

Supplementary Information

Rhenium-Catalyzed Allylation of C-H Bonds of Benzoic and Acrylic Acids

Yoichiro Kuninobu,* Kazuhiro Ohta and Kazuhiko Takai*

Division of Chemistry and Biochemistry, Graduate School of Natural Science and Technology, Okayama University, Tsushima, Kita-ku, Okayama 700-8530, Japan

General. All reactions were carried out in dry solvent under an argon atmosphere. 1,2-Dichloroethane was purchased from Wako Pure Chemical Industries and was dried before use. $\text{Re}_2(\text{CO})_{10}$ was purchased from Aldrich Co. Benzoic acids, acrylic acids, 3-methyl-2,4-pentandione (**4**), allyl acetate (**5**), allyl alcohol (**11**), and D_2O (**14**) were purchased from Aldrich Co., Tokyo Kasei Kogyo Co., Wako Pure Chemical Industries, Nacalai Tesque Inc., and Merck & Co., Inc. Allyl benzoates were prepared by reactions between benzoic chlorides and allyl alcohol in dichloromethane using triethylamine as a base. Allyl acrylates were prepared by condensation of acrylic acids with allyl alcohol in dichloromethane in the presence of dicyclohexylcarbodiimide (DCC) and *N,N*-dimethylaminopyridine (DMAP). Deuterated carboxylic acids **13-d** and **10-d** were prepared by deprotonation of carboxylic acids with NaH and successive treatment with D_2O . Deuterated allyl alcohol, which is a starting material of deuterated allyl ester **1a-d**, was prepared by reduction of acrylic chloride with LiAlD_4 .

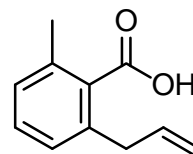
^1H (400 MHz) and ^{13}C (100 MHz) NMR spectra were recorded using a JEOL JNM-LA400 spectrometer. Proton chemical shifts are reported relative to Me_4Si (CDCl_3) at δ 0.00 ppm or residual solvent peak (CDCl_3 at δ 7.26 ppm). Carbon chemical shifts are reported relative to CDCl_3 at δ 77.00 ppm. IR spectra were recorded on a SHIMADZU IRAFFINITY-1 100V J.

Allylated product **2f** was already known. The structure of this reaction product was determined by comparing the spectrum data of this product with those of **2f**.¹

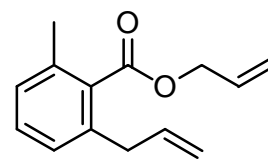
Typical procedure for the synthesis of 2-allyl-6-methylbenzoic acid (2a).

A mixture of $\text{Re}_2(\text{CO})_{10}$ (8.0 mg, 12.5 μmol), allyl benzoate (**1a**, 39.1 mL, 0.250 mmol), allyl acetate (**5**, 26.9 mL, 0.250 mmol), and 1,2-dichloroethane (0.50 mL) was heated at 135 °C for 24 h. After the reaction, the reaction mixture was treated with 3-methyl-2,4-pentandione (**4**) at 115 °C for 6 h, and the solvent was removed in vacuo. The product was isolated by column chromatography on silica gel (hexane : ethyl acetate = 30 : 1) to give 2-allyl-6-methylbenzoic acid (**2a**, 33.5 mg, 76% yield).

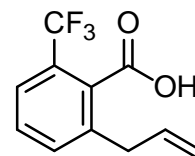
2-Allyl-6-methylbenzoic acid (2a). Solid; Mp = 65-66 °C; ^1H NMR (400 MHz, CDCl_3) δ 2.45 (s, 3H), 3.53 (d, $J = 7.6$ Hz, 2H), 5.07-5.11 (m, 2H), 5.97 (ddt, $J = 16.8, 10.4, 6.8$ Hz, 1H), 7.08-7.14 (m, 2H), 7.28 (dd, $J = 7.6, 7.6$ Hz, 1H); ^{13}C NMR (100 MHz, CDCl_3) δ 20.1, 38.2, 116.2, 127.3, 128.4, 130.0, 132.2, 135.7, 136.7, 137.5, 175.0; IR (Nujol / cm^{-1}) 1701, 1261, 1240, 1165, 1132, 1103, 1074, 995, 945, 912, 820, 783, 738, 723, 664; HRMS (EI^+) Calcd. For $\text{C}_{11}\text{H}_{13}\text{O}_2$ ($[\text{M}+\text{H}]^+$) 177.0916, Found 177.0914.



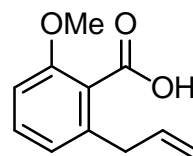
Allyl 2-allyl-6-methylbenzoate (3a). Liquid; ^1H NMR (400 MHz, CDCl_3) δ 2.33 (s, 3H), 3.40 (d, $J = 6.4$ Hz, 2H), 4.80 (dt, $J = 6.0, 1.2$ Hz, 2H), 5.00-5.10 (m, 2H), 5.30 (ddt, $J = 10.0, 1.2, 1.2$ Hz, 1H), 5.42 (ddt, $J = 17.2, 1.2, 1.2$ Hz, 1H), 5.91 (ddt, $J = 16.8, 10.4, 6.8$ Hz, 1H), 6.02 (ddt, $J = 16.8, 10.4, 6.8$ Hz, 1H), 7.03-7.09 (m, 2H), 7.24 (dd, $J = 8.4, 8.0$ Hz, 1H); ^{13}C NMR (100 MHz, CDCl_3) δ 19.7, 38.0, 65.7, 116.1, 119.2, 127.0, 128.2, 129.5, 131.8, 133.5, 135.1, 136.7, 137.0, 169.4; IR (Nujol / cm^{-1}) 1728, 1637, 1595, 1411, 1400, 1381, 1356, 1269, 1238, 1202, 1167, 1117, 1069, 995, 964, 916, 777, 756; HRMS (FAB^+) Calcd. For $\text{C}_{14}\text{H}_{17}\text{O}_2$ ($[\text{M}+\text{H}]^+$) 217.1228, Found 217.1225.



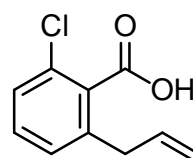
2-Allyl-6-trifluoromethylbenzoic acid (2b). Solid; Mp = 75-77 °C; ^1H NMR (400 MHz, CDCl_3) δ 3.55 (d, $J = 7.9$ Hz, 2H), 5.10-5.17 (m, 2H), 5.95 (ddt, $J = 16.8, 10.4, 6.8$ Hz, 1H), 7.48-7.55 (m, 2H), 7.58-7.62 (m, 1H); ^{13}C NMR (100 MHz, CDCl_3) δ 37.5, 117.4, 124.3 (q, $J = 3.6$ Hz), 124.4, 127.8 (q, $J = 31.9$ Hz), 129.0 (q, $J = 280$ Hz), 130.1, 133.4, 135.4, 138.3, 172.4; IR (Nujol / cm^{-1}) 1701, 1638, 1321, 1312, 1167, 1144, 1099, 1065, 943, 920, 806, 781, 741, 721; HRMS (EI^+) Calcd. For $\text{C}_{11}\text{H}_9\text{F}_3\text{O}_2$ (M^+) 230.0555, Found 230.0566.



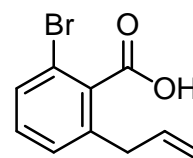
2-Allyl-6-methoxybenzoic acid (2c). Solid (unstable by heating); ^1H NMR (400 MHz, CDCl_3) δ 3.58 (d, $J = 6.4$ Hz, 2H), 3.92 (s, 3H), 5.09 (dd, $J = 17.0, 1.6$ Hz, 1H), 5.10 (dd, $J = 10.4, 1.6$ Hz, 1H), 5.98 (ddt, $J = 17.0, 10.4, 6.4$ Hz, 1H), 6.86 (d, $J = 8.4$ Hz, 1H), 6.91 (d, $J = 7.6$ Hz, 1H), 7.36 (dd, $J = 8.0, 8.0$ Hz, 1H); ^{13}C NMR (100 MHz, CDCl_3) δ 38.1, 56.3, 109.3, 116.3, 121.0, 122.8, 131.5, 136.5, 140.9, 157.0, 170.1; IR (Nujol / cm^{-1}) 1701, 1584, 1267, 1125, 1076, 914, 895, 806, 773; HRMS (FAB $^+$) Calcd. For $\text{C}_{11}\text{H}_{13}\text{O}_3$ ($[\text{M}+\text{H}]^+$) 193.0864, Found 193.0869.



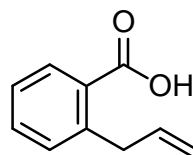
2-Allyl-6-chlorobenzoic acid (2d). Liquid; ^1H NMR (400 MHz, CDCl_3) δ 3.51 (d, $J = 6.8$ Hz, 2H), 5.08-5.16 (m, 2H), 5.93 (ddt, $J = 16.8, 10.4, 6.8$ Hz, 1H), 7.17-7.21 (m, 1H), 7.29-7.34 (m, 2H); ^{13}C NMR (100 MHz, CDCl_3) δ 29.7, 117.1, 127.5, 127.9, 130.7, 130.8, 132.2, 135.5, 139.1, 169.7; IR (Nujol / cm^{-1}) 1699, 1595, 1288, 1261, 1177, 1157, 1117, 1061, 993, 918, 791, 773, 698; HRMS (EI $^+$) Calcd. For $\text{C}_{10}\text{H}_9\text{ClO}_2$ (M^+) 196.0291, Found 196.0299.



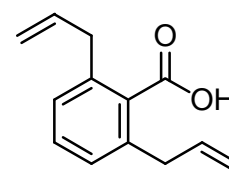
2-Allyl-6-bromobenzoic acid (2e). Solid; Mp = 58-60 °C; ^1H NMR (400 MHz, CDCl_3) δ 3.53 (ddd, $J = 6.8, 1.2, 1.2$ Hz, 2H), 5.13-5.15 (m, 1H), 5.16-5.18 (m, 1H), 5.96 (ddt, $J = 16.8, 10.4, 6.8$ Hz, 1H), 7.24-7.30 (m, 2H), 7.50-7.54 (m, 1H); ^{13}C NMR (100 MHz, CDCl_3) δ 38.0, 117.2, 119.1, 128.5, 130.7, 131.0, 134.5, 135.5, 139.3, 172.3; IR (Nujol / cm^{-1}) 1705, 1593, 1562, 1445, 1287, 1175, 1152, 1111, 1058, 993, 920, 785, 685, 665; HRMS (EI $^+$) Calcd. For $\text{C}_{10}\text{H}_9\text{BrO}_2$ (M^+) 239.9786, Found 239.9797.



2-Allylbenzoic acid (2f). Solid; Mp = 82-84 °C; ^1H NMR (400 MHz, CDCl_3) δ 3.84 (d, $J = 6.4$ Hz, 2H), 5.01-5.08 (m, 2H), 6.05 (ddt, $J = 16.8, 10.4, 6.8$ Hz, 1H), 7.29-7.35 (m, 2H), 7.51 (ddd, $J = 7.6, 7.6, 1.6$ Hz, 1H), 8.05 (dd, $J = 8.4, 1.6$ Hz, 1H); ^{13}C NMR (100 MHz, CDCl_3) δ 38.6, 115.7, 126.3, 128.2, 131.2, 131.6, 133.1, 137.3, 142.8, 173.3.

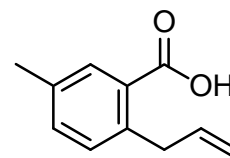


2,6-Diallylbenzoic acid (2f'). Liquid; ^1H NMR (400 MHz, CDCl_3) δ 3.52 (d, $J = 6.8$ Hz, 4H), 5.05-5.12 (m, 4H), 5.96 (ddt, $J = 16.8, 10.4, 6.8$ Hz, 2H), 7.14 (d, $J = 8.0$ Hz, 2H), 7.33 (t, $J = 8.4$ Hz, 1H); ^{13}C NMR (100 MHz, CDCl_3) δ 38.1, 116.4, 127.8, 130.2, 132.0,

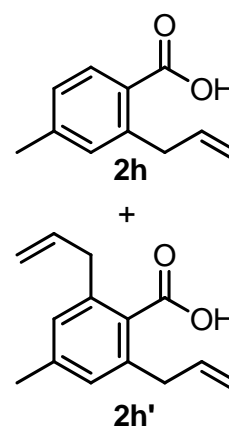


136.6, 137.6, 173.7; IR (Nujol / cm^{-1}) 1701, 1290, 1132, 914, 721, 665; HRMS (EI^+)
Calcd. For $\text{C}_{13}\text{H}_{15}\text{O}_2$ ($[\text{M}+\text{H}]^+$) 203.1072, Found 203.1078.

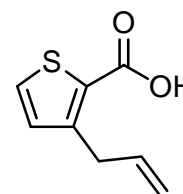
2-Allyl-5-methylbenzoic acid (2g). Solid; Mp = 41-43 °C; ^1H NMR (400 MHz, CDCl_3) δ 2.37 (s, 3H), 3.78 (d, $J = 6.4$ Hz, 2H), 4.99-5.06 (m, 2H), 6.03 (ddt, $J = 16.8, 10.4, 6.8$ Hz, 1H), 7.19 (d, $J = 7.6$ Hz, 1H), 7.31 (d, $J = 7.6$ Hz, 1H), 7.86 (s, 1H); ^{13}C NMR (100 MHz, CDCl_3) δ 20.8, 38.2, 115.5, 127.9, 131.1, 132.0, 133.9, 135.9, 137.5, 139.7, 173.1; IR (Nujol / cm^{-1}) 1694, 1639, 1616, 1570, 1501, 1412, 1298, 1273, 1217, 1078, 1042, 993, 912, 829, 775, 754, 739, 723, 673, 635; HRMS (EI^+) Calcd. For $\text{C}_{11}\text{H}_{12}\text{O}_2$ (M^+) 176.0837, Found 176.0832.



2-Allyl-4-methylbenzoic acid (2h) and 2,6-diallyl-4-methylbenzoic acid (2h'). Liquid; ^1H NMR (400 MHz, CDCl_3) δ 2.32 (s, 3H), 2.39 (s, 3H), 3.50 (d, $J = 6.4$ Hz, 2H), 3.81 (d, $J = 6.4$ Hz, 4H), 5.02-5.12 (m, 2H+4H), 5.90-6.10 (m, 1H+2H), 6.94 (s, 2H), 7.10-7.12 (m, 2H), 7.97 (d, $J = 8.4$ Hz, 1H); ^{13}C NMR (100 MHz, CDCl_3) δ 21.2, 21.5, 38.1, 38.5, 115.5, 116.1, 125.1, 127.1, 127.8, 128.6, 129.8, 131.9, 136.8, 137.5, 137.8, 140.3, 142.9, 143.9, 172.5, 174.8; IR (Nujol / cm^{-1}) 1695, 1610, 1570, 1296, 1277, 1231, 1157, 1076, 912; HRMS (**2h**, EI^+) Calcd. For $\text{C}_{11}\text{H}_{12}\text{O}_2$ (M^+) 176.0837, Found 176.0826.



3-Allylthiophene-2-carboxylic acid (2i). Solid; Mp = 67-68 °C; ^1H NMR (400 MHz, CDCl_3) δ 3.81 (ddd, $J = 6.8, 1.2, 1.2$ Hz, 2H), 5.06-5.15 (m, 2H), 5.99 (ddt, $J = 16.8, 10.4, 6.8$ Hz, 1H), 7.00 (d, $J = 5.2$ Hz, 1H), 7.51 (d, $J = 5.2$ Hz, 1H); ^{13}C NMR (100 MHz, CDCl_3) δ 33.4, 116.2, 126.1, 131.0, 132.0, 135.8, 149.8, 167.6; IR (Nujol / cm^{-1}) 1674, 1298, 1288, 1261, 1105, 1088, 1078, 1020, 997, 918, 804, 721; HRMS (EI^+) Calcd. For $\text{C}_8\text{H}_8\text{O}_2\text{S}$ (M^+) 168.0245, Found 168.0252.

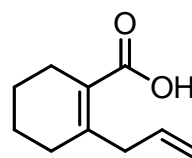


2-Allyl-1-cyclohexenecarboxylic acid (7a). Solid; Mp = 52-53 °C; ¹H

NMR (400 MHz, CDCl₃) δ 1.56-1.67 (m, 4H), 2.15-2.21 (m, 2H),
2.30-2.36 (m, 2H), 3.21 (d, *J* = 6.3 Hz, 2H), 4.98-5.09 (m, 2H), 5.81

(ddt, *J* = 16.8, 10.4, 6.8 Hz, 1H); ¹³C NMR (100 MHz, CDCl₃) δ 22.16,

22.23, 26.4, 31.5, 40.1, 115.8, 124.0, 135.8, 150.7, 172.0; IR (Nujol / cm⁻¹) 1676, 1283,
1263, 1246, 1180, 1067, 1038, 995, 907, 750, 665; HRMS (EI⁺) Calcd. For C₁₀H₁₄O₂
(M⁺) 166.0994, Found 166.0996.

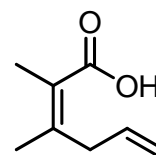


(Z)-2,3-Dimethyl-2,5-hexadienoic acid (7b). Liquid; ¹H NMR (400

MHz, CDCl₃) δ 1.83 (s, 3H), 1.91 (s, 3H), 3.25 (d, *J* = 6.8, 2H),
5.01-5.10 (m, 2H), 5.82 (ddt, *J* = 16.8, 10.4, 6.8 Hz, 1H); ¹³C NMR (100

MHz, CDCl₃) δ 15.8, 20.9, 40.9, 116.1, 122.5, 135.6, 148.6, 174.2; IR

(Nujol / cm⁻¹) 1674, 1398, 1279, 1198, 912, 665; HRMS (EI⁺) Calcd. For C₈H₁₂O₂ (M⁺)
140.0837, Found 140.0834.

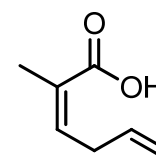


(Z)-2-Methyl-2,5-hexadienoic acid (7c). Liquid; ¹H NMR (400 MHz,

CDCl₃) δ 1.95 (d, *J* = 1.2 Hz, 3H), 3.30 (ddd, *J* = 7.5, 1.2, 1.2 Hz, 2H),
5.01-5.11 (m, 2H), 5.79-5.89 (ddt, *J* = 16.8, 10.4, 6.8 Hz, 1H), 6.11 (tq, *J*

= 7.5, 1.2 Hz, 1H); ¹³C NMR (100 MHz, CDCl₃) δ 20.4, 34.0, 115.7,

126.9, 135.8, 143.2, 173.4; IR (Nujol / cm⁻¹) 1911, 1682, 1641, 1420, 1283, 1258, 1157,
1076, 1047, 993, 916, 806; HRMS (FAB⁺) Calcd. For C₇H₁₀O₂ ([M+Na]⁺) 149.0579,
Found 149.0581.

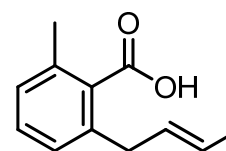


(E)-2-(2-Buten-1-yl)-6-methylbenzoic acid (9). Liquid; ¹H NMR

(400 MHz, CDCl₃) δ 1.67 (d, *J* = 6.0 Hz, 3H), 2.43 (s, 3H), 3.43 (d,
J = 5.2 Hz, 2H), 5.48-5.62 (m, 2H), 7.07-7.10 (m, 2H), 7.24-7.30

(m, 1H); ¹³C NMR (100 MHz, CDCl₃) δ 17.9, 20.0, 37.0, 113.6,

124.4, 127.0, 127.1, 128.2, 129.9, 135.4, 138.3, 173.6; IR (Nujol / cm⁻¹) 3067, 1701,
912, 721; HRMS (EI⁺) Calcd. For C₁₂H₁₄O₂ (M⁺) 190.0994, Found 190.0985.

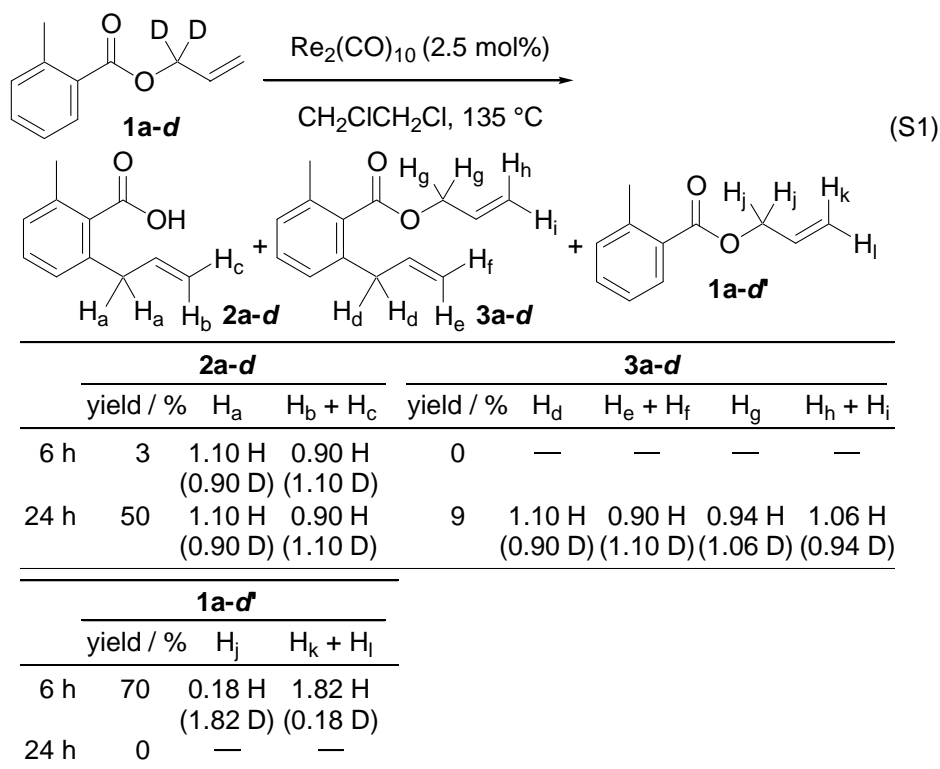


Typical procedure for the reaction of deuterated benzoic acid (12-d) with D₂O (Eqn (4)). A mixture of Re₂(CO)₁₀ (4.1 mg, 6.3 μmol), deuterated 2-methylbenzoic acid

(**12-d**, 34.3 mL, 0.250 mmol), D₂O (9.1 μL, 0.500 mmol), and 1,2-dichloroethane (0.50 mL) was heated at 150 °C for 24 h. After the reaction, the solvent was removed in vacuo to give **12-d'**.

1. S. Ozaki, M. Adachi, S. Sekiya, R. Kamikawa, *J. Org. Chem.*, 2003, **68**, 4586-4589.

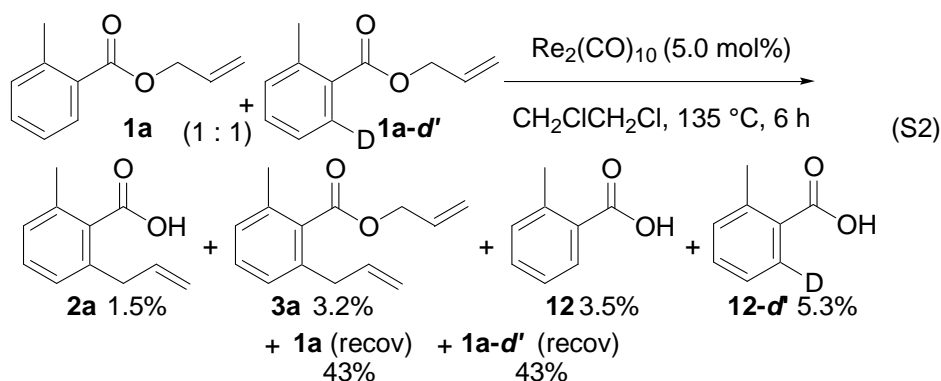
A reaction starting from deuterated allyl benzoate 1a-d.



An Experiment of Kinetic Isotope Effect (KIE).

The KIE value was calculated by the following equation.

The KIE value = [50 - {(the yield of **1a** [%]) + (the yield of **12** [%])}] / [50 - {(the yield of **1a-d'** [%]) + (the yield of **12-d'** [%])}] = 2.1.



- S1. 2-Methylbenzoic acid (**13**) was formed in 30% yield.
- S2. Investigation of several catalysts: $\text{Re}_2(\text{CO})_{10}$, 69%; $[\text{ReBr}(\text{CO})_3(\text{thf})_2]$, 62%; $\text{ReBr}(\text{CO})_5$, 24%; $\text{Mn}_2(\text{CO})_{10}$, 0%; $\text{MnBr}(\text{CO})_5$, 9%; $\text{RhCl}(\text{PPh}_3)_3$, 37%; $\text{RuH}_2(\text{CO})(\text{PPh}_3)_3$, 42%; PtCl_2 , 0%.
- S3. Investigation of several solvents ($150\text{ }^\circ\text{C}$): $\text{CH}_2\text{ClCH}_2\text{Cl}$, 69%; toluene, 29%; THF, 22%; 1,4-dioxane, 26%; DMSO, 0%.
- S4. Investigation of several directing groups instead of a hydroxycarbonyl group ($150\text{ }^\circ\text{C}$; D_2O , 1.0 equiv): 2-pyridyl, 29%; acetyl, 0%; hydroxycarbonyl, 11%; deuterated hydroxycarbonyl, 69%; methoxycarbonyl, 16% + *ortho*-deuterated benzoic acid, 38%.
- S5. There has been a report on iridium-catalyzed deuteration of aromatic compounds. See: J. Kruger, B. Manmontri, G. Fels, *Eur. J. Org. Chem.*, 2005, 1402.
- S6. Acrylic acid **10** was formed in 39% yield.
- S7. The KIE value = $[50 - \{(\text{the yield of } \mathbf{1a} [\%]) + (\text{the yield of } \mathbf{12} [\%])\}] / [50 - \{(\text{the yield of } \mathbf{1a-d'} [\%]) + (\text{the yield of } \mathbf{12-d'} [\%])\}]$.
- S8. Another possible mechanism for the allylation is an electrophilic substitution reaction, such as a Friedel-Crafts reaction. In Table 1, entries 2 and 3, the benzoate with an electron-withdrawing group, **1b**, gave a higher yield of allylic product than the benzoate bearing an electron-donating group, **1c**. It is usually difficult to introduce allyl group(s) to electron deficient aromatic compounds, in particular at the *ortho*-position, by electrophilic substitution reaction (if the reaction proceeds, the reaction must occur at the *meta*-position). Therefore, this reaction did not proceed by the Friedel-Crafts type mechanism.