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Ruthenium-Catalyzed Reaction of α,β-Unsaturated Imines with Carbon Monoxide and Alkenes Leading to β,γ-Unsaturated γ-Butyrolactams: Involvement of Direct Carbonylation at Olefinic C−H Bonds as a Key Step

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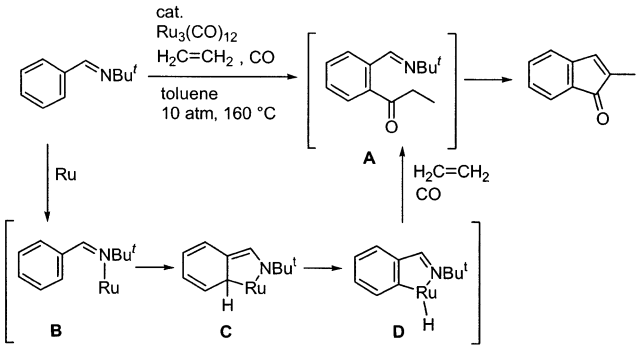
The reaction of α,β-unsaturated imines with CO and alkenes in the presence of $Ru_3(CO)_{12}$ as a catalyst results in a three-component coupling reaction that gives α,α-disubstituted β,γ-unsaturated γ-butyrolactams. The reaction proceeds via a two-step sequence involving the initial formation of ketone derivatives by catalytic carbonylation at the β-olefinic C−H bonds of α,β-unsaturated imines, followed by the (uncatalyzed) intramolecular nucleophilic attack of the imine nitrogen on the ketonic carbon to generate a tetrahedral intermediate, which then undergoes a 1,2-ethyl migration. The reaction of a cyclic unsaturated imine, derived from the reaction of *(1R)*-(−)-myrtenal with *tert*-butylamine, gives a β-aminocyclopentene derivative, which is formed by an aldol-type condensation of the initially formed ketone, indicating the initial formation of ethyl ketone.

Introduction

The carbonylation reaction is one of the most useful and reliable methods for the preparation of a variety of carbonyl-containing compounds.[1] A continuing need exists, however, for the development of new types of carbonylation reactions for preparing carbonyl compounds that are not readily accessible by existing methods,[2,3] although a wide variety of these reactions have already been reported thus far. In the course of our studies on the ruthenium carbonyl-catalyzed carbonylation at C−H bonds,[3] we reported that the ruthenium-catalyzed reaction of aromatic imines with CO and ethylene gives indenones, the proposed formation of

SCHEME 1



which involves the intramolecular aldol-type reaction of the initial products **A** under the reaction conditions used (Scheme 1).[3c] The coordination of the imine-nitrogen to ruthenium, as in **B**, is proposed to be responsible for the observed ortho-selectivity. The issue of whether this reaction is applicable to α,β-unsaturated imines is of interest. Surprisingly, Imhof et al. independently reached the same conclusion.[4] In this paper, we report our

(1) For reviews on carbonylation reactions, see: Colquhoun, H. M.; Thompson, D. J.; Twigg, M. V. *Carbonylation*; Plenum Press: New York, 1991. Kühlein, K.; Geissler, H. In *Transition Metal for Organic Synthesis*; Beller, M., Bolm, C., Eds.; Wiley-VCH: Weinheim, Germany, 1998, pp 79−90. Cornis, B., Herrmann, W. A. *Applied Homogeneous Catalysis with Organometallic Compounds*; Wiley-VCH: Weinheim, Germany, 1996, Vol. 1. Nozaki, K. In *Comprehensive Asymmetric Catalysis*; Jacobsen, E. N., Pfaltz, A., Yamamoto, H., Eds.; Springer-Verlag: Berlin, 1999, Vol. 1, pp 381−413. Beller, M.; Eckert, M. *Angew. Chem., Int. Ed.* **2000**, *39*, 1010. Bertoux, F.; Monflier, E.; Castanet, Y.; Mortreux, A. *J. Mol. Catal. A* **1999**, *143*, 11. El Ali, B.; Alper, H. *Synlett* **2000**, 161. Kiss, G. *Chem. Rev.* **2001**, *101*, 3435.

(2) For our recent papers on carbonylative cycloaddition reactions, see: (a) Morimoto, T.; Chatani, N.; Fukumoto, Y.; Murai, S. *J. Org. Chem.* **1997**, *62*, 3762. (b) Chatani, N.; Morimoto, T.; Fukumoto, Y.; Murai, S. *J. Am. Chem. Soc.* **1998**, *120*, 5335. (c) Chatani, N.; Morimoto, T.; Kamitani, A.; Fukumoto, Y.; Murai, S. *J. Organomet. Chem.* **1999**, *579*, 177. (d) Chatani, N.; Tobisu, M.; Asaumi, T.; Fukumoto, Y.; Murai, S. *J. Am. Chem. Soc.* **1999**, *121*, 7160. (e) Morimoto, T.; Chatani, N.; Murai, S. *J. Am. Chem. Soc.* **1999**, *121*, 1758. (f) Chatani, N.; Tobisu, M.; Asaumi, T.; Murai, S. *Synthesis* **2000**, 925. (g) Tobisu, M.; Chatani, N.; Asaumi, T.; Amako, Y.; Ie, Y.; Fukumoto, Y.; Murai, S. *J. Am. Chem. Soc.* **2000**, *122*, 12663. (h) Kamitani, A.; Chatani, N.; Morimoto, T.; Murai, S. *J. Org. Chem.* **2000**, *65*, 9230. (i) Chatani, N.; Kamitani, A.; Oshita, M.; Fukumoto, Y.; Murai, S. *J. Am. Chem. Soc.* **2001**, *123*, 12686.

(3) For our recent papers on direct carbonylation at C−H bonds, see: (a) Chatani, N.; Fukuyama, T.; Kakiuchi, F.; Murai, S. *J. Am. Chem. Soc.* **1996**, *118*, 493. (b) Chatani, N.; Ie, Y.; Kakiuchi, F.; Murai, S. *J. Org. Chem.* **1997**, *62*, 2604. (c) Fukuyama, T.; Chatani, N.; Kakiuchi, F.; Murai, S. *J. Org. Chem.* **1997**, *62*, 5647. (d) Chatani, N.; Ishii, Y.; Ie, Y.; Kakiuchi, F.; Murai, S. *J. Org. Chem.* **1998**, *63*, 5129. (e) Fukuyama, T.; Chatani, N.; Tatsumi, J.; Kakiuchi, F.; Murai, S. *J. Am. Chem. Soc.* **1998**, *120*, 11522. (f) Ie, Y.; Chatani, N.; Ogo, T.; Marshall, D. R.; Fukuyama, T.; Kakiuchi, F.; Murai, S. *J. Org. Chem.* **2000**, *65*, 1475. (g) Chatani, N.; Fukuyama, T.; Tatamidani, H.; Kakiuchi, F.; Murai, S. *J. Org. Chem.* **2000**, *65*, 4039. (h) Chatani, N.; Asaumi, T.; Ikeda, T.; Yorimitsu, S.; Kakiuchi, F.; Murai, S. *J. Am. Chem. Soc.* **2000**, *122*, 12882.

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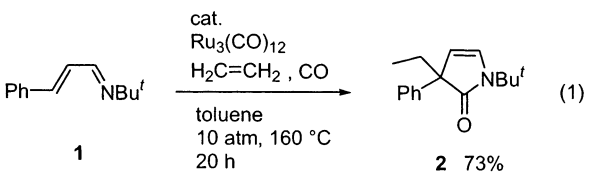
independent results on the $Ru_3(CO)_{12}$-catalyzed reaction of α,*β*-unsaturated imines with CO and alkenes and propose a reaction mechanism, which is different from that proposed by Imhof.[4]

Results and Discussions

The reaction of the α,*β*-unsaturated imine **1** (1 mmol), derived from the reaction of *trans*-cinnamaldehyde with *tert*-butylamine, with CO (initial pressure 10 atm at 25 °C) and ethylene (initial pressure 10 atm at 25 °C) in toluene (2 mL) in the presence of a catalytic amount of $Ru_3(CO)_{12}$ (0.02 mmol) at 160 °C for 20 h gave a 2,3-dihydro-1-(1,1-dimethylethyl)-3-ethyl-3-phenyl-2*H*-pyrrol-2-one (**2**)[5] in 73% isolated yield (eq 1). Prior to carrying out the reaction, we anticipated that the reaction of α,*β*-unsaturated imines with CO and ethylene would give cyclopentadienones, which would be unstable under the reaction conditions, via a path similar to that for aromatic imines as shown in Scheme 1. The reaction was clean, and the anticipated cyclopentadienone or *γ*-lactam, which is formed via a [4 + 1] cycloaddition of **1** and CO,[2b] was not observed either by GC or by TLC.

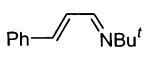
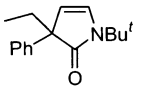
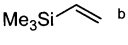
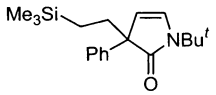
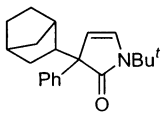
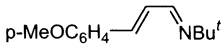
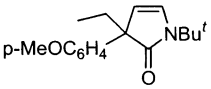
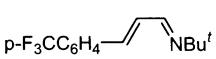
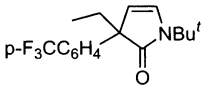
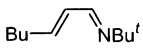
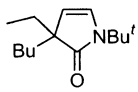
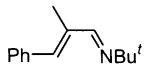
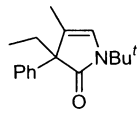


(1)

The use of vinylsilane and norbornene as the alkene partners in place of ethylene also gave the corresponding lactams, **3** and **4**, in high yields, as shown in Table 1. C−C bond formation must occur from the exo-face of norbornene, although we were not able to absolutely confirm face selectivity in the reaction of **1** with norbornene. The reaction of **1** with a terminal alkene such as hexene failed.[6] The substitution of an electron-withdrawing group on the phenyl ring, as in **7**, led to a low conversion. The reaction of an imine, which contains an alkyl group at the *β*-position, as in **9**, gave the corresponding lactam **10** in low yield because of the low efficiency of carbonylation at C−H bond.[7]

A proposed reaction mechanism is shown in Scheme 2. The key step involves the initial formation of ketones by direct carbonylation at C−H bonds. The mechanism is essentially the same as that proposed for the direct carbonylation at C−H bonds in phenylpyridines,[3b] aromatic imines,[3c] and phenyl oxazolines.[3f] An aza-metallacycle **14** (**C** in Scheme 1) is formed as an intermediate by the oxidative cyclization of the imine with ruthenium via the coordination of the sp^2 nitrogen to ruthenium, as in **13** (**B** in Scheme 1). Complex **14** undergoes a 1,2-hydride shift to give a ruthenium hydride complex **15** (**D** in Scheme 1) in which the insertion of ethylene and CO followed by reductive elimination occurs to give *β*-propionyl-α,*β*-unsaturated imine **17**. Nucleophilic attack of the intramolecular imine nitrogen on the ketonic carbon in **17** generates a tetrahedral intermediate **18**, which undergoes a 1,2-ethyl migration to give the final product **19**. We propose that **14** is in equilibrium with **15**, which can be controlled by the reaction conditions. The insertion of CO takes place in the metallacycle **14** to give a [4 + 1] cycloaddition product in the absence of ethylene.[2e] When the reaction is carried out in the presence of ethylene, the reaction of **15** with ethylene is more rapid than the insertion of CO into **14**, leading to the formation of **17**,

TABLE 1. $Ru_3(CO)_{12}$-Catalyzed Reaction of α,*β*-Unsaturated Imines with CO and Alkenes[a]

imine	alkene	γ-lactam [c]
 **1**	$H_2C=CH_2$	 **2** 73%
1	 [b]	 **3** 72%
1	 [b]	 **4** 44%
 **5**	$H_2C=CH_2$	 **6** 68%
 **7**	$H_2C=CH_2$	 **8** 27%
 **9**	$H_2C=CH_2$	 **10** 35%
 **11**	$H_2C=CH_2$	 **12** 75%

[a] Reaction conditions: imine (1 mmol), ethylene (10 atm), CO (initial pressure 10 atm at 25 °C), $Ru_3(CO)_{12}$ (0.02 mmol) in toluene (2 mL) at 160 °C for 20 h in a 50 mL stainless autoclave, unless otherwise noted. [b] Alkene (5 mmol) was used. [c] Isolated yield based on the imine used.

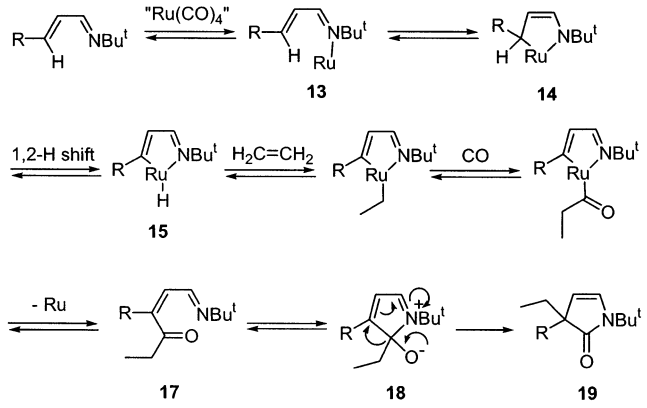
(4) (a) Berger, D.; Imhof, W. *Chem. Commun.* **1999**, 1457. (b) Berger, D.; Imhof, W. *Tetrahedron* **2000**, *56*, 2015. (c) Göbel, A.; Imhof, W. *Chem. Commun.* **2001**, 593. (d) Imhof, W.; Berger, D.; Kötteritzsch, M.; Rost, M.; Schönecker, B. *Adv. Synth. Catal.* **2001**, *343*, 795.

(5) All new compounds were characterized by NMR, IR, mass spectral data, and either elemental analyses or high-resolution mass spectra. For detailed data, see Supporting Information.

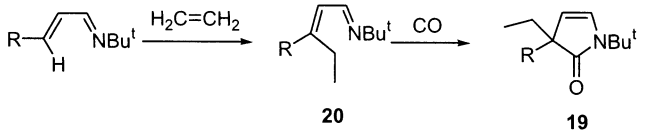
(6) These experimental results are consistent with a direct carbonylation at the ortho C−H bonds in the present reaction. In all carbonylation reactions at ortho C−H bonds reported thus far, hexene was found to be unreactive. See refs 3b, 3c, and 3f.

(7) A similar trend was observed for the $Ru_3(CO)_{12}$-catalyzed reaction of pyridyl olefins with CO and alkenes. See ref 3d.

SCHEME 2. Our Proposed Reaction Mechanism



SCHEME 3. Alternative Mechanism

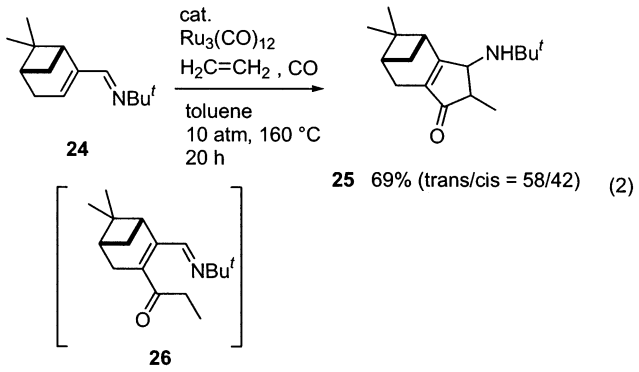


which affords **19** via an irreversible 1,2-ethyl shift. If aldol-type condensation takes place in **17**, cyclopentadienone derivatives could be formed. However, this was not the case because of the instability of cyclopentadienones.

Another alternative mechanism involves ethylation at the β-carbon followed by carbonylative [4 + 1] cycloaddition (Scheme 3). This mechanism may be legitimately proposed because we have already reported that the reaction of aromatic imines with alkenes under *nitrogen* in the presence of $Ru_3(CO)_{12}$ results in the addition of ortho C−H bonds across the alkene double bond[8] and the step **20** − **19** ([4 + 1] cycloaddition)[2e] could also be achieved using $Ru_3(CO)_{12}$. However, we found that the alkylation of C−H bonds in imines and oxazolines (related path to **20**) does not proceed effectively, even when carried out under an atmosphere of CO.[9,10] Moreover, the reaction of β,β-disubstituted imines with CO leading to the formation of lactams (the step **20** − **19**) require higher reaction temperatures.[11] Thus, the reaction does not effectively proceed to give the corresponding lactams under the present reaction conditions (160 °C). Consequently, we conclude that this mechanism is not likely to be valid for the present reaction.

Imhof proposed the following reaction mechanism.[4] Carbonylation at a C−H bond at the β-position takes place to give an aldehyde **21**. An intramolecular attack by the nitrogen on the aldehyde carbon gives **22**, which undergoes a 1,2-hydride shift to give the β,γ-unsaturated lactam **23**. The subsequent insertion of ethylene into the C−H bond α to the carbonyl group in **23** gives the final product **19**. This possibility can be ruled out for the following reasons. Direct carbonylation at C−H bonds leading to aldehydes is an endothermic process,[12] indicating that this process is catalytically unfavorable under thermal conditions. In addition, there is no precedent to indicate the addition of a C−H bond α to the ketone across alkenes occurs except for a combination of active methylene compounds and activated alkenes, such as acrylic esters.[13] They cited our paper as the reference paper for the conversion of **23** to **19**.[14] However, this is not an appropriate citation because our work was concerned with the addition of C−H bonds at the ortho position on the phenyl ring in aromatic ketones but not at the α position of ketones. Since it is reasonable to assume that the isomerization of a β,γ-unsaturated lactam **23** to an α,β-unsaturated isomer would be expected to be a fast process, **23** does not have a sufficiently long lifetime to permit it to react with ethylene under the reaction conditions employed (160 °C).

In the reaction of aromatic imines with CO and ethylene, ethyl aryl ketones (related to **17**) were isolable as a major reaction product when five-membered heteroaromatic imines were used as the substrate.[3c] On the basis of this finding, we would have expected that an ethyl ketone would be isolated when cyclic imines are used as a substrate. Interestingly, the reaction of imine **24** did not give the expected ethyl ketone, but instead, **25** was obtained as the main product (eq 2). The ketone **25** was apparently formed by an aldol-type condensation of the initially formed ketone **26**. No lactam was obtained in this reaction. We have no explanation for why the nitrogen does not attack the carbonyl group in **26** to give a lactam, but this result suggests the initial formation of an ethyl ketone in the $Ru_3(CO)_{12}$-catalyzed reaction of α,β-unsaturated imines with CO and ethylene.



(2)

The reaction of **27** also provides clear evidence for the intermediacy of a ketone as the initial product (eq 3). The reaction of **27** gave the tricyclic compound **28** as the sole isolable product. The intramolecular attack on the initial product **29** gives a tetrahedral intermediate **30**, which undergoes deprotonation to give **31** prior to a 1,2-ethyl

(8) Kakiuchi, F.; Yamauchi, M.; Chatani, N.; Murai, S. *Chem. Lett.* **1996**, 111. Kakiuchi, F.; Sato, T.; Yamauchi, M.; Chatani, N.; Murai, S. *Chem. Lett.* **1999**, 19.

(9) When the reaction of aromatic imines or oxazolines with ethylene was carried out even at a pressure of 1 atm of CO in the presence of $Ru_3(CO)_{12}$ as the catalyst, ethylation was accompanied by carbonylation and some side reactions. Unpublished results.

(10) Imhof also observed an unseletive reaction. Berger, D.; Gobel, A.; Imhof, W. *J. Mol. Catal. A* **2001**, *165*, 37.

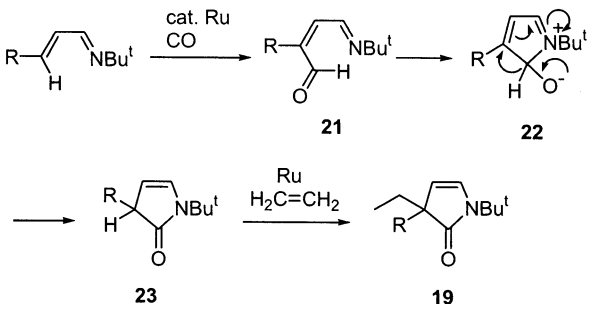
(11) The reaction of β,β-disubstituted imines with CO required at least 180 °C for the reaction to reach completion. When the reaction was carried out at 160 °C, the yields were dramatically decreased. See ref 2b. In addition, the presence of ethylene was found to inhibit the [4 + 1] cycloaddition of α,β-unsaturated imines and CO.

(12) Fisher, B. J.; Eisenberg, R. *Organometallics* **1983**, *2*, 764.

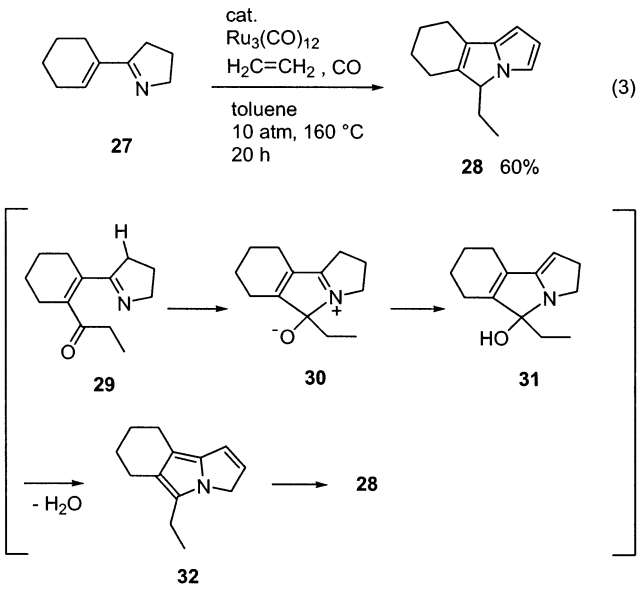
(13) The transition-metal-catalyzed Michael addition of active methylene compounds and activated alkenes is well-known. For a recent review; see: Christoffers, J. *Eur. J. Org. Chem.* **1998**, *1259*, 9.

(14) Sonoda, M.; Kakiuchi, F.; Chatani, N.; Murai, S. *Bull. Chem. Soc. Jpn.* **1997**, *70*, 3117.

SCHEME 4. Mechanism Proposed by Imhof[6]



shift. Dehydration takes place in **31** to afford a tricyclic compound **32**, which undergoes double bond isomerization to afford the more stable isomer **28**. The formation of **28** clearly excludes the possibility of an alternative reaction mechanism such as that shown in Schemes 3 and 4.



Summary

We demonstrate here the $Ru_3(CO)_{12}$-catalyzed carbonylation of α,β-unsaturated imines with CO and alkenes. The results suggest that the reaction proceeds via the initial formation of ketone derivatives, produced by direct carbonylation at the β-vinylic C−H bonds of α,β-unsaturated imines. An intramolecular attack by the imino nitrogen on the carbonyl group followed by a 1,2-shift of the ethyl group then gives the final product. A [4 + 1] cycloaddition of α,β-unsaturated imines and CO did not compete with the present reaction. The presence of ethylene inhibits the [4 + 1] cycloaddition.

Experimental Section

Materials. Toluene was distilled from CaH_2 prior to use. $Ru_3(CO)_{12}$ was prepared according to a literature procedure[15] and was used after recrystallization from hexane. Aldimines **1**, **5**, **7**, **9**, **11**, and **24** were prepared by the treatment of the corresponding aldehydes with *tert*-butylamine in the presence of $MgSO_4$[16] and were used after distillation. Cyclic ketimine **27** was prepared by the reaction of methyl 1-cyclohexene-1-carboxylate with 1-vinyl-2-pyrrolidinone using a modification of the method described by Cosford.[17]

2-Methyl-*N*-[3-(4-methoxyphenyl)-2-propenylidene]-2-propanamine (5).[18] Yellow oil; ^{1}H NMR ($CDCl_3$) δ 1.25 (s, 9H), 3.79 (s, 3H), 6.79−6.92 (m, 4H), 7.40 (d, J = 7.0 Hz, 2H), 8.00 (d, J = 7.6 Hz, 1H); ^{13}C NMR ($CDCl_3$) δ 29.7, 55.2, 56.9, 114.0, 127.0, 128.3, 128.5, 140.4, 157.2, 160.0; MS, *m/z* (relative intensity, %) 217 (M^+, 20), 160 (100).

2-Methyl-*N*-[3-(4-trifluoromethylphenyl)-2-propenylidene]-2-propanamine (7). Pale yellow oil; bp 120−125 °C/(0.1 mmHg); ^{1}H NMR ($CDCl_3$) δ 1.27 (s, 9H), 6.97 (s, 1H), 7.00 (s, 1H), 7.55 (d, J = 15.1 Hz, 2H), 7.61 (d, J = 15.1 Hz, 2H), 8.05 (dd, J = 1.6 Hz, J = 6.2 Hz, 1H); ^{13}C NMR ($CDCl_3$) δ 29.6, 57.4, 124.3 (q, J = 270.0 Hz, CF_3), 125.5 (complex), 127.0, 130.2 (q, J = 32.2 Hz), 131.5, 138.8, 139.2, 156.5; IR (KBr) 1622 s; MS, *m/z* (relative intensity, %) 255 (M^+, 3), 57 (100); exact mass calcd for $C_{14}H_{16}F_3N$ 255.1235, found 255.1231.

Typical Procedure. A 50 mL stainless autoclave was charged with *N*-*tert*-butyl-*trans*- cinnamaldimine (**1**) (1 mmol, 187 mg), toluene (2 mL), and $Ru_3(CO)_{12}$ (0.02 mmol, 13 mg). After flushing the system with 10 atm of ethylene three times, it was pressurized with ethylene to 10 atm and then with an additional 10 atm of carbon monoxide. The autoclave was immersed in an oil bath at 160 °C. After 20 h had elapsed, the autoclave was removed from the oil bath and allowed to cool for 1 h. The gases were then released. The contents were transferred to a round-bottomed flask with ether and the volatiles removed in vacuo. The residue was subjected to column chromatography on silica gel (eluent; hexane/EtOAc = 4/1) to give 2,3-dihydro-1-(1,1-dimethylethyl)-3-ethyl-3-phenylpyrrol-2-one (**2**) (180 mg, 74% yield) as a clear oil.

2,3-Dihydro-1-(1,1-dimethylethyl)-3-ethyl-3-phenylpyrrol-2-one (2).[6b] Clear oil; R_f 0.61 (hexane/EtOAc = 2/1); ^{1}H NMR ($CDCl_3$) δ 0.81 (t, J = 7.3 Hz, 3H), 1.43 (s, 9H), 1.88−2.09 (m, 2H), 5.50 (d, J = 6.1 Hz, 1H), 6.72 (d, J = 6.1 Hz, 1H), 7.16−7.31 (m, 3H), 7.42−7.46 (m, 2H); ^{13}C NMR ($CDCl_3$) δ 9.1, 28.1, 31.3, 54.3, 58.9, 111.8, 126.3, 126.5, 128.1, 130.1, 140.3, 179.7; MS, *m/z* (relative intensity, %) 243 (M^+, 16), 158 (100).

2,3-Dihydro-1-(1,1-dimethylethyl)-3-phenyl-3-(2-trimethylsilylethyl)pyrrol -2-one (3). Yellow solid; mp 48−49 °C (hexane); R_f 0.73 (hexane/EtOAc = 3/1); ^{1}H NMR ($CDCl_3$) δ 0.00 (s, 9H), 0.37−0.46 (m, 2H), 1.48 (s, 9H), 1.92−1.98 (m, 2H), 5.57 (d, J = 5.4 Hz, 1H), 6.77 (d, J = 5.4 Hz, 1H), 7.21−7.36 (m, 3H), 7.48−7.52 (m, 2H); ^{13}C NMR ($CDCl_3$) δ −1.8, 11.1, 28.3, 33.4, 54.3, 60.0, 111.9, 126.5, 126.6, 128.2, 130.2, 140.3, 179.8; IR (KBr) 1690 s; MS, *m/z* (relative intensity, %) 315 (M^+, 0.1), 73 (100). Anal. Calcd for $C_{19}H_{29}NOSi$: C, 72.32; H, 9.26; N, 4.44. Found: C, 72.19; H, 9.10; N, 4.45.

2,3-Dihydro-3-(bicyclo[2,2,1]hept-2-yl)-1-(1,1-dimethylethyl)-3-phenylpyrrol-2-one (4). The ^{1}H and ^{13}C NMR spectra and IR data were obtained as a mixture of two isomers. Pale yellow solid; R_f 0.57, 0.49 (hexane/EtOAc 2/1); ^{1}H NMR ($CDCl_3$) δ 0.85−1.29 (m, 8H), [1.32 (major isomer), 1.35 (minor isomer), s, 9H, CCH_3], 1.85 (bs, 1H), 2.04−2.10 (m, 1H), 2.25−2.36 (m, 1H), [5.45 (d, J = 5.1 Hz, major isomer), 5.46 (d, J = 5.1 Hz, minor isomer), 1H, 4-CH], [6.65 (d, J = 5.1 Hz, major isomer), 6.67 (d, J = 5.1 Hz, minor isomer), 1H, 5-CH], 7.10−7.24 (m, 3H), 7.41−7.47 (m, 2H); ^{13}C NMR ($CDCl_3$) δ [28.0 (minor isomer), 28.3 (major isomer), CCH_3], 31.2, 31.7, 33.4, 35.2, 36.2, 36.8, 37.0, 38.0, 38.2, 38.5, 49.6, 50.0, 54.3, 54.4, 61.5, 61.7, [110.0 (major isomer), 110.2 (minor isomer), 4-C], 126.5, 127.0, 127.1, 127.9, 128.1, [129.9 (minor isomer), 130.4 (major isomer), 5-C], 139.6, [179.4 (major isomer), 179.9 (minor isomer), 2-C]; IR (KBr) 1692 s; MS, *m/z* (relative intensity, %)

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for major isomer 309 (M^+, 0.56), 159 (100), for minor isomer 309 (M^+, 0.68), 159 (100); exact mass calcd for $C_{21}H_{27}NO$ 309.2093, found 309.2092 (major isomer), 309.2074 (minor isomer).

2,3-Dihydro-1-(1,1-dimethylethyl)-3-ethyl-3-(4-methoxyphenyl)pyrrol-2-one (6). Pale yellow solid; mp 72−73 °C (hexane); R_f 0.50 (hexane/EtOAc 3/1); ^{1}H NMR ($CDCl_3$) δ 0.72 (t, J = 7.3 Hz, 3H), 1.38 (s, 9H), 1.76−1.98 (m, 2H), 3.68 (s, 3H), 5.42 (d, J = 5.1 Hz, 1H), 6.65 (d, J = 5.1 Hz, 1H), 6.76 (d, J = 9.2 Hz, 2H), 7.28 (d, J = 9.2 Hz, 2H); ^{13}C NMR ($CDCl_3$) δ 9.2, 28.3, 31.4, 54.4, 55.1, 58.4, 112.1, 113.6, 127.5, 130.0, 132.5, 158.2, 180.2; IR (KBr) 1682 s; MS, *m*/*z* (relative intensity, %) 273 (M^+, 18), 188 (100). Anal. Calcd for $C_{17}H_{23}NO_2$: C, 74.69; H, 8.48; N, 5.12. Found: C, 74.57; H, 8.43; N, 5.09.

2,3-Dihydro-1-(1,1-dimethylethyl)-3-ethyl-3-(4-trifluoromethylphenyl)-pyrrol-2-one (8). Clear oil; R_f 0.56 (hexane/EtOAc 3/1); ^{1}H NMR ($CDCl_3$) δ 0.71 (t, J = 7.3 Hz, 3H), 1.37 (s, 9H), 1.84−1.99 (m, 2H), 5.45 (d, J = 5.4 Hz, 1H), 6.71 (d, J = 5.4 Hz, 1H), 7.45−7.52 (m, 5H); ^{13}C NMR ($CDCl_3$) δ 9.0, 28.2, 31.5, 54.6, 59.1, 111.3, 124.2 (q, J = 271.0 Hz, CF_3), 125.0−125.6 (complex, Ar), 127.1, 129.0 (q, J = 32.4 Hz, Ar), 131.0, 144.6, 179.4; IR (neat) 1698 s; MS, *m*/*z* (relative intensity, %) 311 (M^+, 4), 57 (100); exact mass calcd for $C_{17}H_{20}F_3NO$ 311.1497, found 311.1486.

2,3-Dihydro-3-butyl-1-(1,1-dimethylethyl)-3-ethylpyrrol-2-one (10). Clear oil; R_f 0.60 (hexane/EtOAc 3/1); ^{1}H NMR ($CDCl_3$) δ 0.71 (t, J = 7.3 Hz, 3H), 0.84 (t, J = 7.0 Hz, 3H), 0.99−1.29 (m, 4H), 1.44 (s, 9H), 1.46−1.68 (m, 4H), 5.08 (d, J = 2.7 Hz, 1H), 6.61 (d, J = 2.7 Hz, 1H); ^{13}C NMR ($CDCl_3$) δ 8.7, 14.0, 23.1, 26.5, 28.3, 29.8, 36.5, 54.2, 56.1, 111.8, 129.6, 181.9; IR (neat) 1698 s; MS, *m*/*z* (relative intensity, %) 223 (M^+, 5), 110 (100). Anal. Calcd for $C_{14}H_{25}NO$: C, 75.28; H, 11.28; N, 6.27. Found: C, 75.00; H, 11.13; N, 6.14.

2,3-Dihydro-1-(1,1-dimethylethyl)-3-ethyl-4-methyl-3-phenylpyrrol-2-one (12). Clear oil; R_f 0.49 (hexane/EtOAc 3/1); ^{1}H NMR ($CDCl_3$) δ 0.78 (t, J = 7.6 Hz, 3H), 1.47 (s, 9H), 1.56 (d, J = 1.6 Hz, 3H), 1.81−1.94 (m, 1H), 2.21−2.34 (m, 1H), 6.46 (d, J = 1.6 Hz, 1H), 7.18−7.32 (m, 5H); ^{13}C NMR ($CDCl_3$) δ 8.3, 10.9, 25.5, 28.3, 54.2, 61.3, 120.6, 125.1, 126.2, 126.6, 128.3, 139.7, 180.4; IR (neat) 1698 s; MS, *m*/*z* (relative intensity, %) 257 (M^+, 13), 172 (100). Anal. Calcd for $C_{17}H_{23}NO$: C, 79.33; H, 9.01; N, 5.44. Found: C, 79.05; H, 8.84; N, 5.30.

2,3,4,5,6,7-Hexahydro-3-(1,1-dimethylethylamino)-2,5,5-trimethyl-1*H*-4,6- methanoinde-1-one (25). The reaction of imine **24** gives two isomers of **25**. For one isomer: White solid; mp 80−82 °C (hexane); R_f 0.24 (hexane/EtOAc 3/1); ^{1}H NMR ($CDCl_3$) δ 0.70 (s, 3H), 1.06 (s, 9H), 1.12 (d, J = 6.2 Hz, 1H), 1.17 (d, J = 7.6 Hz, 3H), 1.34(s, 3H), 2.15 (dq. J = 7.6 Hz, J = 1.2 Hz, 1H), 2.20−2.24 (m, 1H), 2.29−2.33 (m, 2H), 2.44−2.48 (m, 1H), 2.50−2.58 (m, 1H), 3.36 (bs, 1H); ^{13}C NMR ($CDCl_3$) δ 15.8, 21.6, 25.4, 26.0, 30.1, 31.6, 39.8, 40.2, 43.3, 50.4, 53.1, 60.7, 133.5, 184.3, 208.9; IR (KBr) 1694 s; MS, *m*/*z* (relative intensity, %) 261 (M^+, 21), 58 (100); exact mass calcd for $C_{17}H_{27}NO$ 261.2092, found 261.2087. For another isomer: White solid; mp 66−68 °C (hexane); R_f 0.07 (hexane/EtOAc 3/1); ^{1}H NMR ($CDCl_3$) δ 0.69 (s, 3H), 1.08 (s, 9H), 1.13 (d, J = 9.2 Hz, 1H), 1.17 (d, J = 7.6 Hz, 3H), 1.34(s, 3H), 2.10 (q. J = 7.6 Hz, 1H), 2.19−2.23 (m, 1H), 2.29−2.34 (m, 2H), 2.47−2.60 (m, 2H), 3.26 (bs, 1H); ^{13}C NMR ($CDCl_3$) δ 16.0, 21.0, 25.4, 26.1, 30.1, 31.6, 40.2, 40.4, 42.8, 50.6, 52.6, 62.1, 133.9, 184.4, 208.5; IR (KBr) 1694 s; MS, *m*/*z* (relative intensity, %) 261 (M^+, 19), 58 (100). Anal. Calcd for $C_{17}H_{27}NO$: C, 78.11; H, 10.41; N, 5.36. Found: C, 77.82; H, 10.14; N, 5.31.

6,7,8,9-Tetrahydro-5-ethyl-5*H*-pyrrolo[2,1-a]isoindole (28). Dark brown oil; R_f 0.67 (hexane/EtOAc 3/1); ^{1}H NMR ($CDCl_3$) δ 0.67 (t, J = 7.3 Hz, 3H), 1.67−1.80 (m, 5H), 1.82−2.00 (m, 1H), 2.18−2.20 (m, 2H), 2.33−2.39 (m, 2H), 4.33 (bs, 1H), 5.77 (d, J = 3.2 Hz, 1H), 6.20 (dd, J = 3.2 Hz, J = 2.7 Hz, 1H), 6.80 (d, J = 2.7 Hz, 1H); ^{13}C NMR ($CDCl_3$) δ 7.6, 21.9, 22.4, 22.8, 23.2, 25.6, 64.8, 94.0, 110.4, 115.1, 120.1, 137.4, 142.2; IR (neat) 2928 s, 1470 m; MS, *m*/*z* (relative intensity, %) 187 (M^+, 72), 172 (100). Anal. Calcd for $C_{13}H_{17}N$: C, 83.37; H, 9.15; N, 7.48. Found: C, 83.17; H, 9.00; N, 7.46.

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Supporting Information Available: Text listing full characterization of all of new compounds obtained and figures showing ^{1}H NMR spectra for aldimine **7**, products **4**, **8**, and **25**. This material is available free of charge via the Internet at http://pubs.acs.org.

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