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Palladium-Catalyzed Carbonylation of Homoallylic Amine Derivatives in the Presence of a Copper Co-catalyst

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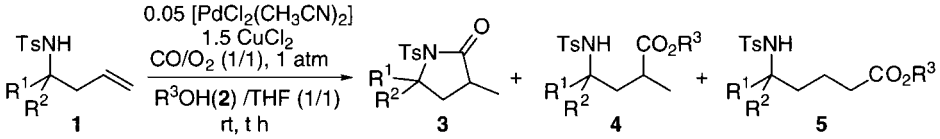
γ-Lactams were synthesized from *N*-tosylhomoallylamines by a carbonylation reaction catalyzed by palladium and copper salts under the normal pressure of CO and O_2 at room temperature. Monocarbonylation proceeded by the use of $[PdCl_2(CH_3CN)_2]$ and $CuCl_2$ to afford 3-methyl-2-pyrrolidones, while the use of $PdCl_2$ and CuCl switched the reaction from monocarbonylation to dicarbonylation to produce alkyl 2-oxopyrrolidine-3-acetate in good yields, respectively.

The transition-metal catalyzed carbonylation of alkenes with CO is a useful method for the preparation of homologated carbonyl compounds.[1] Especially, the intramolecular carbonylation of unsaturated alcohols and amines is an attractive way to produce heterocyclic compounds that are often difficult to prepare by other methods. Concerning the cyclization of olefinic amines, the intramolecular monocarbonylation of allylamine in the presence of $Co_2(CO)_8$ was reported to give a mixture of 3-methyl-2-pyrrolidone and 2-piperidone.[2] Utilizing a rhodium catalyst instead of a cobalt catalyst, 2-pyrrolidone was selectively obtained.[3] The hydrocarbonylation of 3-butenamides catalyzed by rhodium gave 3,4-dihydro-2(1*H*)-pyridinone or 4-methyl-3-pyrrolin-2-one derivatives, depending on the reaction conditions.[4] The intramolecular cyclocarbonylation of 2-aminostyrenes or 2-allylanilines in the presence of palladium catalysts produced the corresponding five, six, or seven-membered ring lactams.[5] Furthermore, the rhodium-catalyzed tandem cyclohydrocarbonylation/CO insertion of α-imino alkynes under CO and H_2 gave 2-oxo-3-pyrroline-4-carbaldehyde, regarded as intra- and intermolecular dicarbonylation products.[6] However, these reactions were conducted under drastic conditions, such as high pressure and high temperature. The development of the intramolecular carbonylation of unsaturated amines under mild conditions is still regarded as being a challenging problem for the synthesis of lactams, which have biological activity[7] and are versatile synthetic intermediates for nitrogen-containing chemicals.[8] We recently reported on selective mono- and bis(alkoxycarbonylation) reactions of terminal olefins catalyzed by palladium salts in the presence of copper salts under the normal pressure of CO and O_2 at room temperature. Furthermore, γ-butyrolactones were prepared from homoallylic alcohols under similar conditions.[9,10] When the homoallylamine derivatives were subjected to the carbonylation reaction, the formation of one carbon homologated 2-pyrrolidones was anticipated. Herein, we describe selective mono- and dicarbonylation reactions of *N*-tosylhomoallylamines catalyzed by palladium in the presence of $CuCl_2$ or CuCl under remarkably mild conditions to afford 3-methyl-1-tosyl-2-pyrrolidones or methyl 2-oxo-1-tosylpyrrolidine-3-acetate, respectively.

Results and Discussion

First, a carbonylation reaction of homoallylamine derivatives was carried out in the presence of a 0.05 molar amount of $[PdCl_2(CH_3CN)_2]$ and 1.5 molar amounts of $CuCl_2$ under a CO and O_2 [ca. 1/1, v/v, 1 atm (= 1.0×10^5 Pa)] atmosphere in MeOH (**2a**) and THF (1/1, v/v) at room temperature (Scheme 1).[9b] In the reaction of *N*-benzoyl and *N*-benzyloxycarbonyl substituted homoallylamines, intramolecularly carbonylated products were not formed, but only intermolecularly monocarbonylated esters were obtained. To the contrary, *N*-tosylhomoallylamine **1A** afforded γ-lactam, 3-methyl-1-tosyl-2-pyrrolidone (**3A**) in 52% yield accompanied by intermolecularly carbonylated esters, methyl 4-(*N*-tosylamino)-2-methylbutanoate (**4Aa**) and methyl 5-(*N*-tosylamino)pentanoate (**5Aa**) (Table 1, Entry 1). In the case of *N*-trifluoromethylsulfonylhomoallylamine, only intermolecularly monocarbonylated esters were again obtained. In order to suppress intermolecular carbonylation, the influence of alcohols was examined. When EtOH (**2b**), ^{i}PrOH (**2c**), and ^{t}BuOH (**2d**) were used instead of MeOH (**2a**), the intramolecular carbonylation proceeded more selectively (Entries 2–4). Utilizing 3-ethyl-3-pentanol (**2e**), γ-lactam **3A** was selectively obtained in 86% yield (Entry 5). Furthermore, PhOH (**2f**) was found to be effective for selective intramolecular carbonylation to afford **3A** in 88% yield (Entry 6). Even in the absence of alcohols, the



Scheme 1.

Table 1. Monocarbonylation of Homoallylamine Derivatives **1** Using $CuCl_2$ as a Co-catalyst

Entry	R^1	R^2	**1**	R^3OH	**2**	*t*/h	**3**/%	**4**/%	**5**/%
1	H	H	**A**	MeOH	**a**	17	52	6	9
2				EtOH	**b**	19	73	6	9
3				^{i}PrOH	**c**	19	80	2	10
4				^{t}BuOH	**d**	19	82	—	14
5				Et_3COH	**e**	21	86	—	trace
6				PhOH	**f**	37	88	—	—
7				—		47	57[a]	—	—
8	Ph	H	**B**	Et_3COH	**e**	39	86[b]	—	—
9				PhOH	**f**	38	79[b]	—	—
10	$Ph(CH_2)_3$	H	**C**	Et_3COH	**e**	27	86[b]	—	—
11				PhOH	**f**	74	75[b]	—	—
12	$-(CH_2)_5-$		**D**	Et_3COH	**e**	17	78	—	< 6[c]
13				PhOH	**f**	162	88	—	—

a) The starting compound **1A** was recovered (21%). b) The ratios of diastereomers were ca. 1/1. c) Contaminated with small amounts of unknown substrates that could not be separated.

reaction proceeded, but was rather sluggish (Entry 7).

Under the optimized conditions, the intramolecular monocarbonylation of several homoallylic *N*-tosylamines was carried out in the presence of 3-ethyl-3-pentanol (**2e**) or PhOH (**2f**). In the reactions of monosubstituted homoallylic amines **1B**,**C**, a ca. 1/1 mixture of diastereomers was produced (Entries 8–11). In all cases including disubstituted homoallylic amine **1D**, the corresponding γ-lactams **3** were obtained in good yields (Entries 8–13).

Next, the intra- and intermolecular dicarbonylation reaction was investigated in the presence of a 0.05 molar amount of $PdCl_2$ and 1.5 molar amounts of CuCl under a CO and O_2 (1/1, v/v, 1 atm) atmosphere in MeOH at room temperature (Scheme 2).[9b] In the reaction of **1A**, intra- and intermolecularly dicarbonylated lactam **6A** and intermolecularly bis(alkoxycarbonyl)ated diesters **7A** were obtained (Table 2, Entry 1). By the addition of THF as a co-solvent, intra- and intermolecular dicarbonylation proceeded selectively to afford γ-lactam **6A** bearing a methoxycarbonylmethyl side chain in 84% yield accompanied by monocarbonylated γ-lactam **3A** (6%) (Entry 2). The dicarbonylation of **1B–D** was also carried out in MeOH/THF to give the corresponding γ-lactams, methyl 5-substituted 2-oxo-1-tosylpyrrolidine-3-acetate **6B–D** in good yields (Entries 3–5).

Although the precise mechanism of the present reaction is still an open question, one possible reaction pathway is shown in Fig. 1. In the present carbonylation, copper might work not only as an oxidant, but also as a co-catalyst to generate active species. That is, copper salts react with CO to give the copper-carbonyl complex **8**,[11] followed by a reaction with homoallylamine derivatives **1** to afford **10**. The aminocarbonyl group

Table 2. Dicarbonylation of Homoallylamine Derivatives **1** Using CuCl as a Co-catalyst

Entry	R^1	R^2	**1**	Co-solvent	*t*/h	**6**/%	**7**/%
1	H	H	**A**	—	48	69	17
2				THF	46	84[a]	—
3	Ph	H	**B**	THF	42	82[b]	< 13[c]
4	$Ph(CH_2)_3$	H	**C**	THF	65	70[b]	trace
5	$-(CH_2)_5-$		**D**	THF	72	85	trace

a) Monocarbonylated γ-lactam **3A** was also obtained (6%). b) The ratios of diastereomers were ca. 1/1. c) Contaminated with small amounts of unknown substrates that could not be separated.

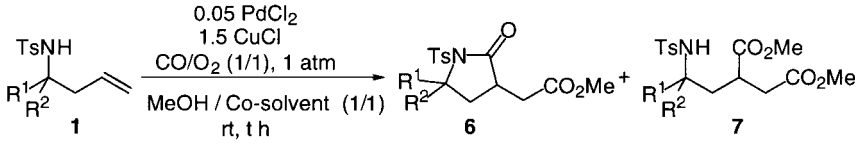
was transferred to palladium chloride to generate complex **11**, in which olefin can coordinate to the palladium metal. Successive carbopalladation to internal olefin gave the cyclized intermediate **12**. In a reaction using copper(II) chloride, protonation by HCl generated from **8** and R^3OH furnished monocarbonylated lactam **3**. On the other hand, second carbonylation proceeded via **13**, generated from **12** by a carbonyl transfer from **9**, formed by using CuCl, followed by reductive elimination to give dicarbonylated lactam **6**. Palladium(II) is regenerated by a reaction with O_2 and copper salt.[12,13]

As described above, a novel synthetic method for the construction of γ-lactam by the carbonylation of homoallylic amine derivatives was realized by utilizing palladium and copper salts under remarkably mild conditions. Depending on the kinds of used copper salts, mono- and dicarbonylation could be controlled to give a different type of γ-lactams chemoselectively.

Experimental

All of the melting points were determined with a micro melting apparatus (Yanagimoto-Seisakusho) and were uncorrected. The ^{1}H NMR spectra were recorded on a JEOL Lambda 400 spectrometer with tetramethylsilane as an internal standard. The IR spectra were measured with a JASCO FT/IR-230 spectrometer. The MS spectra were measured with a Hitachi M-80, or a JMS-SX102A mass spectrometer. The specific optical rotations were recorded on a JASCO DIP-370 spectrometer. THF was freshly distilled from sodium diphenylketyl. All other solvents were distilled and stored over drying agents. Thin-layer chromatography (TLC), column chromatography, and HPLC were performed on Merck's silica gel 60 PF254 (Art. 7749), Cica-Merck's silica gel 60 (No. 9385-5B), and JAIGL-SIL (s-043-15), respectively.

***N*-(3-Butenyl)-*p*-toluenesulfonamide (1A):**[16] To a mixture of 4-amino-1-butene[17] (177 mg, 2.5 mmol), triethylamine (0.5 mL, 3.8 mmol), a catalytic amount (ca. 5 mg) of 4-(dimethylamino)-pyridine in CH_2Cl_2 (5 mL) was added tosyl chloride (572 mg, 3.0 mmol) under a nitrogen atmosphere, and the reaction mixture was stirred for 3 h. The reaction mixture was quenched with H_2O and extracted with ethyl acetate. The combined extracts were wa-



Scheme 2.

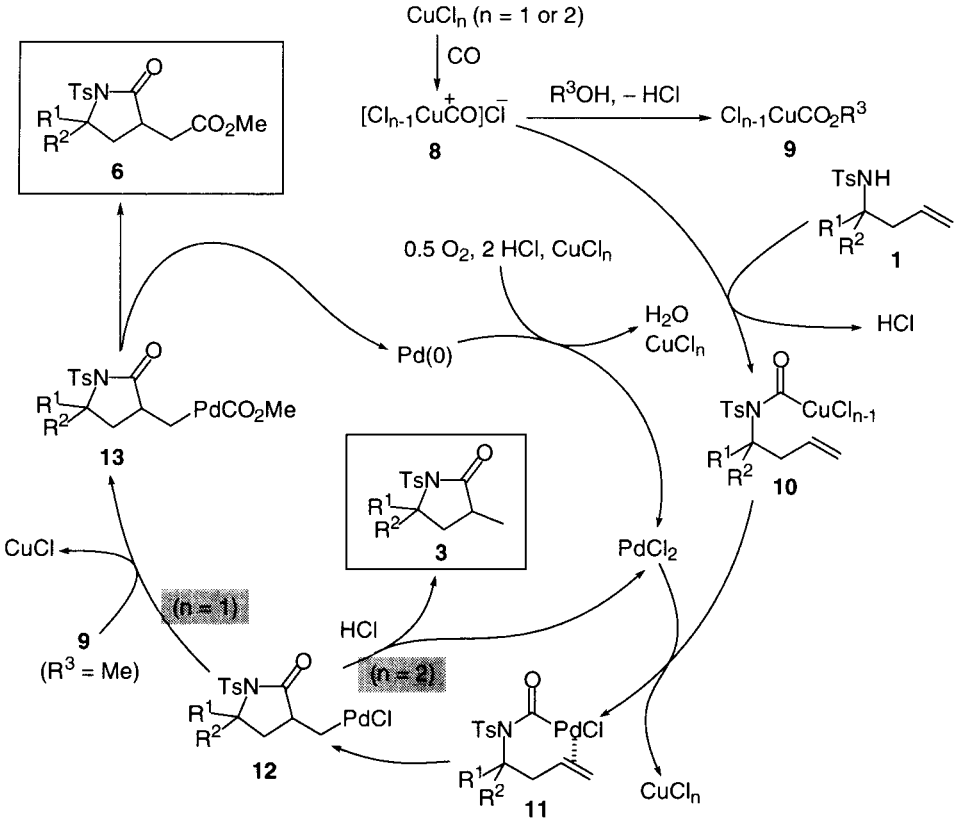


Fig. 1.

shed with H_2O and brine and dried over Na_2SO_4; the solvent was removed under reduced pressure. The residue was purified by flash column chromatography (SiO_2, hexane/ethyl acetate = 4/1, v/v) to give **1A** in 64% yield (383 mg). An oil; MS *m/z* 225 (M^+, 2.28%), 210 (0.36), 184 (100.00), 155 (98.36), 139 (2.34), 91 (6.27); IR (neat) 3283, 3079, 2925, 1639, 1597, 1495, 1424, 1324, 1159, 1093, 1019, 990, 919, 872, 815, 661 cm^{-1}; ^1H NMR ($CDCl_3$) δ 2.20 (2H, q, $J = 6.83$ Hz), 2.43 (3H, s), 3.01 (2H, q, $J = 6.83$ Hz), 4.56–4.68 (1H, br), 5.02 (1H, d, $J = 17.31$ Hz), 5.05 (1H, d, $J = 10.48$ Hz), 5.62 (1H, ddt, $J = 17.31$, 10.48, 6.83 Hz), 7.31 (2H, d, $J = 8.29$ Hz), 7.75 (2H, d, $J = 8.29$ Hz).

***N*-(1-Phenyl-3-butenyl)-*p*-toluenesulfonamide (1B):**[18] To a suspension of *N*-benzylidene-*p*-toluenesulfonamide (781 mg, 3.0 mmol) and Zn powder (351 mg, 5.4 mmol) in DMF (3 mL) was slowly added allyl bromide (0.38 mL, 4.5 mmol) under a nitrogen atmosphere and the solution was stirred overnight. After the addition of sat. aqueous NH_4Cl, the solution was extracted several times with ether. The combined extracts were washed by water and brine, dried over Na_2SO_4, and condensed under reduced pressure. The residue was purified by recrystallization (hexane/toluene) to give **1B** (623 mg, 69%). Mp 74.5–75.3 °C (from hexane/toluene), (lit., an oil);[18] IR (KBr) 3254, 3063, 3031, 2977, 2897, 1642, 1601, 1497, 1458, 1319, 1310, 1289, 1165, 1096, 1059, 992, 955, 933, 919, 833, 813, 760, 702, 680 cm^{-1}; ^1H NMR ($CDCl_3$) δ 2.37 (3H, s), 2.36–2.54 (2H, m), 4.37 (1H, q, $J = 6.58$ Hz), 4.78–4.87 (1H, br), 5.06 (1H, d, $J = 16.09$ Hz), 5.07 (1H, d, $J = 10.72$ Hz), 5.50 (1H, ddt, $J = 16.09$, 10.72, 7.07 Hz), 7.04–7.12 (2H, m), 7.14 (2H, d, $J = 8.05$ Hz), 7.15–7.24 (3H, m), 7.55 (2H, d, $J = 8.05$ Hz). Found: C, 67.54; H, 6.44; N, 4.63%. Calcd for $C_{17}H_{19}NO_2S$: C, 67.75; H, 6.35; N, 4.65%.

***N*-[1-(3-Phenylpropyl)-3-butenyl]-*p*-toluenesulfonamide (1C):** To a toluene (15 mL) solution of 4-phenylbutanenitrile (726 mg, 5.0 mmol) was added diisobutylaluminum hydride (1.0 M solution in toluene, 5.0 mL, 5.0 mmol) at −78 °C under a nitrogen atmosphere and the reaction mixture was gradually warmed to room temperature over a period of 6 h. To the solution, allylmagnesium bromide (1.0 M solution in Et_2O, 6.0 mL, 6.0 mmol) was added and the reaction mixture was stirred overnight. After quenching with sat. aqueous Na_2SO_4 (0.36 mL) at 0 °C, the precipitate was filtered off. To the filtrate was added 6 M HCl with stirring and the organic layer was separated. The aqueous solution was made basic by adding an aqueous NaOH solution and extracted several times with ether. The combined extracts were washed by brine and dried over Na_2SO_4, and condensed under reduced pressure to give almost pure 4-amino-7-phenyl-1-heptene (493 mg, 52%). The obtained homoallylamine (300 mg, 1.58 mmol) was tosylated without further purification according to the procedure described for **1A** to give **1C** (455 mg, 83%). An oil; MS *m/z* 343 (M^+, 0.39%), 342 ($M^+ - 1$, 0.88), 302 (88.82), 279 (6.88), 224 (11.25), 172 (29.33), 155 (47.84), 131 (97.51), 91 (100.00), 65 (13.21); IR (neat) 3280, 3062, 3026, 2939, 2860, 1640, 1598, 1495, 1453, 1425, 1325, 1304, 1159, 1092, 1028, 997, 916, 814, 749, 700, 665 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.32–1.64 (4H, m), 2.08 (2H, t, $J = 6.83$ Hz), 2.40 (3H, s), 2.46–2.52 (2H, m), 3.26–3.37 (1H, m), 4.31 (1H, d, $J = 8.05$ Hz), 4.94 (1H, dd, $J = 17.07$, 1.70 Hz), 5.01 (1H, d, $J = 10.24$ Hz), 5.52 (1H, ddt, $J = 17.07$, 10.24, 7.31 Hz), 7.07 (2H, d, $J = 8.53$ Hz), 7.14–7.20 (1H, m), 7.22–7.28 (4H, m), 7.73 (2H, d, $J = 8.53$ Hz).

***N*-(1-Allylcyclohexyl)-*p*-toluenesulfonamide (1D):** 1-Allylcyclohexanecarboxylic acid (1.682 g, 10 mmol) was treated with thionyl chloride (10 mL) and the solution was refluxed for 2 h and condensed under reduced pressure to give the corresponding acyl

chloride (2.104 g). To an acetone (6 mL) solution of the crude acyl chloride was added a H_2O (3 mL) solution of sodium azide (90% purity) (1.083 g, 15 mmol) and the solution was stirred for 30 min.[19] After the addition of H_2O (15 mL), the reaction mixture was extracted with toluene several times and the combined extracts were dried over Na_2SO_4. After filtration of Na_2SO_4, the filtrate was refluxed for 1 h, followed by cooling to room temperature and evaporating the solvent under reduced pressure. To the residue, 6 M HCl (1M = 1 mol dm^{-3}) (8 mL) was added, and the mixture was gradually warmed and refluxed for 30 min.[20] After cooling to room temperature, the mixture was washed with ether and the resulting aqueous layer was made basic by adding sodium carbonate and extracted with ether. The combined extracts were dried over Na_2SO_4, and the solvent was evaporated under reduced pressure to give almost pure 1-allyl-1-aminocyclohexane (1.188 g, 85%). The obtained homoallylamine was tosylated without further purification.

The obtained 1-allyl-1-aminocyclohexane (557 mg, 4.0 mmol) was treated with tosyl chloride (991 mg, 5.2 mmol) and triethylamine (0.85 mL, 6.0 mmol), as described for **1A** to give **1D** (752 mg) in 64% yield. Mp 123.5–124.4 °C (from hexane/ethyl acetate); IR (KBr) 3302, 3264, 3073, 2938, 2863, 1639, 1598, 1493, 1445, 1420, 1331, 1310, 1288, 1152, 1093, 1038, 1018, 996, 916, 853, 813, 775, 753, 705, 647, 660 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 1.22–1.46 (8H, m), 1.68–1.80 (2H, m), 2.39 (2H, d, J = 7.33 Hz), 2.42 (3H, s), 4.30 (1H, br), 5.07 (1H, d, J = 17.23 Hz), 5.11 (1H, d, J = 10.27 Hz), 5.73 (1H, ddt, J = 17.23, 10.27, 7.33 Hz), 7.27 (2H, d, J = 8.25 Hz), 7.77 (2H, d, J = 8.25 Hz). Found: C, 65.23; H, 8.00; N, 4.67%. Calcd for $C_{16}H_{23}NO_2S$: C, 65.49; H, 7.90; N, 4.77%.

The Representative Procedure for Monocarbonylation of 1A: A mixed solution of *N*-(3-butenyl)-*p*-toluenesulfonamide (**1A**) (112 mg, 0.5 mmol), [$PdCl_2(CH_3CN)_2$] (5.78 mg, 0.025 mmol), and $CuCl_2$ (101 mg, 0.75 mmol) in PhOH (2 mL) and THF (2 mL) was stirred under a CO/O_2 (ca. 1/1, v/v, 1 atm) atmosphere for 37 h at room temperature. After the addition of a 10% aqueous $NaHCO_3$ solution, the insoluble substance was filtered off through Celite. The filtrate was extracted with ethyl acetate, and the combined extracts were washed with water and brine, dried over Na_2SO_4, and condensed in vacuo. The residue was purified by TLC (SiO_2, benzene/ethyl acetate = 6/1, v/v) to give 3-methyl-1-tosyl-2-pyrrolidone (**3A**) (112 mg, 88%).

In a similar manner, 3-methyl-2-pyrrolidone **3B–D** were prepared from the corresponding homoallylamine derivatives **1B–D**. Diastereomers of **3B**,**C** were carefully separated by HPLC and subjected to analyses.

3-Methyl-1-tosyl-2-pyrrolidone (3A): Mp 85.0–85.9 °C (from hexane/ethyl acetate); IR (KBr) 3095, 3057, 2979, 2938, 2898, 2879, 1735, 1595, 1493, 1455, 1398, 1355, 1294, 1233, 1204, 1168, 1104, 1052, 1015, 984, 918, 902, 817, 801, 722, 712, 661 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 1.14 (3H, d, J = 7.07 Hz), 1.70 (1H, dddd, J = 12.44, 10.49, 9.76, 8.29 Hz), 2.26 (1H, dddd, J = 12.44, 8.29, 6.83, 2.44 Hz), 2.47 (1H, ddq, J = 10.49, 8.29, 7.07 Hz), 2.44 (3H, s), 3.68 (1H, td, J = 9.76, 6.83 Hz), 3.95 (1H, ddd, J = 9.76, 8.29, 2.44 Hz), 7.31 (2H, d, J = 8.29 Hz), 7.92 (2H, d, J = 8.29 Hz). Found: C, 56.79; H, 5.99; N, 5.55%. Calcd for $C_{12}H_{15}NO_3S$: C, 56.90; H, 5.97; N, 5.53%.

3-Methyl-5-phenyl-1-tosyl-2-pyrrolidone (3B): Diastereomer 1: Mp 133.4–134.6 °C (from hexane/AcOEt); IR (KBr) 3066, 3035, 2978, 2940, 2896, 2879, 1728, 1594, 1492, 1455, 1361, 1332, 1302, 1262, 1224, 1192, 1169, 1122, 1085, 1072, 1046, 994, 930, 912, 817, 800, 762, 700, 671 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 1.18 (3H, d, J = 7.07 Hz), 2.15–2.26 (2H, m), 2.40 (3H, s), 2.80 (1H, ddq, J = 10.49, 8.53, 7.07 Hz), 5.41 (1H, dd, J = 6.83, 2.92 Hz), 7.08–7.13 (2H, m), 7.19 (2H, d, J = 8.29 Hz), 7.24–7.32 (3H, m), 7.62 (2H, d, J = 8.29 Hz). Found: C, 65.48; H, 5.82; N, 4.10%. Calcd for $C_{18}H_{19}NO_3S$: C, 65.63; H, 5.81; N, 4.25%. Diastereomer 2: Mp 117.2–118.0 °C (from hexane/AcOEt); IR (KBr) 3030, 2971, 2927, 2877, 1714, 1598, 1495, 1461, 1361, 1334, 1268, 1221, 1186, 1166, 1096, 1043, 988, 922, 870, 810, 771, 729, 698, 669 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 1.22 (3H, d, J = 7.07 Hz), 1.63 (1H, ddd, J = 12.44, 9.75, 7.80 Hz), 2.40 (3H, s), 2.65 (1H, tq, J = 9.75, 7.07 Hz), 2.74 (1H, ddd, J = 12.44, 9.75, 7.80 Hz), 5.20 (1H, t, J = 7.80 Hz), 7.15–7.20 (2H, m), 7.19 (2H, d, J = 8.53 Hz), 7.25–7.32 (3H, m), 7.56 (2H, d, J = 8.53 Hz). Found: C, 65.62; H, 5.91; N, 4.15%. Calcd for $C_{18}H_{19}NO_3S$: C, 65.63; H, 5.81; N, 4.25%.

3-Methyl-5-(3-phenylpropyl)-1-tosyl-2-pyrrolidone (3C): Diastereomer 1: An oil; MS m/z 371 (M^+, 64.76%), 307 (6.31), 252 (14.71), 216 (100.00), 203 (4.80), 188 (4.90), 155 (35.14), 131 (7.47), 98 (16.58), 91 (79.81), 65 (10.20); IR (neat) 3061, 3026, 2932, 2862, 1733, 1598, 1496, 1454, 1359, 1291, 1213, 1170, 1124, 1091, 1065, 1031, 1019, 924, 896, 815, 749, 703, 667 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 1.09 (3H, d, J = 6.83 Hz), 1.50–1.72 (3H, m), 1.77 (1H, td, J = 12.44, 8.56 Hz), 1.98 (1H, ddd, J = 11.22, 8.29, 3.17 Hz), 2.06 (1H, dd, J = 12.44, 8.56 Hz), 2.43 (3H, s), 2.50–2.71 (3H, m), 4.31 (1H, td, J = 8.56, 3.71 Hz), 7.14 (2H, d, J = 8.29 Hz), 7.17–7.25 (1H, m), 7.25–7.33 (4H, m), 7.89 (2H, d, J = 8.29 Hz). Diastereomer 2: An oil; MS m/z 371 (M^+, 40.80%), 307 (9.33), 252 (13.01), 216 (100.00), 203 (6.25), 188 (5.63), 155 (34.68), 143 (4.86), 131 (4.71), 98 (16.51), 91 (83.35), 65 (10.53); IR (neat) 3061, 3026, 2970, 2932, 2866, 1732, 1598, 1496, 1454, 1361, 1307, 1293, 1213, 1169, 1121, 1089, 1043, 934, 869, 815, 752, 726, 702, 665 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 1.13 (3H, d, J = 6.58 Hz), 1.28–1.40 (1H, m), 1.52–1.66 (3H, m), 2.30–2.50 (3H, m), 2.43 (3H, s), 2.57–2.73 (2H, m), 4.15–4.25 (1H, m), 7.15 (2H, d, J = 8.29 Hz), 7.16–7.25 (1H, m), 7.25–7.33 (4H, m), 7.90 (2H, d, J = 8.29 Hz).

3-Methyl-1-tosyl-1-azaspiro[4.5]decan-2-one (3D): Mp 120.5–120.7 °C (from hexane/ethyl acetate); IR (KBr) 3071, 3038, 2985, 2931, 2868, 1728, 1597, 1494, 1452, 1405, 1366, 1346, 1308, 1255, 1211, 1188, 1171, 1157, 1122, 1076, 1028, 1003, 975, 939, 906, 866, 813, 799, 712, 705, 683, 657 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 1.11 (3H, d, J = 6.58 Hz), 1.24–1.51 (4H, m), 1.64–1.88 (5H, m), 2.42 (3H, s), 2.47 (1H, ddq, J = 10.97, 9.03, 6.58 Hz), 2.38–2.60 (1H, m), 2.55 (1H, dd, J = 12.19, 9.03 Hz), 2.88 (1H, td, J = 12.19, 4.14 Hz), 7.29 (2H, d, J = 8.29 Hz), 7.93 (2H, d, J = 8.29 Hz). Found: C, 63.42; H, 7.37; N, 4.29%. Calcd for $C_{17}H_{23}NO_3S$: C, 63.53; H, 7.21; N, 4.36%.

The Representative Procedure for Dicarbonylation of 1A: A mixed solution of *N*-(3-butenyl)-*p*-toluenesulfonamide (**1A**) (112 mg, 0.5 mmol), $PdCl_2$ (4.43 mg, 0.025 mmol), and CuCl (74 mg, 0.75 mmol) in THF (2 mL) and MeOH (2 mL) was stirred under a CO/O_2 (ca. 1/1, v/v, 1 atm) atmosphere for 46 h at room temperature. After the addition of a 10% aqueous $NaHCO_3$ solution, the insoluble substance was filtered off through Celite. The filtrate was extracted with ethyl acetate several times and the combined extracts were washed with water and brine, dried over Na_2SO_4, and condensed in vacuo. The residue was purified by TLC (SiO_2, benzene/ethyl acetate = 5/1, v/v) to give methyl 2-oxo-1-tosyl-3-pyrrolidineacetate (**6A**) (131 mg, 84%) and **1A** (8 mg, 6%).

In a similar manner, 3-(methoxycarbonylmethyl)-2-pyrrolidones **6B–D** were prepared from the corresponding homoallylamine derivatives **1B–D**. Diastereomers of **6B**,**C** were carefully separated by HPLC and subjected to analyses.

Methyl 2-Oxo-1-tosyl-3-pyrrolidineacetate (6A): Mp 63.0–64.2 °C (from hexane/ethyl acetate); IR (KBr) 2953, 1734, 1595, 1437, 1357, 1267, 1228, 1166, 1123, 1089, 1018, 992, 893, 814, 760, 718, 659 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.81 (1H, dddd, $J = 12.74$, 10.97, 10.00, 8.78 Hz), 2.38 (1H, dddd, $J = 12.74$, 8.78, 7.07, 1.71 Hz), 2.40 (1H, dd, $J = 16.80$, 8.78 Hz), 2.44 (3H, s), 2.79 (1H, dd, $J = 16.80$, 4.14 Hz), 2.86 (1H, dtd, $J = 10.97$, 8.78, 4.14 Hz), 3.64 (3H, s), 3.72 (1H, td, $J = 10.00$, 7.07 Hz), 3.99 (1H, ddd, $J = 10.00$, 8.78, 1.71 Hz), 7.33 (2H, d, $J = 8.05$ Hz), 7.92 (2H, d, $J = 8.05$ Hz). Found: C, 53.84; H, 5.51; N, 4.53%. Calcd for $C_{14}H_{17}NO_5S$: C, 54.01; H, 5.50; N, 4.50%.

Methyl 2-Oxo-5-phenyl-1-tosyl-3-pyrrolidineacetate (6B): Diastereomer 1: Mp 139.0–140.2 °C (from hexane/AcOEt); IR (KBr) 3033, 2980, 2953, 2932, 1736, 1726, 1593, 1492, 1457, 1437, 1383, 1360, 1335, 1290, 1250, 1223, 1171, 1145, 1121, 1105, 1089, 1030, 1016, 996, 970, 898, 814, 763, 717, 704, 668 cm^{-1}; ^1H NMR ($CDCl_3$) δ 2.29 (1H, ddd, $J = 12.44$, 8.53, 1.21 Hz), 2.34 (1H, ddd, $J = 12.44$, 11.71, 8.53 Hz), 2.40 (3H, s), 2.46 (1H, dd, $J = 17.07$, 8.53 Hz), 2.83 (1H, dd, $J = 17.07$, 4.39 Hz), 3.17 (1H, dtd, $J = 11.71$, 8.53, 4.39 Hz), 3.64 (3H, s), 5.45 (1H, dd, $J = 8.53$, 1.21 Hz), 7.09–7.15 (2H, m), 7.19 (2H, d, $J = 8.29$ Hz), 7.25–7.34 (3H, m), 7.61 (2H, d, $J = 8.29$ Hz). Found: C, 61.90; H, 5.54; N, 3.60%. Calcd for $C_{20}H_{21}NO_5S$: C, 62.00; H, 5.46; N, 3.62%. Diastereomer 2: Mp 105.5–106.4 °C (from hexane/AcOEt); IR (KBr) 3068, 3033, 2955, 2927, 1733, 1597, 1496, 1459, 1436, 1404, 1362, 1327, 1237, 1198, 1161, 1104, 1089, 1006, 983, 890, 817, 767, 701, 665 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.79 (1H, ddd, $J = 12.91$, 10.72, 8.29 Hz), 2.40 (3H, s), 2.53 (1H, dd, $J = 17.31$, 8.29 Hz), 2.79 (1H, dt, $J = 12.91$, 8.29 Hz), 2.84 (1H, dd, $J = 17.31$, 3.90 Hz), 3.00 (1H, dtd, $J = 10.72$, 8.29, 3.90 Hz), 3.65 (3H, s), 5.21 (1H, t, $J = 8.29$ Hz), 7.18 (2H, d, $J = 8.29$ Hz), 7.18–7.24 (2H, m), 7.26–7.32 (3H, m), 7.53 (2H, d, $J = 8.29$ Hz). Found: C, 61.83; H, 5.54; N, 3.54%. Calcd for $C_{20}H_{21}NO_5S$: C, 62.00; H, 5.46; N, 3.62%.

Methyl 2-Oxo-5-(3-phenylpropyl)-1-tosyl-3-pyrrolidineacetate (6C): Diastereomer 1: An oil; MS m/z 429 (M^+, 89.95%), 398 (15.78), 370 (19.91), 365 (9.00), 310 (13.13), 306 (17.04), 274 (61.99), 242 (55.24), 214 (7.95), 155 (25.48), 124 (12.50), 91 (100.00), 65 (9.97); IR (neat) 3060, 3027, 2951, 2927, 2861, 1733, 1597, 1496, 1454, 1438, 1362, 1262, 1234, 1169, 1115, 1090, 1019, 995, 896, 816, 752, 703, 667 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.41 (1H, ddd, $J = 12.92$, 10.00, 8.05 Hz), 1.52–1.66 (3H, m), 2.34 (1H, dd, $J = 17.80$, 10.00 Hz), 2.35–2.45 (1H, m), 2.43 (3H, s), 2.52 (1H, ddd, $J = 12.92$, 10.00, 8.05 Hz), 2.57–2.72 (2H, m), 2.78 (1H, dd, $J = 17.80$, 3.90 Hz), 2.82 (1H, qd, $J = 10.00$, 3.90 Hz), 3.63 (3H, s), 4.23 (1H, qd, $J = 8.05$, 2.68 Hz), 7.15 (2H, d, $J = 8.29$ Hz), 7.17–7.25 (1H, m), 7.26–7.40 (4H, m), 7.89 (2H, d, $J = 8.29$ Hz). Diastereomer 2: An oil; MS m/z 429 (M^+, 37.81%), 398 (11.57), 370 (5.55), 365 (11.62), 310 (9.24), 306 (5.93), 274 (72.10), 242 (94.16), 214 (7.77), 155 (31.09), 124 (11.82), 91 (100.00), 65 (12.80); IR (neat) 3061, 3025, 2951, 2927, 2863, 1733, 1597, 1495, 1454, 1437, 1362, 1168, 1088, 1029, 995, 887, 815, 754, 702, 662 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.52–1.76 (3H, m), 1.89 (1H, td, $J = 12.44$, 8.53 Hz), 1.98 (1H, ddd, $J = 10.97$, 7.31, 3.14 Hz), 2.17 (1H, dd, $J = 12.44$, 8.53 Hz), 2.33 (1H, dd, $J = 17.07$, 8.53 Hz), 2.43 (3H, s), 2.63 (2H, m), 2.76 (1H, dd, $J = 17.07$, 4.14 Hz), 2.95 (1H, ddd, $J = 12.44$, 8.53, 4.14 Hz), 3.63 (3H, s), 4.36 (1H, td, $J = 8.53$, 3.41 Hz), 7.15 (2H, d, $J = 8.24$ Hz), 7.17–7.24 (1H, m), 7.26–7.33 (4H, m), 7.88 (2H, d, $J = 8.24$ Hz).

Methyl 2-Oxo-1-tosyl-1-azaspiro[4.5]decan-3-acetate (6D): Mp 159.7–161.3 °C (from hexane/ethyl acetate); IR (KBr) 2979, 2938, 2867, 1723, 1596, 1442, 1363, 1342, 1311, 1301, 1261, 1215, 1178, 1161, 1152, 1089, 1066, 998, 882, 826, 740, 706, 683, 656 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.22–1.38 (2H, m), 1.38–1.54 (2H, m), 1.64–1.72 (2H, m), 1.74–1.89 (3H, m), 2.32 (1H, dd, $J = 16.78$, 8.53 Hz), 2.42 (3H, s), 2.48 (1H, td, $J = 13.44$, 3.68 Hz), 2.66 (1H, dd, $J = 12.68$, 9.03 Hz), 2.80 (1H, dd, $J = 16.78$, 3.90 Hz), 2.84–2.94 (2H, m), 3.65 (3H, s), 7.31 (2H, d, $J = 8.53$ Hz), 7.92 (2H, d, $J = 8.53$ Hz). Found: C, 59.92; H, 6.66; N, 3.65%. Calcd for $C_{19}H_{25}NO_5S$: C, 60.14; H, 6.64; N, 3.69%.

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