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DIRECT CATALYTIC ASYMMETRIC VINYLOGOUS MICHAEL REACTION OF α,β-UNSATURATED γ-BUTYROLACTAM UNDER DINUCLEAR NICKEL SCHIFF BASE CATALYSIS

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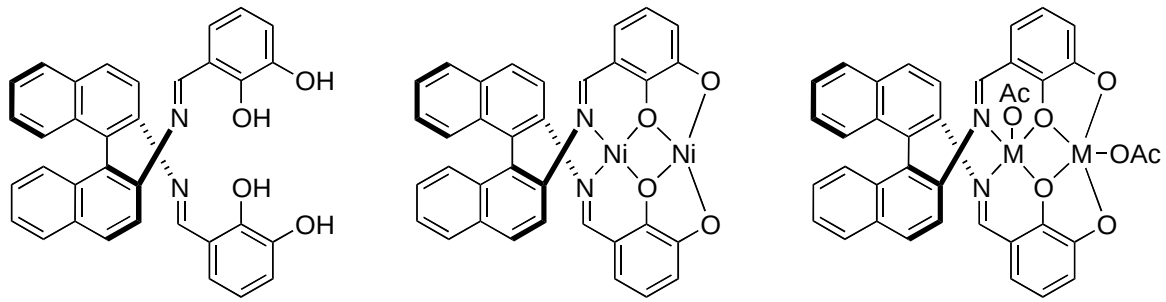
This paper is dedicated to Professor Ei-ichi Negishi on the occasion of his 77th birthday.

Abstract – Direct catalytic asymmetric vinylogous Michael reaction is described. 2.5 mol % of homobimetallic (*S*)-Ni_2-Schiff base complex efficiently catalyzed the addition of α,β-unsaturated γ-butyrolactam to nitroalkenes under simple proton transfer conditions, giving vinylogous Michael products in 83-99% yield, 16:1->30:1 dr, and 96-99% ee.

INTRODUCTION

Chiral butyrolactams are ubiquitous heterocyclic structural motifs found in many natural products and biologically active compounds, e.g. lactacystin,[1] a proteasome inhibitor, and A-315675,[2] an anti-influenza agent. The synthetic utility of these compounds has led to the development of various methods to synthesize chiral butyrolactams.[3] Catalytic asymmetric vinylogous reactions of α,β-unsaturated γ-butyrolactams can be a very powerful and straightforward method for stereoselective synthesis of versatile building blocks towards functionalized chiral butyrolactams. In contrast to related γ-butenolides,[4] however, catalytic asymmetric vinylogous reactions using α,β-unsaturated γ-butyrolactams remained unexplored until Suga and Kekehi's pioneering work in 2007.[5] Suga and Kekehi used preformed 2-siloxypyrroles as latent enolates to establish a Lewis acid-catalyzed enantioselective vinylogous Mukaiyama-type Michael reaction. Casiraghi, Zanardi, and Curti *et al.* also recently reported efficient Lewis base- and Lewis acid-catalyzed highly enantioselective vinylogous

reactions.[6] In terms of atom-economy, however, a *direct* vinylogous addition of α,β-unsaturated γ-butyrolactams under simple proton transfer conditions would be more favorable. To address this issue, we and others recently reported bifunctional metal- and organo-catalyzed enantioselective vinylogous Michael and Mannich-type reactions.[7,8] In this article, we describe the full details of our work on a direct catalytic asymmetric vinylogous Michael reaction of nitroalkenes under bimetallic Schiff base **1** catalysis (Figure 1).



(*S*)-Schiff base **1**-H_4 (*S*)-Ni_2-**1** complex M = Co(III): (*S*)-Co_2-**1** cat.
M = Mn(III): (*S*)-Mn_2-**1** cat.

Figure 1. Structures of dinucleating Schiff base (*R*)-**1**-H_4, and bimetallic Schiff base complexes

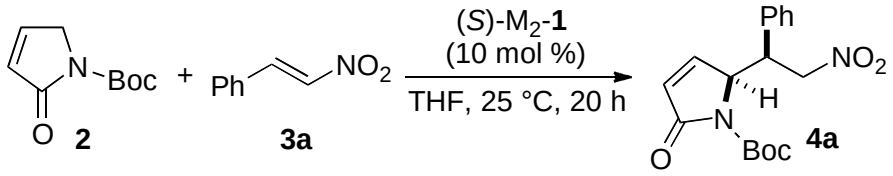
RESULTS AND DISCUSSION

The direct vinylogous reaction with α,β-unsaturated γ-butyrolactam **2** first requires the chemoselective activation of **2** as a donor. Electrophilic activation of the α,β-unsaturated γ-butyrolactam unit in both **2** and the vinylogous Michael products leads to undesirable side reaction such as polymerization, and must therefore be avoided. Chemoselective deprotonation from pro-nucleophile **2** while suppressing undesirable deprotonation from vinylogous Michael products is also important because epimerization of the products decreases the diastereoselectivity. These points must be carefully considered, in addition to kinetic control of the enantioselectivity, diastereoselectivity, and α/γ-selectivity of the metal dienolate. Among acid/base bifunctional catalysts developed in our group,[9] bimetallic Schiff base **1** catalysts,[10-14] used for catalytic deprotonation of the α-proton in carbonyl donors, showed promising results in the present vinylogous Michael reactions. Optimization studies using α,β-unsaturated γ-butyrolactam **2** and nitroalkene **3a** are summarized in Table 1 and Table 2.

To select a suitable catalyst for the vinylogous reaction of **2**, we screened several metals as shown in Table 1. We first utilized dinuclear Co_2-**1**[10] and Mn_2-**1**[11] complexes, which have been used for Michael reactions to nitroalkenes with β-keto esters and *N*-Boc oxindoles as donors. Use of the Co_2-**1** and Mn_2-**1** complexes (entries 1-2) resulted in good diastereoselectivity, but the yield and enantioselectivity were only moderate. On the other hand, the use of a dinuclear Ni_2-**1** complex[12] gave promising results, affording product **4a** in 64% yield, 30:1 dr, and 91% ee in THF at 25 °C (entry 3). No α-adduct was

detected in entry 3. Other bimetallic catalysts, such as Zn_2-**1**, and Cu_2-**1** complexes resulted in poor reactivity (entries 4-5).

Table 1. Metal Effects

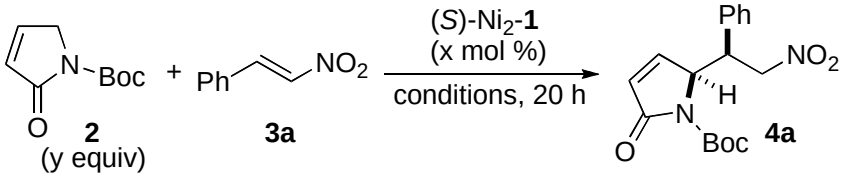


entry	cat.	% yield [a]	dr[a] *syn*:*anti*	% ee[b]
1	Co_2-**1**	28	20:1	47
2	Mn_2-**1**	28	8:1	50
3	Ni_2-**1**	64	30:1	91
4	Cu_2-**1**	trace	N.D.	N.D.
5	Zn_2-**1**	trace	N.D.	N.D.

Footnote [a] Determined by ^{1}H NMR analysis of crude mixture. [b] Determined by chiral stationary-phase HPLC analysis using CHIRALPAK IC.

To further improve the reactivity and enantioselectivity, we further optimized the reaction conditions using Ni_2-**1** catalysts, as summarized in Table 2. Among the solvents screened (entries 1-7), 1,4-dioxane gave the best diastereoselectivity and enantioselectivity (entry 3). Other solvents resulted in less satisfactory reactivity and/or selectivity. Increasing the amount of donor **2** improved the yield to some extent (entries 8-9). With 2 equiv of donor **2**, catalyst loading was reduced to 2.5 mol %, giving the product **4a** in 85% yield, >30:1 dr, and 95% ee after 20 h (entry 10). To accelerate the reaction, molecular sieves were added in entries 11-12,[15] but this resulted in less satisfactory reactivity and selectivity. Raising the reaction temperature to 50 °C improved the reactivity, and product **4a** was obtained in quantitative conversion after 13 h (entry 13, 98% isolated yield). It is noteworthy that high enantioselectivity was maintained even at an elevated temperature (entry 9: 95% ee vs entry 13: 97% ee). When catalyst loading was further reduced to 1.0 mol %, the reaction did not complete even when the reaction time was prolonged (36 h), and the stereoselectivity was slightly decreased (entry 14). Thus, we selected the conditions in entry 13 as optimum.

Table 2. Optimization of Reaction Conditions

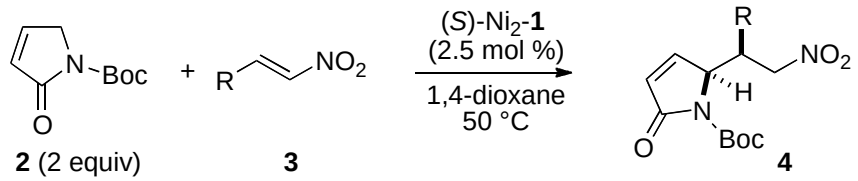


entry	cat. (x mol %)	solvent	**2** (y equiv)	additive	temp (°C)	time (h)	% yield [a]	dr[a] *syn*:*anti*	% ee[b]
1	10	THF	1.1	none	25	20	64	30:1	91
2	10	Et_2O	1.1	none	25	20	44	>30:1	92
3	10	1,4-dioxane	1.1	none	25	20	64	>30:1	96
4	10	*i*Pr_2O	1.1	none	25	20	trace	N. D.	60
5	10	MeCN	1.1	none	25	20	7	8:1	70
6	10	toluene	1.1	none	25	20	30	>30:1	69
7	10	CH_2Cl_2	1.1	none	25	20	10	>30:1	88
8	10	1,4-dioxane	1.5	none	25	20	75	>30:1	96
9	10	1,4-dioxane	2.0	none	25	20	88	>30:1	95
10	2.5	1,4-dioxane	2.0	none	25	20	85	>30:1	95
11	2.5	1,4-dioxane	2.0	MS 4Å	25	20	66	>30:1	94
12	2.5	1,4-dioxane	2.0	MS 5Å	25	20	58	>30:1	92
13	2.5	1,4-dioxane	2.0	none	50	13	98[c]	>30:1	97
14	1.0	1,4-dioxane	2.0	none	50	36	84[c]	29:1	93

Footnote [a] Determined by ^{1}H NMR analysis of crude mixture. [b] Determined by chiral stationary-phase HPLC analysis using CHIRALPAK IC. [c] Isolated yield after purification by column chromatography.

The substrate scope of the reaction under optimized reaction conditions with homodinuclear (*S*)-Ni_2-**1** is summarized in Table 3. β-Aryl-substituted nitroalkenes with either an electron-withdrawing group or an electron-donating group gave the products in high yield with high stereoselectivity (entries 2-4). Notably, sterically-hindered 2-bromo-substituted nitroalkene **3c** also showed good reactivity and enantioselectivity, although the diastereoselectivity was somewhat decreased (entry 3, 16:1 dr). β-Heteroaryl-substituted nitroalkenes **3e** and **3f** also gave comparably high reactivity and selectivity (entries 5-6). As for β-alkyl-substituted nitroalkenes, both linear and branched nitroalkenes **3g** and **3h** gave the products in good yield and with high selectivity, although a slightly longer reaction time (24 h) was required (entries 7-8). Nitrodiene **3i** was also applicable, giving predominantly the 1,4-adduct in 83% yield, 25:1 dr, and 99% ee (entry 9). The absolute and relative configurations of product **4b** were unequivocally determined by X-ray crystallographic analysis (Figure 2),[16] and those of other products were assigned by analogy.

Table 3. Direct Catalytic Asymmetric Vinylogous Michael Reaction of an α,β-Unsaturated γ-Butyrolactam to Nitroalkenes[a]



2 (2 equiv) **3** **4**

entry	R: **3**		cat (x mol %)	time (h)	**4**	% yield[b]	dr[c]	% ee[d]
1	Ph-	**3a**	2.5	13	**4a**	98	>30:1	97
2	4-Br-C_6H_4-	**3b**	2.5	12	**4b**	96	29:1	99
3	2-Br-C_6H_4-	**3c**	2.5	11	**4c**	98	16:1	98
4	4-MeO-C_6H_4-	**3d**	2.5	25	**4d**	98	>30:1	98
5	2-furyl	**3e**	2.5	11	**4e**	98	>30:1	98
6	2-thienyl	**3f**	2.5	15	**4f**	99	>30:1	98
7	$PhCH_2CH_2$-	**3g**	2.5	24	**4g**	89	26:1	96
8	*i*-propyl	**3h**	2.5	24	**4h**	97	>30:1	99
9	(*E*)-Ph-CH=CH-	**3i**	2.5	16	**4i**	83	25:1	99

Footnote [a] Reaction was run using 2 equiv of **3** in 1,4-dioxane (0.15 M) at 50 °C. [b] Isolated yield after purification by column chromatography. [c] Determined by ^{1}H NMR analysis of crude mixture. [d] Determined by HPLC using chiral column IC, IB or AD-H. See experimental section for detail.

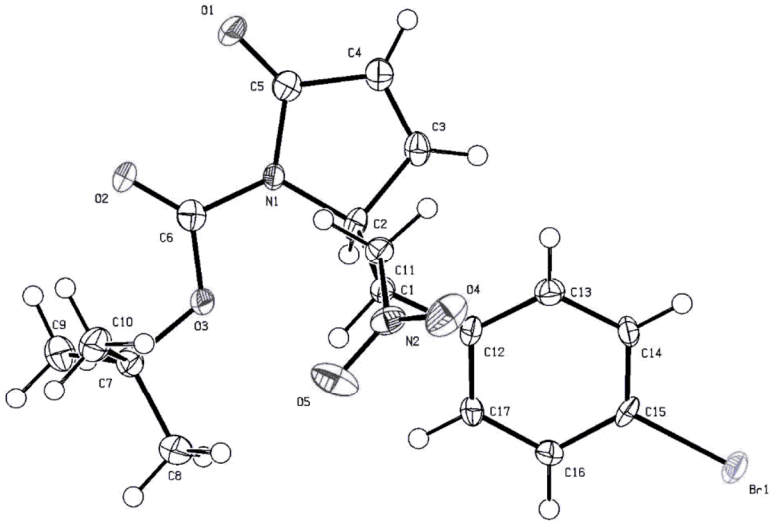


Figure 2. ORTEP plot of product **4b** (50% probability thermal ellipsoids).

The postulated catalytic cycle of the reaction under dinuclear nickel catalysis is shown in Figure 3. Based on previous studies of dinuclear Ni-catalysis,[12] we speculate that one of the Ni-O bonds in the outer O_2O_2

cavity works as a Brønsted base to deprotonate **2** and generate Ni-vinylogous enolate *in situ*. The other Ni in the inner N_2O_2 cavity functions as a Lewis acid to control the position of nitroalkenes **3**, similar to conventional metal-salen Lewis acid catalysis. The C-C bond-formation, followed by protonation, affords product **4** and regenerates the Ni_2-**1** catalyst. The high diastereoselectivity observed in Table 2 suggests that negligible undesired epimerization of the products occurred via deprotonation. A control experiment using γ-Me-substituted α,β-unsaturated γ-butyrolactam under the present Ni_2-**1** catalysis did not proceed, suggesting that the steric hindrance suppressed the epimerization by the Ni_2-**1** catalyst.

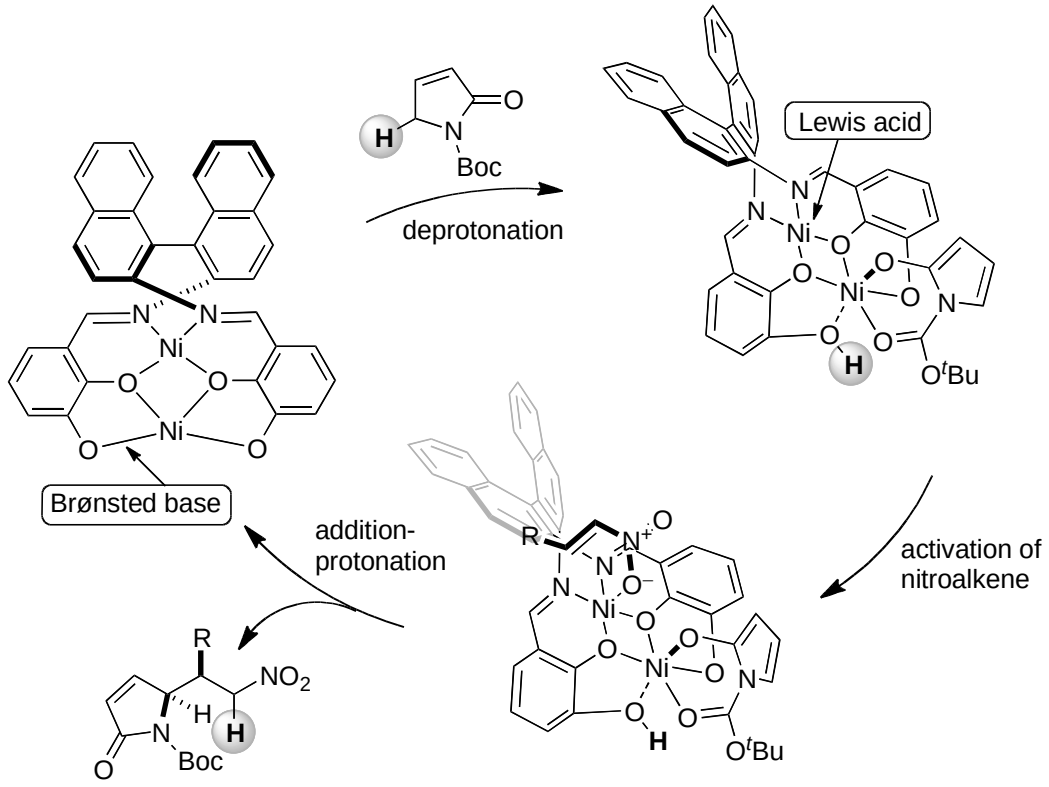


Figure 3. Postulated catalytic cycle of vinylogous Michael reaction under dinuclear Schiff base catalysis

In summary, we developed a highly enantio- and diastereoselective catalytic asymmetric vinylogous Michael reaction of α,β-unsaturated γ-butyrolactam to nitroalkenes. A homodinuclear Ni_2-Schiff base **1** complex was suitable for the reaction and vinylogous Michael adducts were obtained in 83-99% yield, 16:1->30:1 dr, and 96-99% ee.

EXPERIMENTAL

General: Infrared (IR) spectra were recorded on a JASCO FT/IR 410 Fourier transform infrared spectrophotometer. NMR spectra were recorded on JEOL ECX500 spectrometers, operating at 500 MHz for ^{1}H NMR and 125.65 MHz for ^{13}C NMR. Chemical shifts in $CDCl_3$ were reported in the scale relative

to tetramethylsilane (0 ppm) for ^{1}H NMR. For ^{13}C NMR, chemical shifts were reported in the scale relative to $CHCl_3$ (77.0 ppm) as an internal reference. Column chromatography was performed with silica gel Merck 60 (230-400 mesh ASTM). Optical rotations were measured on a JASCO P-1010 polarimeter. ESI mass spectra were measured on Waters micromass ZQ (for LRMS) and ESI mass spectra for HRMS were measured on a JEOL JMS-T100LC AccuTOF spectrometer. The enantiomeric excess (ee) was determined by HPLC analysis. HPLC was performed on JASCO HPLC systems consisting of the following: pump, PU-2080 plus; detector, UV-2075 plus, measured at 254 nm; column, DAICEL CHIRALPAK IC, IB or AD-H; mobile phase, hexane-*i*PrOH.

General Procedure for Direct Catalytic Asymmetric Vinylogous Michael Reaction of α,β-Unsaturated γ-Butyrolactam 2:

To a stirred solution of (*S*)-Ni_2-Schiff base **1** catalyst (4.8 mg, 7.5 μmol, 2.5 mol %) in 1,4-dioxane (2.0 mL) at room temperature were added successively α,β-unsaturated γ-butylolactam **2** (0.6 mmol) and nitroalkene **3** (0.3 mmol). The resulting mixture was stirred at 50 ºC for indicated time in Table 3. After cooling down to room temperature, silica gel (ca. 30 mg) suspension in EtOAc was added. The resulting suspension was stirred at room temperature for 15 min. Then, the mixture was filtrated to remove silica gel and the catalyst. The filtrate was concentrated under reduced pressure, and the residue was purified by silica gel flash column chromatography (hexane/ethyl acetate = 10/1 to 2/1) to give product **4**.

(*S*)-*tert*-Butyl 2-((*S*)-2-nitro-1-phenylethyl)-5-oxo-2,5-dihydro-1*H*-pyrrole-1-carboxylate (4a): Colorless solid; IR (KBr) ν 3097, 2979, 1775, 1696, 1556, 1362, 1274 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 1.66 (s, 9H), 4.48-4.56 (m, 1H), 4.64-4.74 (m, 2H), 4.87-4.90 (m, 1H), 6.18 (dd, *J* = 1.9, 6.1 Hz 1H), 7.03 (dd, *J* = 2.2, 6.1 Hz 1H), 7.27-7.45 (m, 5H); ^{13}C NMR ($CDCl_3$) δ 28.0, 43.8, 65.0, 73.2, 84.1, 127.6, 128.5, 128.6, 129.2, 134.8, 146.1, 149.2, 168.2; LRMS (ESI): *m/z* 355 $[M+Na]^+$; HRMS (ESI): *m/z* calculated for $C_{17}H_{20}N_2O_5Na^+$ $[M+Na]^+$: 355.1264, found: 355.1258; $[\alpha]_D^{24.0}$ –155 (*c* 0.93, $CHCl_3$); HPLC (DAICEL CHIRALPAK IC, EtOH, flow rate: 0.7 mL/min, detection at 254 nm) t_R 9.4 min (minor) and 13.8 min (major).

(*S*)-*tert*-Butyl 2-((*S*)-1-(4-bromophenyl)-2-nitroethyl)-5-oxo-2,5-dihydro-1*H*-pyrrole-1-carboxylate (4b): Colorless solid; IR (KBr) ν 3103, 2979, 2933, 1759, 1555, 1489, 1368, 1298, 1253, 1157, 1048, 1009, 822 cm^{-1}; ^{1}H NMR ($CDCl_3$, 500 MHz) δ 1.63 (s, 9H), 4.52 (dd, *J* = 4.7, 12.6 Hz, 1H), 4.56-4.60 (m, 1H), 4.66 (dd, *J* = 9.5, 12.6 Hz, 1H), 4.83-4.86 (m, 1H), 6.16 (dd, *J* = 1.7, 6.2 Hz, 1H), 7.00 (dd, *J* = 2.1, 6.2 Hz, 1H), 7.12-7.15 (m, 2H), 7.51-7.54 (m, 2H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 28.1, 43.5, 64.6, 73.3, 84.4, 122.6, 128.9, 129.3, 132.5, 133.8, 145.8, 149.5, 167.8; LRMS (ESI): *m/z* 433, 435 $[M+Na]^+$; HRMS

(FAB): *m/z* calculated for $C_{17}H_{19}Br^{81}N_2O_5Na^+$ $[M+Na]^+$: 435.0355, found: 435.0350; HPLC (chiral column: DAICEL CHIRALPAK IC, ethanol, flow rate: 0.4 mL/min, detection: at 254 nm): t_R = 15.1 min (*R,R*) and 24.1 min (*S,S*); $[\alpha]_D^{29.7} = -114$ (*c* 0.50, $CHCl_3$).

(*S*)-*tert*-Butyl 2-((*S*)-1-(2-bromophenyl)-2-nitroethyl)-5-oxo-2,5-dihydro-1*H*-pyrrole-1-carboxylate (4c): Colorless solid; IR (KBr) ν 3105, 2982, 2949, 1766, 1558, 1474, 1368, 1288, 1159, 1046, 829, 772, 729 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.65 (s, 9H), 4.66-4.75 (m, 2H), 5.10-5.16 (m, 2H), 6.10 (dd, *J* =1.6, 6.3 Hz, 1H), 6.98-7.01(m, 1 H), 7.10 (dd, *J* = 3.0, 6.3 Hz, 1H), 7.19-7.23 (m, 1H), 7.33-7.37 (m, 1H), 7.63-7.67(m,1H); ^{13}C NMR ($CDCl_3$) δ 28.1, 43.1, 62.1, 74.0, 84.4, 125.4, 128.0, 128.3, 130.0, 133.7, 134.1, 146.7, 149.7, 168.3; LRMS (ESI): *m/z* 433, 435 $[M+Na]^+$; HRMS (FAB): *m/z* calculated for $C_{17}H_{19}Br^{81}N_2O_5Na^+$ $[M+Na]^+$: 435.0355, found: 435.0349; $[\alpha]_D^{24.0}$ –127 (*c* 0.99, $CHCl_3$), HPLC (DAICEL CHIRALPAK IC, ethanol, flow rate: 0.4 mL/min, detection at 254 nm) t_R 18.6 min (minor) and 27.0 min (major).

(*S*)-*tert*-Butyl 2-((*S*)-1-(4-methoxyphenyl)-2-nitroethyl)-5-oxo-2,5-dihydro-1*H*-pyrrole-1-carboxylate (4d): Colorless oil; IR (neat) ν 2979, 2839, 1783, 1612, 1557, 1514, 1368, 1255, 1157, 1103, 1034, 824, 753 cm^{-1}; ^1H NMR ($CDCl_3$, 500 MHz) δ 1.65 (s, 9H), 3.80 (s, 3H), 4.49 (dd, *J* = 4.3, 12.5 Hz, 1H), 4.56-4.60 (m, 1H), 4.64 (dd, *J* = 9.6, 12.5 Hz, 1H), 4.83-4.86 (m, 1H), 6.16 (dd, *J* = 1.9, 6.1 Hz, 1H), 6.90-6.93 (m, 2H), 7.04 (dd, *J* = 2.1, 6.1 Hz, 1H), 7.15-7.19 (m, 2H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 28.1, 43.3, 55.3, 65.2, 73.7, 84.2, 144.7, 126.5, 128.6, 128.8, 146.4, 149.5, 159.6, 168.2; LRMS (ESI): *m/z* 385 $[M+Na]^+$; HRMS (FAB): *m/z* calculated for $C_{18}H_{22}NaN_2O_6^+$ $[M+Na]^+$: 385.1370, found: 385.1364; HPLC (chiral column: DAICEL CHIRALPAK IC, ethanol, flow rate: 0.4 mL/min, detection: at 254 nm): t_R = 20.2 min (minor) and 29.7 min (major); $[\alpha]_D^{24.9} = -94.7$ (*c* 0.90, $CHCl_3$).

(*S*)-*tert*-Butyl 2-((*S*)-1-(furan-2-yl)-2-nitroethyl)-5-oxo-2,5-dihydro-1*H*-pyrrole-1-carboxylate (4e): Colorless solid; IR (KBr) 2969, 1789, 1698, 1552, 1369, 1288, 1254, 1162, 1051, 916, 848, 795, 755 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.62 (s, 9H), 4.34 (dd, *J* = 4.3, 13.5 Hz, 1H), 4.54 (dd, *J* = 9.8, 13.5 Hz ,1H), 4.76 (ddd, *J* = 4.3, 4.3, 9.8 Hz, 1H), 4.97 (ddd, *J* = 1.7, 2.1, 4.3 Hz, 1H), 6.22 (dd, *J* = 1.7, 6.2 Hz, 1H), 6.31 (brd, *J* = 3.4 Hz, 1H), 6.38 (dd, *J* = 1.9, 3.4 Hz, 1H), 7.19 (dd, *J* = 2.1, 6.2 Hz, 1H), 7.44 (dd, *J* = 0.7, 1.9 Hz, 1H); ^{13}C NMR ($CDCl_3$) δ 28.0, 38.1, 63.4, 72.5, 84.2, 108.8, 110.7, 128.6, 143.1, 146.8, 148.9, 149.0, 168.1; LRMS (ESI): *m/z* 345 $[M+Na]^+$; HRMS (ESI): *m/z* calculated for $C_{15}H_{18}N_2O_6Na^+$ $[M+Na]^+$: 345.1057, found: 345.1053; $[\alpha]_D^{24.0}$ –179 (*c* 1.11, $CHCl_3$), HPLC (DAICEL CHIRALPAK IC, ethanol, flow rate: 0.7 mL/min, detection at 254 nm) t_R 8.6 min (minor) and 10.4 min (major).

(*S*)-*tert*-Butyl 2-((*S*)-2-nitro-1-(thiophen-2-yl)ethyl)-5-oxo-2,5-dihydro-1*H*-pyrrole-1-carboxylate (4f): Colorless solid; IR (KBr) ν 3099, 2981, 1782, 1693, 1556, 1358. 1277, 1152, 1107, 1032, 835, 714 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.64 (s, 9H), 4.50 (dd, *J* = 4.8, 13.4 Hz, 1H), 4.57 (dd, *J* = 9.5, 13.4 Hz, 1H), 4.89 (ddd, *J* = 4.8, 4.8, 9.5, 1H), 4.94-4.96 (m, 1H), 6.20 (dd, *J* = 1.5, 6.1 Hz, 1H), 6.97 (d, *J* = 3.4 Hz, 1H), 7.01 (dd, *J* = 3.4, 5.2 Hz, 1H), 7.16 (dd, *J* = 2.1, 6.1 Hz, 1H), 7.30 (d, *J* = 5.2 Hz, 1H); ^{13}C NMR ($CDCl_3$) δ 28.0, 39.8, 64.8, 74.9, 84.3, 125.7, 126.3, 127.4, 128.8, 137.2, 146.3, 149.1, 168.1; LRMS (ESI): *m/z* 361 $[M+Na]^+$; HRMS (ESI): *m/z* calculated for $C_{15}H_{18}N_2O_5SNa^+$ $[M+Na]^+$: 361.0829, found: 362.0826; $[\alpha]_D^{24.0}$ –184 (*c* 1.03, $CHCl_3$), HPLC (DAICEL CHIRALPAK IC, ethanol, flow rate: 0.4 mL/min, detection at 254 nm) t_R 18.3 min (minor) and 27.1 min (major).

(*S*)-*tert*-Butyl 2-((*S*)-1-nitro-4-phenylbutan-2-yl)-5-oxo-2,5-dihydro-1*H*-pyrrole-1-carboxylate (4g): Colorless oil; IR (neat) ν 3022, 2980, 2932, 1778, 1555, 1456, 1370, 1314, 1158, 1105, 1049, 825, 753, 700 cm^{-1}; ^1H NMR ($CDCl_3$, 500 MHz) δ 1.49 (s, 9H), 1.77-1.82 (m, 2H), 2.72-2.75 (m, 2H), 3.27-3.33 (m, 1H), 4.04 (dd, *J* = 7.3, 13.1 Hz, 1H), 4.14 (dd, *J* = 5.2, 13.1 Hz, 1H), 4.78-4.80 (m, 1H), 6.17 (dd, *J* = 1.5, 6.2 Hz, 1H), 7.06 (dd, *J* = 1.7, 6.2 Hz, 1H), 7.13-7.27 (m, 5H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 27.9, 31.8, 33.3, 37.9, 63.1, 75.1, 84.0, 126.5, 128.1, 128.7, 129.2, 140.1, 145.8, 149.2, 168.2; LRMS (ESI): *m/z* 383 $[M+Na]^+$; HRMS (FAB): *m/z* calculated for $C_{19}H_{24}NaN_2O_5^+$ $[M+Cs]^+$: 383.1577, found: 383.1574; HPLC (chiral column: DAICEL CHIRALPAK AD-H, solvent: hexane/2-propanol = 9/1, flow rate: 0.5 mL/min, detection: at 254 nm): t_R = 31.9 min (minor) and 36.5 min (major); $[\alpha]_D^{29.7}$ = –113.6 (*c* = 0.70, $CHCl_3$).

(*S*)-*tert*-Butyl 2-((*S*)-3-methyl-1-nitrobutan-2-yl)-5-oxo-2,5-dihydro-1*H*-pyrrole-1-carboxylate (4h): Colorless solid; IR (KBr) ν 3090, 2973, 1787, 1708, 1552, 1474, 1366, 1281, 1162, 1047, 848, 825, 752 cm^{-1}; ^1H NMR ($CDCl_3$, 500 MHz) δ 1.07 (d, *J* = 6.7 Hz, 3H), 1.15 (d, *J* = 6.7 Hz, 3H), 1.57 (s, 9H), 1.77-1.84 (m, 1H), 3.11-3.16 (m, 1H), 3.92 (dd, *J* = 4.4, 13.8 Hz, 1H), 4.13 (dd, *J* = 6.9, 13.8 Hz, 1H), 4.93-4.94 (m, 1H), 6.21 (dd, *J* = 1.4, 6.2 Hz, 1H), 7.10 (dd, *J* = 1.9, 6.2 Hz, 1H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 20.5, 20.6, 28.0, 29.5, 43.9, 62.0, 73.6, 83.9, 129.3, 146.1, 149.0, 168.2; LRMS (ESI): *m/z* 321 $[M+Na]^+$; HRMS (ESI): *m/z* calculated for $C_{14}H_{22}NaN_2O_5^+$ $[M+Na]^+$: 321.1421, found: 321.1427; HPLC (chiral column: DAICEL CHIRALPAK IC, solvent: ethanol, flow rate: 0.4 mL/min, detection: at 254 nm): t_R = 14.8 min (minor) and 21.9 min (major); $[\alpha]_D^{29.7}$ = –177 (*c* = 1.0, $CHCl_3$).

(*S*)-*tert*-Butyl 2-((*S*,*E*)-1-nitro-4-phenylbut-3-en-2-yl)-5-oxo-2,5-dihydro-1*H*-pyrrole-1-carboxylate (4i): Colorless oil; IR (neat) ν 2980, 1780, 1742, 1555, 1369, 1315, 1157, 1105, 1049, 969, 824, 751, 693 cm^{-1}; ^1H NMR ($CDCl_3$, 500 MHz) δ 1.53 (s, 9H), 4.00-4.05 (m, 1H), 4.20 (dd, *J* = 9.9, 12.9 Hz, 1H), 4.27

(dd, *J* = 4.6, 12.9 Hz, 1H), 4.77-4.79 (m, 1H), 5.95 (dd, *J* = 8.6, 15.9 Hz, 1H), 6.13 (dd, *J* = 1.3, 6.1 Hz, 1H), 6.58 (d, *J* = 15.9 Hz, 1H), 7.12 (dd, *J* = 1.2, 6.1 Hz, 1H), 7.17-7.28 (m, 5H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 28.0, 42.5, 64.1, 74.9, 84.3, 122.2, 126.6, 128.6, 128.7, 128.8, 135.5, 136.3, 146.4, 149.5, 168.1; LRMS (ESI): *m*/*z* 381 $[M+Na]^+$; HRMS (ESI): *m*/*z* calculated for $C_{19}H_{22}NaN_2O_5^+$ $[M+Na]^+$: 381.1421, found: 381.1419; HPLC (chiral column: DAICEL CHIRALPAK IB, solvent: hexane/2-propanol = 4/1, flow rate: 1.0 mL/min, detection: at 254 nm): t_R = 75.2 min (minor) and 89.5 min (major); $[\alpha]_D^{29.7}$ = –169 (*c* = 0.90, $CHCl_3$).

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15. Molecular sieves were effective in some previously reported reactions using the dinuclear Ni_2-**1** catalyst. See, reference 12. In contrast, DRIERITE ($CaSO_4$) was not effective to accelerate the reaction.
16. CCDC 786778 contains the supplementary crystallographic data for **4b**. The data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.