_{13}NO$: C, 76.97; H, 7.01; N, 7.48. Found: C, 76.91; H, 7.04; N, 7.49.

N-Benzyl-3,4-dihydro-2-pyridone (2a) was obtained selectively on using $RhCl(CO)(PPh_3)_2$ (1 mol %) with 20 equiv of PPh_3 as the catalyst. The GLC analysis of the reaction mixture revealed that 2a was formed with 91% selectivity. After the same isolation procedure to that described above, 2a was isolated in 72% yield.

Synthesis of *N*-Benzyl-6-formyl-2-piperidone (5). A 25-mL reaction vessel containing 2a (187 mg, 1.00 mmol) and $RhCl(PPh_3)_3$ (9.2 mg, 1.0×10^{-2} mmol) in THF (3.0 mL) was placed in a 300-mL stainless steel autoclave. The reaction was carried out at 100 °C and 1600 psi (CO, 1300 psi; H_2, 300 psi) for 40 h

with stirring. The gases were released, and the solvent was evaporated to give crude product as an oily residue. The ^1H NMR analysis of the crude product showed the formation of **5** (87%) accompanied by a small amount of its 5-formyl isomer **6** (13%). The crude product was submitted to a column chromatography on neutral alumina (eluant: ethyl acetate) to give **5** cleanly as a pale yellow oil (173 mg, 80% yield).

5: IR (CH_2Cl_2) 1730 (CO), 1630 (CO) cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.50–2.21 (m, 4 H), 2.47–2.54 (m, 2 H), 3.38 (d, J = 15.0 Hz, 1 H), 3.92–3.96 (m, 1 H), 5.44 (d, J = 15.0 Hz, 1 H), 7.2–7.4 (m, 5 H), 9.45 (d, J = 1.2 Hz, 1 H); ^{13}C NMR ($CDCl_3$) δ 18.51, 23.37, 31.95, 49.23, 64.98, 128.31, 128.95, 129.38, 170.54, 199.78; MS (m/e) 217 (M^+, 12), 188 (10), 146 (11), 118 (10), 106 (23), 92 (10), 91 (100), 65 (8). Anal. Calcd for $C_{13}H_{15}NO_2$: C, 71.86; H, 6.97; N, 6.45. Found: C, 72.01; H, 7.01; N, 6.44.

6: ^1H NMR ($CDCl_3$) δ 1.50–2.21 (m, 4 H), 2.58–2.72 (m, 1 H), 3.44 (dd, J = 12.6, 7.5 Hz, 1 H), 3.38 (dd, J = 12.6, 6.6 Hz, 1 H), 4.53 (d, J = 14.9 Hz, 1 H), 4.71 (d, J = 14.9 Hz, 1 H), 9.62 (d, J = 1.2 Hz, 1 H). Anal. Calcd for $C_{13}H_{15}NO_2$: C, 71.86; H, 6.97; N, 6.45. Found: C, 71.91; H, 6.94; N, 6.51.

Hydrocarbonylation of *N*-*tert*-Butyl-3-butenamide (1b) and *N*-Trityl-3-butenamide (1c). A 50-mL reaction vessel containing *N*-*tert*-butyl-3-butenamide (**1b**) (212 mg, 1.50 mmol) and $HRh(CO)(PPh_3)_2$ (14 mg, 1.5×10^{-2} mmol) in THF (3.6 mL) was placed in a 300-mL stainless steel autoclave. The reaction was run at 100 °C and 1200 psi (CO/H_2 = 1) for 18 h with stirring. The gases were released, and the solvent was removed to give crude product as brown oil (265 mg). The GLC analysis of the crude product revealed the formation of *N*-*tert*-butyl-4-methyl-3-pyrrolin-2-one (**3b**) (44%), *N*-*tert*-butyl-3,4-dihydro-2-pyridone (**2b**) (7%), and *N*-*tert*-butyl-4-formylbutanamide (**7**) (44%) in 90% total yield. A column chromatography of the crude product on neutral alumina (eluant: hexane/EtOAc = 1/1) gave **3b** (76 mg, 33% yield), **7** (44 mg, 17% yield), and **2b** (12 mg, 5% yield).

2b: colorless oil; IR (CH_2Cl_2) 1668 (CO) cm^{-1}; ^1H NMR δ 1.34 (s, 9 H), 2.18 (m, 2 H), 2.44 (t, J = 7.5 Hz, 2 H), 5.11 (m, 1 H), 6.34 (d, J = 8.1 Hz, 1 H); MS (m/e) 153 (M^+, 23), 98 (8), 97 (100), 96 (26), 70 (5), 69 (88), 68 (27), 57 (16); HRMS (m/e) calcd for $C_9H_{15}NO$ 153.1154, found 153.1168.

3b: colorless oil; IR (CH_2Cl_2) 1680 (CO) cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.44 (s, 9 H), 2.01 (s, 3 H), 3.89 (s, 2 H), 5.74 (s, 1 H); ^{13}C NMR ($CDCl_3$) δ 15.00, 28.05, 53.65, 54.32, 124.73, 127.37, 172.63; MS (m/e) 153 (M^+, 18), 139 (9), 138 (100), 110 (62), 99 (27), 97 (9), 96 (15), 69 (14), 55 (9), 41 (8); HRMS (m/e) calcd for $C_9H_{15}NO$ 153.1154, found 153.1161.

7: colorless oil; IR (CH_2Cl_2) 3294 (NH), 1723 (CO), 1665 (CO) cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.35 (s, 9 H), 1.95 (m, 2 H), 2.15 (t, J = 7.1 Hz, 2 H), 2.55 (t, J = 7.2 Hz, 2 H), 9.78 (t, J = 1.3 Hz, 1 H); MS (m/e) 171 (M^+, 1), 156 (9), 115 (7), 99 (23), 71 (20), 60 (3), 59 (16), 58 (100), 57 (29), 56 (11), 55 (12), 42 (11), 41 (20); HRMS (m/e) calcd for $C_9H_{17}NO_2$ 171.1259, found 171.1246.

In a similar manner, the reaction of *N*-trityl-3-butenamide (**1c**) was carried out with **1c** (495 mg, 1.50 mmol) and $RhCl(CO)(PPh_3)_2$ (10 mg, 1.5×10^{-2} mmol) in THF (4.6 mL) at 100 °C and 1200 psi (CO/H_2 = 1) for 18 h. The ^1H NMR analysis of the crude product showed the formation of *N*-trityl-4-methyl-3-pyrrolin-2-one (**3c**) (47%) and *N*-trityl-4-formylbutanamide (**8**) (47%). The crude product was subjected to a column chromatography on neutral alumina (eluant: hexane/AcOEt = 2/1) to give **3c** (147 mg, 29% yield) and **8** (80 mg, 15% yield).

3c: white solid; mp 173 °C dec; IR (CH_2Cl_2) 1684 (CO) cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.99 (s, 3 H), 3.82 (s, 2 H), 5.83 (s, 1 H), 7.25 (m, 15 H); ^{13}C NMR ($CDCl_3$) δ 15.30, 59.07, 124.36, 126.33, 127.56, 128.68, 129.79, 143.37, 172.85. Anal. Calcd for $C_{24}H_{21}NO$: C, 84.92; H, 6.24; N, 4.13. Found: C, 84.77; H, 6.24; N, 3.88.

8 (terminal): white solid; mp 175 °C dec; IR (CH_2Cl_2) 3302 (NH), 1725 (CO), 1678 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.84 (m, 2 H), 2.33 (t, J = 7.0 Hz, 2 H), 2.36 (t, J = 7.2 Hz, 2 H), 9.62 (t, J = 1.4 Hz, 1 H). Anal. Calcd for $C_{24}H_{23}NO_2$: C, 80.64; H, 6.48; N, 3.92. Found: C, 80.46; H, 6.51; N, 3.73.

8 (branched): ^1H NMR ($CDCl_3$) δ 1.09 (d, J = 7.5 Hz, 3 H), 2.61 (d, J = 7.4 Hz, 1 H), 2.66 (d, J = 7.4 Hz, 1 H), 2.88 (m, 1 H), 9.65 (d, J = 1.3 Hz, 1 H). Anal. Calcd for $C_{24}H_{23}NO_2$: C, 80.64; H, 6.48; N, 3.92. Found: C, 80.87; H, 6.59; N, 3.75.

Synthesis of 4-Methyl-3-pyrrolin-2-one (3). To a solution of **3c** (104 mg, 0.31 mmol) in 15 mL of methanol was added Dowex 50X2-400 cation exchange resin (200 mg), and the suspension was stirred under reflux for 16 h. Then, the resin was removed by filtration, and the filtrate was concentrated to dryness. The resulted pale yellow solid was triturated in pentane to give **3** as a white solid (26 mg, 86% yield). The melting point and spectral data were identical with those of an authentic sample (vide supra).

Synthesis of 5-Methyl-3,4-dihydro-2-pyridone (10). A 50-mL reaction vessel containing 4-pentenamide (**9**) (447 mg, 4.50 mmol) and $Rh_4(CO)_{12}$ (33 mg, 4.5×10^{-2} mmol) in THF (12 mL), was placed in a 300-mL stainless steel autoclave. The reaction was run at 100 °C and 1200 psi (CO/H_2 = 1) for 18 h with stirring. The gases were released, and the solvent was removed from the reaction mixture to give a brown solid (479 mg), which was redissolved in 25 mL of ethyl acetate. The resulted precipitate was filtered off, and the solution was treated with Norit to give a yellow solid (470 mg) after removal of the solvent. Chromatographic purification on a neutral alumina column by using ethyl acetate as the eluant gave **10** as a white solid (458 mg, 92% yield).

10: mp 71–72 °C; IR ($CHCl_3$) 3236 (NH), 1672 (CO) cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.70 (s, 3 H), 2.26 (t, J = 8.1 Hz, 3 H), 2.49 (t, J = 8.1 Hz, 3 H), 5.81 (d, J = 1.0 Hz, 1 H), 7.08 (bs, 1 H); ^{13}C NMR ($CDCl_3$) δ 19.20, 25.66, 30.05, 114.24, 119.32, 171.00; MS (m/e) 111 (M^+, 100), 96 (36), 83 (16), 82 (30), 70 (16), 68 (30), 67 (10), 56 (12), 43 (11). Anal. Calcd for C_6H_9NO: C, 64.83; H, 8.18; N, 12.60. Found: C, 64.74; H, 8.28; N, 12.39.

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