Rhodium-Catalyzed Addition/Ring-Opening Reaction of Arylboronic Acids with Cyclobutanones

Takanori Matsuda, Masaomi Makino, and Masahiro Murakami*

*Department of Synthetic Chemistry and Biological Chemistry, Kyoto University, Katsura,
Kyoto 615-6510, Japan*

Supporting Information

General. All reactions were carried out with standard Schlenk techniques under an argon atmosphere. NMR spectra were recorded on a Varian Mercury 400 (^1H at 400.44 MHz) or a Varian Gemini 2000 (^1H at 300.77 MHz and ^{13}C NMR at 75.46 MHz). Chemical shifts are reported in δ ppm referenced to a residual chloroform (δ 7.26 for ^1H , δ 77.0 for ^{13}C). Infrared spectra were recorded on a Mettler-Toledo ReactIR 4000. High resolution mass spectra were recorded on a JEOL JMS-SX102A. Preparative thin-layer chromatography was performed with silica Gel 60 PF₂₅₄ (Merck).

Materials. Cyclobutanones **1a-c**¹ and **1d**^{2,3} were prepared according to the literature procedures. *p*-Tolylboronic acid pinacol ester **2b** was prepared by esterification of *p*-tolylboronic acid with pinacol in methylene chloride. 1,4-Dioxane was distilled over LiAlH_4 before using for catalytic reactions. All other commercially available chemical resources were used without further purifications.

Rh-Catalyzed Reaction of Cyclobutanones **1** and Arylboronic Acids **2** (Table 1)

1,3-Diphenylbutan-1-one (3ac) [1533-20-6].⁴ To a mixture of $\text{Rh}(\text{acac})(\text{C}_2\text{H}_4)_2$ (6.46 mg, 0.025 mmol), **2c** (183 mg, 1.50 mmol), and Cs_2CO_3 (163 mg, 0.50 mmol) were added 1,4-dioxane (1.0 mL), $\text{P}(t\text{-Bu})_3$ (10.1 mg, 0.050 mmol), and **1a** (73.1 mg, 0.50 mmol). After being stirred for 24 h at 100 °C, the reaction mixture was extracted with ether (50 mL),

washed with brine, and dried over MgSO_4 . Bulb-to-bulb distillation (220 °C/1–2 mmHg) gave **3ac** (106.5 mg, 95 %) as a colorless oil. **1a**: ^{13}C NMR δ 21.7, 35.3, 46.8, 126.2, 126.8, 127.9, 128.1, 128.4, 132.9, 137.1, 146.5, 198.9.

3-(2-Naphthyl)-1-phenylbutan-1-one (3bc). To a mixture of $\text{Rh}(\text{acac})(\text{C}_2\text{H}_4)_2$ (6.46 mg, 0.025 mmol), **2c** (181 mg, 1.49 mmol), and Cs_2CO_3 (163 mg, 0.50 mmol) were added 1,4-dioxane (1.0 mL), $\text{P}(t\text{-Bu})_3$ (10.1 mg, 0.050 mmol), and **1b** (98 mg, 0.51 mmol). After being stirred for 24 h at 100 °C, the reaction mixture was filtered through a pad of Florisil® (ether). The filtrate was evaporated and the residue was purified by preparative thin-layer chromatography of silica gel (hexane:AcOEt = 8:1) to afford **3bc** (102 mg, 78%). **3bc**: ^1H NMR (300 MHz) δ 1.49 (d, J = 7.0 Hz, 3H), 3.32 (dd, J = 16.5, 8.1 Hz, 1H), 3.45 (dd, J = 16.5, 5.7 Hz, 1H), 3.75 (sext, J = 7.0 Hz, 1H), 7.40–7.50 (m, 5H), 7.50–7.58 (m, 1H), 7.70–7.73 (m, 1H), 7.77–7.84 (m, 3H), 7.93–7.99 (m, 2H); ^{13}C NMR δ 21.9, 35.6, 46.9, 124.9, 125.3, 125.6, 125.9, 127.5, 127.6, 128.0, 128.1, 128.5, 132.2, 132.9, 133.5, 137.1, 144.0, 198.9; HRMS (EI) calcd for $\text{C}_{20}\text{H}_{18}\text{O}$ 274.1358, found 274.1358.

3-Methyl-1-phenylundecan-1-one (3cc). According to the procedure described for **3bc**, **3cc** (98 mg, 75%) was prepared from **1c** (92 mg, 0.50 mmol) and **2c** (183 mg, 1.50 mmol). **3cc**: IR (neat) 2925, 1688, 1598, 1449, 1364, 1281, 1214, 1003, 751, 691 cm^{-1} ; ^1H NMR (400 MHz) δ 0.87 (t, J = 6.8 Hz, 3H), 0.94 (d, J = 6.4 Hz, 3H), 1.20–1.42 (m, 14H), 2.09–2.22 (m, 1H), 2.74 (dd, J = 15.6, 8.0 Hz, 1H), 2.94 (dd, J = 15.6, 5.6 Hz, 1H), 7.42–7.48 (m, 2H), 7.51–7.57 (m, 1H), 7.92–7.97 (m, 2H); ^{13}C NMR δ 14.0, 19.9, 22.6, 26.9, 29.2, 29.5, 29.7, 31.8, 37.1, 45.9, 128.1, 128.5, 132.8, 137.5, 200.5 [one carbon signal is missing]; HRMS (EI) calcd for $\text{C}_{18}\text{H}_{28}\text{O}$ 260.2140, found 260.2145; Anal. Calcd. for $\text{C}_{18}\text{H}_{28}\text{O}$: C,

83.02; H, 10.84. Found: C, 83.30; H, 10.67.

1,2-Diphenylbutan-1-one (3dc) [16282-16-9] and 1,4-Diphenylbutan-1-one (3'dc) [5407-91-0]. According to the procedure described for **3bc**, a 77:23 mixture of **3da** and **3'da** (25 mg, 52%) was prepared from **1d** (31 mg, 0.21 mmol) and **2c** (78 mg, 0.64 mmol). **3dc**: ^1H NMR (400 MHz) δ 0.91 (t, $J = 7.2$ Hz, 3H), 1.86 (dq, $J = 13.8, 7.3$ Hz, 1H), 2.21 (dq, $J = 13.8, 7.3$ Hz, 1H), 4.45 (t, $J = 7.2$ Hz, 1H), 7.17-7.22 (m, 1H), 7.25-7.32 (m, 4H), 7.36-7.42 (m, 2H), 7.45-7.50 (m, 1H), 7.94-7.98 (m, 2H); ^{13}C NMR δ 12.3, 27.1, 55.5, 126.9, 128.2, 128.4, 128.6, 128.8, 132.7, 137.0, 139.6, 200.0. **3'dc**: ^1H NMR (400 MHz) δ 2.09 (quint, $J = 7.4$ Hz, 2H), 2.73 (t, $J = 7.6$ Hz, 2H), 2.98 (t, $J = 7.2$ Hz, 2H), 7.17-7.24 (m, 2H), 7.24-7.32 (m, 2H), 7.42-7.48 (m, 2H), 7.52-7.57 (m, 1H), 7.90-7.94 (m, 2H); ^{13}C NMR δ 25.7, 35.2, 37.7, 125.9, 128.0, 128.4, 128.48, 128.52, 132.9, 137.0, 141.6, 200.0.

1-(2-Methylphenyl)-3-phenylbutan-1-one (3aa). According to the procedure described for **3bc**, **3aa** (86 mg, 72%) was prepared from **1a** (73 mg, 0.50 mmol) and **2a** (203 mg, 1.49 mmol). **3aa**: ^1H NMR (400 MHz) δ 1.34 (d, $J = 6.8$ Hz, 3H), 2.37 (s, 3H), 3.12 (dd, $J = 16.8, 8.4$ Hz, 1H), 3.23 (dd, $J = 16.4, 6.4$ Hz, 1H), 3.46 (sext, $J = 6.8$ Hz, 1H), 7.17-7.40 (m, 8H), 7.52-7.59 (m, 1H); ^{13}C NMR δ 20.7, 21.9, 35.8, 49.9, 125.5, 126.2, 126.9, 128.1, 128.5, 131.0, 131.8, 137.8, 138.4, 146.3, 203.6; HRMS (EI) calcd for $\text{C}_{17}\text{H}_{18}\text{O}$ 238.1358, found 238.1358. Anal. Calcd for $\text{C}_{17}\text{H}_{18}\text{O}$: C, 85.67; H, 7.61. Found: C, 85.69; H, 7.64.

1-(4-Methylphenyl)-3-phenylbutan-1-one (3ab). According to the procedure described

for **3bc**, **3ab** (98 mg, 82%) was prepared from **1a** (74 mg, 0.50 mmol) and **2b** (203 mg, 1.49 mmol). ^1H NMR (400 MHz) δ 1.36 (d, J = 7.2 Hz, 3H), 2.42 (s, 3H), 3.18 (dd, J = 16.2, 8.2 Hz, 1H), 3.30 (dd, J = 16.2, 5.8 Hz, 1H), 3.53 (sext, J = 7.0 Hz, 1H), 7.18-7.40 (m, 7H), 7.84-7.92 (m, 2H); ^{13}C NMR δ 21.6, 21.8, 35.6, 46.9, 126.2, 126.8, 128.1, 128.4, 129.2, 134.6, 143.6, 146.6, 198.6; HRMS (EI) calcd for $\text{C}_{17}\text{H}_{18}\text{O}$ 238.1358, found 238.1358.

1-(4-Trifluoromethylphenyl)-3-phenylbutan-1-one (3ad). According to the procedure described for **3bc**, **3ad** (57 mg, 39%) was prepared from **1a** (76 mg, 0.52 mmol) and **2d** (285 mg, 1.50 mmol). **3ad**: ^1H NMR (400 MHz) δ 1.37 (d, J = 6.8 Hz, 3H), 3.22 (dd, J = 16.4, 8.0 Hz, 1H), 3.35 (dd, J = 16.4, 6.0 Hz, 1H), 3.52 (sext, J = 6.9 Hz, 1H), 7.19-7.38 (m, 5H), 7.69-7.77 (m, 2H), 7.99-8.07 (m, 2H); ^{13}C NMR δ 21.9, 35.5, 47.3, 123.6 ($^1J_{\text{C-F}}$ = 272.5 Hz), 125.6 ($^3J_{\text{C-F}}$ = 3.5 Hz), 126.4, 126.8, 128.3, 128.6, 134.2 ($^2J_{\text{C-F}}$ = 32.8 Hz), 139.7, 146.1, 198.0; HRMS (EI) calcd for $\text{C}_{17}\text{H}_{15}\text{F}_3\text{O}$ 292.1075, found 292.1078.

1-(4-Methoxyphenyl)-3-phenylbutan-1-one (3ae) [62557-94-2].⁵ According to the procedure described for **3bc**, **3ae** (54 mg, 42%) was prepared from **1a** (74 mg, 0.51 mmol) and **2e** (228 mg, 1.50 mmol). **3ae**: HRMS (EI) calcd for $\text{C}_{17}\text{H}_{18}\text{O}_2$ 254.1307, found 254.1309.

Rh-Catalyzed Ring-Opening of Cyclobutanol **4aa** (Scheme 2)

A mixture of $\text{Rh}(\text{acac})(\text{C}_2\text{H}_4)_2$ (6.5 mg, 0.025 mmol), $\text{P}(t\text{-Bu})_3$ (10 mg, 0.050 mmol), Cs_2CO_3 (163 mg, 0.50 mmol), and **4aa** (115 mg, 0.48 mmol) in 1,4-dioxane (1.0 mL) were stirred at 100 °C for 48 h. The reaction mixture was extracted with ether (50 mL), washed with brine, dried over MgSO_4 . Concentration under reduced pressure afforded a mixture of

3aa and **4aa** (108 mg, 94%). The yield of **3aa** was estimated to be 89% by ^1H NMR.

Rh-Catalyzed Reaction of 3-Phenylcyclobutanone 1a with *p*-Tolylboronic Acid Pinacol Ester 2'b in D₂O (Scheme 3).

A mixture of Rh(acac)(C₂H₄)₂ (6.5 mg, 0.025 mmol), P(*t*-Bu)₃ (10 mg, 0.050 mmol), **1a** (72 mg, 0.49 mmol), and **2'b** (330 mg, 1.50 mmol) in 1,4-dioxane/D₂O (1:1, 2.0 mL) were heated at 100 °C for 24 h. The reaction mixture was extracted with ether (50 mL) and evaporated. The residue was purified by preparative thin-layer chromatography on silica gel (hexane:AcOEt = 8:1) to afford **3ab-d** as a diastereomeric mixture (83%; 92% D, 64:36 ratio by ^1H NMR). **3ab-d**: ^1H NMR (400 MHz) δ 1.32 (d, J = 6.8 Hz, major 3H), 1.33 (d, J = 6.8 Hz, minor 3H), 2.40 (s, 3H), 3.13 (dt, J = 8.4, 2.3 Hz, minor 1H), 3.23 (dt, J = 5.2, 2.3 Hz, major 1H), 3.49 (quint, J = 6.8 Hz, 1H), 7.16-7.32 (m, 8H), 7.81-7.85 (m, 2H); ^{13}C NMR δ 21.6, 21.8 (major), 21.9 (minor), 35.6, 46.5 ($^1J_{\text{C-D}}$ = 76.1 Hz), 126.2, 126.8, 128.2, 128.4, 129.2, 134.6, 143.7, 146.6, 198.7; HRMS (EI) calcd for C₁₇H₁₇DO 239.1419, found 239.1419.

¹³C spectrum of 3bc

¹³C OBSERVE

Pulse Sequence: #2pul
 Solvent: CDCl₃
 Ambient temperature
 GEMINI-300DB "varian2"

Relax. delay 1.158 sec
 Pulse 45.0 degrees
 Acq. time 0.842 sec
 Width 19000.0 Hz
 2848 repetitions

OBSERVE C13, 75.4519721 MHz
 DECOUPLE H1, 300.0687335 MHz
 Power 36 dB
 continuously on

WALTZ-16 modulated
 DATA PROCESSING
 Line broadening 1.0 Hz
 Pt size 32768
 Total time 5 hr, 49 min, 43 sec

¹H spectrum of 3dc

STANDARD IN OBSERVE

Pulse Sequence: zgpg30

Solvent: CDCl3

Ambient temperature

Mercury-400B "varian"

Relax. delay 1.500 sec

Pulse 45.0 degrees

Acq. time 3.500 sec

Width 6006.0 Hz

28 Repetitions

OBSERVE H1, 400.4437695 MHz

DATA PROCESSING

PT size 65536

Total time 15 hr, 52 min, 13 sec

¹H spectrum of 3'dc

STANDARD IN OBSERVE

Pulse sequence: zgpg30

Solvent: CDCl₃

Ambient temperature

Mercury-400B "varian"

Relax. delay 1.500 sec

Pulse 45.0 degrees

Acq. time 3.500 sec

Width 6006.0 Hz

100 repetitions

OBSERVE: HL, 400.4437695 MHz

NUC1: 13C

PT: 4.00000000 sec

Total time 15 hr, 52 min, 13 sec

¹H spectrum of 3'dc

13C OBSERVE

Pulse Sequence: s2pul
 Solvent: CDCl3
 Ambient temperature
 GEMINI-300DB "variant2"
 Relax. delay 1.158 sec
 Pulse 45.0 degrees
 Acq. time 0.842 sec
 Width 19000.0 Hz
 27072 repetitions
 OBSERVE C13, 75.4519663 MHz
 DECOUPLE H1, 300.0687335 MHz
 Power 36 dB
 continuously on
 WALTZ-16 modulated
 DATA PROCESSING
 F2: 75.4519663 MHz
 F1: 300.0687335 MHz
 Total time 58 hr, 17 min, 0 sec

¹H spectrum of 3ad

STANDARD IN OBSERVE

Pulse Sequence: zgpg30

Solvent: CDCl₃

Ambient temperature

Pressure: 400.000 mmHg

Relax. delay: 1.500 sec

Pulse: 45.0 degrees

Acq. time: 3.500 sec

Width: 6008.0 Hz

24 repetitions

Observed: 400.4437695 MHz

NUC1: 13C

NUC2: 1H

Proton: 54935

Total time: 9 min, 31 sec

¹³C OBSERVE

¹³C spectrum of 3ab-d

Pulse sequence: zgpg30
 Solvent: CDCl₃
 Ambient temperature
 GEMINI-300NB "variant"
 Relax delay 1.150 sec
 Pulse 45.0 degree
 Acq. time 0.842 sec
 Width 19000.0 Hz
 17348 repetitions
 OBSERVE C13, 75.4519698 MHz
 DECOUPLE M1, 300.0687335 MHz
 Power 36 dB
 continuously on
 WALTZ-16 modulated
 DATA PROCESSING
 Line broadening 1.0 Hz
 FT size 32768
 Total time 58 hr, 17 min, 0 sec

References

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