Decarboxylation of indole-3-carboxylic acids under metal-free conditions

Xia Chen & Xiao-Yu Zhou

 View supplementary material

 Published online: 14 Feb 2020.

 Submit your article to this journal

 View related articles

 View Crossmark data

Check for updates

Decarboxylation of indole-3-carboxylic acids under metal-free conditions
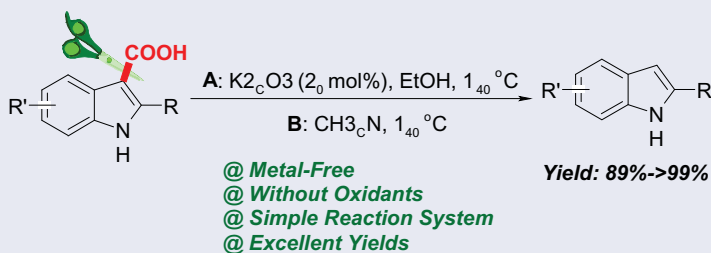
Xia Chen and Xiao-Yu Zhou

School of Chemistry and Materials Engineering, Liupanshui Normal University, Liupanshui, China

ABSTRACT

Two reaction systems have been developed for the decarboxylation of indole-3-carboxylic acids. The decarboxylation can be achieved smoothly under K_2CO_3-catalyzed or acetonitrile-promoted basic conditions. It provided an efficient and simple method for the transformation of indole-3-carboxylic acids and the corresponding indoles were isolated with good to excellent yields. From the experimental facts, we put forward the possible reaction mechanism.

GRAPHICAL ABSTRACT

A: K_2CO_3 (20 mol%), EtOH, 140 °C

B: CH_3CN, 140 °C

@ Metal-Free
@ Without Oxidants
@ Simple Reaction System
@ Excellent Yields

Yield: 89%->99%

Decarboxylation is an available method in organic chemistry and bioscience[1] and many efforts have been devoted to the decarboxylative functionalization of carboxylic acids and carboxylates.[2] Enzyme or transition-metal catalyzed oxidative decarboxylation and decarboxylative functionalization are primary means. Among these transformations, the main areas were focused on the decarboxylation of amino acids,[3] decarboxylative functionalization of aromatic[4] and aliphatic[5] carboxylic acids. Especially, the development of decarboxylative functionalization had been promoted by photocatalytic technique.[6] Many works also focused on the research of decarboxylative mechanism and quantum chemistry calculation,[7] such as the mechanism of protonic acid-catalyzed decarboxylative protonation of pyrrole-2-carboxylic acid,[8] p-chloranil catalyzed decarboxylative alkoxylation[9] and decarboxylative arylation[10] of 2-picolinic acid in the presence of tert-butyl hypochlorite (tBuOCl). The decarboxylative transformation of hetero-aromatic carboxylic acids is also an important field for the synthesis of hetero-cyclic compounds.
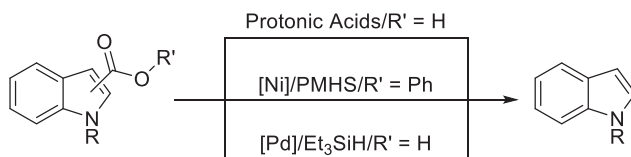
**Scheme 1.** Decarboxylation of indolecarboxylic acids and its derivatives.
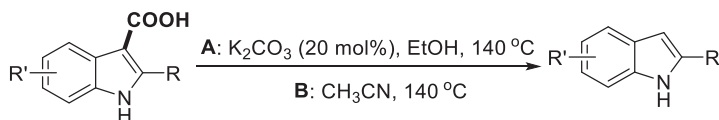
Scheme 2. Decarboxylation of indole carboxylic acids.

Indole-3-carboxylic acids can be prepared[11] and used as starting materials in organic synthesis. In the previous works, there were some findings on the decarboxylative functionalization of indolyl carboxylic acids.[12] And, a few works had been focused on the decarboxylation of indole-3-carboxylic acids (Scheme 1). In 2012, the mechanism for the decarboxylation of indole-2-carboxylic acid and indole-3-carboxylic acid in acidic conditions had been revealed by Kluger and his coworkers.[13] And, kinetic analysis over a wide range of solution acidities showed the importance of protonated carbonic acid as a reaction intermediate. On the other hand, the selective decarbonylative reduction of aryl and heteroaryl esters and amides were developed in Rueping's group.[14] The ester and amide groups from arenes and heteroarenes can be removed using $Ni(OAc)_2 \cdot 4H_2O$ as a catalyst and commercially available hydrosilane as a reagent. Most recently, Szostak et al.[15] reported a palladium-catalyzed reduction of carboxylic acids to arenes in the presence of Et_3SiH. It provided a practical method for the construction of arenes and the DFT study was conducted to demonstrate the mechanism.

Through our study, decarboxylation of indole-3-carboxylic acid can be achieved under inorganic base-catalyzed or acetonitrile-promoted conditions (Scheme 2). These new findings are described herein.

Our study began by evaluating the decarboxylation of indole-3-carboxylic acid (**1a**) in 1,4-dioxane at 140 °C and trace amount 1H-indole (**2a**) was detected (Table 1, Entry 1). After some experimentation, we found that inorganic base-catalyzed protocol consisting of Na_2CO_3 (100 mol%) in 1,4-dioxane afforded **2a** in 24% isolated yield at 140 °C (Entry 2). Subsequently, the effects of base, solvent and temperature were screened. The results indicated that K_2CO_3 (100 mol%) had more positive effect on the decarboxylation of **1a** in 1,4-dioxane with 37% yield (Entry 3) and the yield increased to 98% in ethanol (EtOH, Entry 4). The solubility of base in EtOH is higher than 1,4-dioxane, which may be the predominant factor. In order to simplify the reaction system, the dosage of base was tested (Entries 5–7), and it was confirmed that K_2CO_3 (20 mol%) was essential to afford the target product with >99% yield (Entry 5). Moreover, 1,4-dioxane, toluene, water and n-hexanol as a solvent in the presence of K_2CO_3 (20 mol%) led to lower yields (42–76%, Entries 8–11). Surprisingly, >99% yields can be obtained with or without K_2CO_3 in acetonitrile (CH_3CN, Entries 12 and 13). Besides, CH_3CN showed no catalytic roles in the transformation due to almost no target product detected in the
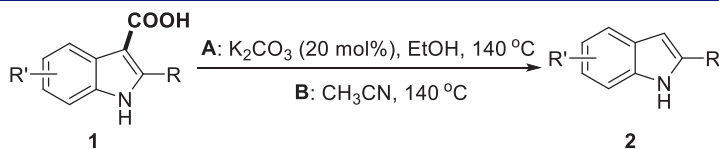
Table 1. Conditions optimization.[a]
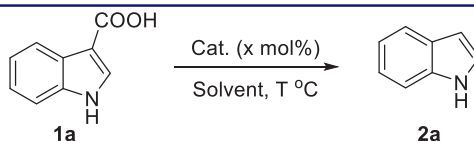
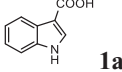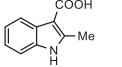| Entry	Cat. (x)	Solvent (T)	T (°C)	Yield (%)[b]
1	None	1,4-dioxane	140	Trace
2	Na$_2$CO$_3$ (100 mol%)	1,4-dioxane	140	24
3	K$_2$CO$_3$ (100 mol%)	1,4-dioxane	140	37
4	K$_2$CO$_3$ (100 mol%)	EtOH	140	98
5	K$_2$CO$_3$ (20 mol%)	EtOH	140	> 99
6	K$_2$CO$_3$ (10 mol%)	EtOH	140	87
7	None	EtOH	140	Trace
8	K$_2$CO$_3$ (20 mol%)	1,4-dioxane	140	60
9	K$_2$CO$_3$ (20 mol%)	Toluene	140	42
10	K$_2$CO$_3$ (20 mol%)	water	140	76
11	K$_2$CO$_3$ (20 mol%)	n-hexanol	140	53
12	K$_2$CO$_3$ (20 mol%)	CH$_3$CN	140	>99
13	None	CH$_3$CN	140	>99
14	CH$_3$CN (200 mol%)	EtOH	140	N/A
15	K$_2$CO$_3$ (20 mol%)	EtOH	120	79
16	K$_2$CO$_3$ (20 mol%)	EtOH	100	56
17	K$_2$CO$_3$ (20 mol%)	EtOH	90	45
18	None	CH$_3$CN	120	71
19	None	CH$_3$CN	100	49
20	None	CH$_3$CN	90	36
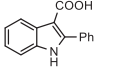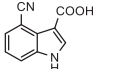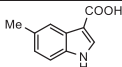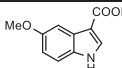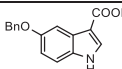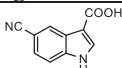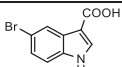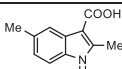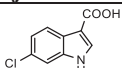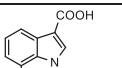
[a]Unless other stated, all reactions are carried out with **1a** (81 mg, 0.5 mmol), catalyst and solvent (3.0 mL) under air at T °C.
[b]Isolated yields.

presence of 200 mol% CH$_3$CN in EtOH (Entry 14). The strong solvent dependence of acetonitrile was noticed that may be due to the solvation effect to help stabilize ionic intermediates. Lastly, the temperature was tested in the above two reaction systems consisting of K$_2$CO$_3$ (20 mol%)/EtOH or CH$_3$CN, respectively. And, the results showed that 140 °C was a better choice for all these two reaction conditions (Entries 15–20).

With these conditions in hand, we next turned our attention to evaluating the scope of this reaction under optimal conditions. As evident from the results compiled in Table 2, Entries 1–12, the decarboxylation can be applied to a wide number of indole-3-carboxylic acids. Indoles **2a–2l** were obtained in good to excellent yields (89%−>99%) with indole-3-carboxylic acids possessing alkyl, chloro, bromo, alkoxy, cyano or nitro substituents at either C2, C4, C5, C6 and/or C7 (**1a–1l**) as starting materials. However, there was an unexpected fact that these two optimal conditions failed to conduct decarboxylation of N-methyl-1H-indole-3-carboxylic acid **1m** and N-benzyl-1H-indole-3-carboxylic acid **1n** (Entries 13 and 14). It is suggested that a procedure involving N–H may have been undergone in the decarboxylation of indole-3-carboxylic acids. In order to further expand the scope of the decarboxylation reaction, ethyl 1H-indole-3-carboxylate **1o**, indole-3-carboxylic acid **1p**, indole-4-carboxylic acid **1q** and 2-naphthoic acid **1r** were tested in these two optimal conditions (Entries 15–18), and the substrates were recovered almost completely. Therefore, the optimal conditions are limited to be applied to the decarboxylation of 3-carboxyl indoles.

Table 2. The screening on the scope of substrate.[a]

Reaction scheme: Substrate **1** (indole-3-carboxylic acid with R' and 2-R substituents) converts to product **2** under conditions **A**: K$_2$CO$_3$ (20 mol%), EtOH, 140 °C; **B**: CH$_3$CN, 140 °C.

Entry	Substrate 1	Product 2	Yield (%)[b]
1	**1a**	**2a**	A: > 99% B: > 99%
2	**1b** (2-Me)	**2b** (2-Me)	A: 95% B: 89%
3	**1c** (2-Ph)	**2c** (2-Ph)	A: 91% B: 98%
4	**1d** (4-CN)	**2d** (4-CN)	A: > 99% B: 97%
5	**1e** (5-Me)	**2e** (5-Me)	A: 97% B: > 99%
6	**1f** (5-MeO)	**2f** (5-MeO)	A: > 99% B: > 99%
7	**1g** (5-BnO)	**2g** (5-BnO)	A: 96% B: > 99%
8	**1h** (5-NC)	**2h** (5-NC)	A: > 99% B: 99%
9	**1i** (5-Br)	**2i** (5-Br)	A: > 99% B: 93%
10	**1j** (5-Me, 2-Me)	**2j** (5-Me, 2-Me)	A: 91% B: > 99%
11	**1k** (6-Cl)	**2k** (6-Cl)	A: > 99% B: > 99%
12	**1l** (7-NO$_2$)	**2l** (7-NO$_2$)	A: 96% B: 98%

13	**1m** (COOH, N–Me indole)	**2m** (N–Me indole)	NA
14	**1n** (COOH, N–Bn indole)	**2n** (N–Bn indole)	NA
15	**1o** (COOEt indole)	**2a**	NA
16	**1p** (2-COOH indole)	**2a**	NA
17	**1q** (4-COOH indole)	**2a**	NA
18	**1r** (naphthalene-2-COOH)	**2r** (naphthalene)	NA

aReaction conditions **A**: **1** (0.50 mmol), K_2CO_3 (13.8 mg, 0.10 mmol, 20 mol%), EtOH (3.0 mL), 140 °C, 24 h; Reaction conditions **B**: **1** (0.50 mmol), CH_3CN (3.0 mL), 140 °C, 24 h.
bIsolated yield.
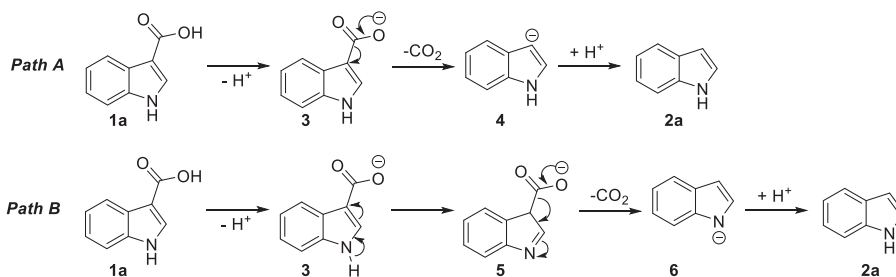
Scheme 3. Proposed mechanism for decarboxylation of indole-3-carboxylic acid.

Based on the reaction results and the known mechanism of protonic acid-catalyzed decarboxylation of pyrrole-2-carboxylic acid,[8] the possible mechanism for decarboxylation of indole-3-carboxylic acids is proposed in Scheme 3. The 1H-indole-3-carboxylate anion **3** is produced under the standard conditions from **1a**. In the proposed path **A**, the decarboxylation of **3** may occur directly to form a carbon anion **4** and be protonated to produce the product **2a**. In the proposed path **B**, the formation of intermediate cyclic-imine **5** from the isomerization of **4** under the optimal conditions is favored. Then, the decarboxylation process may occur to produce **6** and be protonated to produce the product **2a**. In consistent with the decarboxylation of N-alkyl-1H-indole-3-carboxylic acids **1m** and **1n**, it is firmly held that the proposed path **B** is reasonable than path **A**.

In summary, K_2CO_3-catalyzed and acetonitrile-promoted decarboxylation of indole-3-carboxylic acids are achieved, respectively, and the approaches allow for a wide range of 3-carboxyl indoles with good to excellent yields. More applications of base-catalyzed decarboxylative functionalization of indole-2-carboxylic acids and indole-3-carboxylic acids are under active investigation in our laboratory and will be disclosed in due course.

Experimental section

General methods

All commercially available reagents were used without further purification. Column chromatography was performed on silica gel (200–300 mesh). The chemical shifts (δ) of the ^1H NMR (600 MHz) signals are reported in ppm relative to tetramethylsilane (TMS) and by employing the residual solvent resonance as the internal standard. Data are reported in the following order: chemical shift, multiplicity [s (singlet), d (doublet), dd (doublet of doublets), t (triplet), q (quartet), and m (multiplet)], coupling-constants (Hz), and integration. The chemical shifts (δ) of the 13CNMR (151 MHz) signals are reported in ppm relative tetramethylsilane (TMS) and by employing the solvent resonance as the internal standard.

Procedure A: A mixture of indole-3-carboxylic acid **1** (0.50 mmol) and K_2CO_3 (13.8 mg, 0.10 mmol, 20 mol%) in EtOH (3 mL) was added into a Schlenk flask (25 mL) and stirred at 140 °C. The reaction was monitored using thin layer chromatography until the disappearance of starting material **1**. Then, the solvent was evaporated under reduced pressure and the residue was purified using column chromatography (petroleum ether/ethyl acetate 20:1 to 10:1).

Procedure B: A mixture of indole-3-carboxylic acid **1** (0.50 mmol) in CH_3CN (3 mL) was added into a Schlenk flask (25 mL) and stirred at 140 °C. The reaction was monitored by thin layer chromatography until the disappearance of starting material **1**. Then the solvent was evaporated under reduced pressure and the residue was purified by column chromatography (petroleum ether/ethyl acetate 20:1 to 10:1).

1 H-indole (2a)

Yield **A**: > 99%, 59.0 mg; Yield **B**: > 99%, 59.0 mg. White solid, mp 50–52 °C, R_f 0.51 (Hexane/EtOAc, 10:1). ^1H NMR (600 MHz, CDCl$_3$) δ 8.08 (s, 1 H), 7.74 (d, $J = 7.9$ Hz, 1 H), 7.43 (dd, $J = 8.1$, 0.6 Hz, 1 H), 7.31–7.26 (m, 1 H), 7.24–7.19 (m, 2 H), 6.64 (t, $J = 2.1$ Hz, 1 H); ^{13}C NMR (151 MHz, CDCl$_3$) δ 135.8, 127.9, 124.2, 122.0, 120.8, 119.9, 111.1, 102.6.

Full experimental detail, ^1H and ^{13}C NMR spectra. This material can be found via the "Supplementary Content" section of this article's webpage.

Funding

References

[1] (a) Lichtenberger, L. M.; Delansorne, R.; Graziani, L. A. *Nature* **1982**, *295*, 698. DOI: 10.1038/295698a0. (b) Hilpert, W.; Dimroth, T. *Nature* **1982**, *296*, 584. DOI: 10.1038/296584a0.

[2] (a) Weaver, J. D.; Recio III., A.; Grenning, A. J.; Tunge, J. A. *Chem. Rev.* **2011**, *111*, 1846. DOI: 10.1021/cr1002744. (b) Xuan, J.; Zhang, Z.-G.; Xiao, W.-J. *Angew. Chem. Int. Ed. Engl.* **2015**, *54*, 15632. DOI: 10.1002/anie.201505731. (c) Wei, Y.; Hu, P.; Zhang, M.; Su, W. *Chem. Rev.* **2017**, *117*, 8864. DOI: 10.1021/acs.chemrev.6b00516.

[3] (a) Bi, H.-P.; Zhao, L.; Liang, Y.-M.; Li, C.-J. *Angew. Chem. Int. Ed. Engl.* **2009**, *48*, 792. DOI: 10.1002/anie.200805122. (b) Kalutharage, N.; Yi, C. S. *Angew. Chem. Int. Ed. Engl.* **2013**, *52*, 13651. DOI: 10.1002/anie.201307766. (c) Noble, A.; Mega, R. S.; Pfl-Sterer, D.; Myers, E. J.; Aggarwal, V. K. *Angew. Chem. Int. Ed. Engl.* **2018**, *57*, 2155. DOI: 10.1002/anie.201712186.

[4] (a) Gooßen, L. J.; Deng, G.; Levy, L. M. *Science* **2006**, *313*, 662. DOI: 10.1126/science.1128684. (b) Goossen, L. J.; Zimmermann, B.; Knauber, T. *Angew. Chem. Int. Ed. Engl.* **2008**, *47*, 7103. DOI: 10.1002/anie.200800728. (c) Hu, P.; Shang, Y.; Su, W. *Angew. Chem. Int. Ed. Engl.* **2012**, *51*, 5945. DOI: 10.1002/anie.201200153. (d) Song, B.; Knauber, T.; Gooßen, L. J. *Angew. Chem. Int. Ed. Engl.* **2013**, *52*, 2954. DOI: 10.1002/anie.201208025. (e) Howe, G. W.; Vandersteen, A. A.; Kluger, R. *J. Am. Chem. Soc.* **2016**, *138*, 7568. DOI: 10.1021/jacs.6b01770. (f) Perry, G. J. P.; Quibell, J. M.; Panigrahi, A.; Larrosa, I. *J. Am. Chem. Soc.* **2017**, *139*, 11527. DOI: 10.1021/jacs.7b05155. (g) Drapeau, M. P.; Bahri, J.; Lichte, D.; Gooßen, L. J. *Angew. Chem. Int. Ed. Engl.* **2019**, *58*, 892. DOI: 10.1002/anie.201812068.

[5] (a) Goossen, L. J.; Rudolphi, F.; Oppel, C.; Rodríguez, N. *Angew. Chem. Int. Ed. Engl.* **2008**, *47*, 3043. DOI: 10.1002/anie.200705127. (b) Hu, F.; Shao, X.; Zhu, D.; Lu, L.; Shen, Q. *Angew. Chem. Int. Ed. Engl.* **2014**, *53*, 6105. DOI: 10.1002/anie.201402573. (c) Chu, L.; Lipshultz, J. M.; MacMillan, D. W. C. *Angew. Chem. Int. Ed. Engl.* **2015**, *54*, 7929. DOI: 10.1002/anie.201501908. (d) Huang, H.; Zhang, G.; Chen, Y. *Angew. Chem. Int. Ed. Engl.* **2015**, *54*, 7872. DOI: 10.1002/anie.201502369. (e) Tan, H.; Li, H.; Ji, W.; Wang, L. *Angew. Chem. Int. Ed. Engl.* **2015**, *54*, 8374. DOI: 10.1002/anie.201503479. (f) Jian, W.; Ge, L.; Jiao, Y.; Qian, B.; Bao, H. *Angew. Chem. Int. Ed. Engl.* **2017**, *56*, 3650. DOI: 10.1002/anie.201612365. (g) Till, N. A.; Smith, R. T.; MacMillan, D. W. C. *J. Am. Chem. Soc.* **2018**, *140*, 5701. DOI: 10.1021/jacs.8b02834.

[6] (a) Blake, J. A.; Lukeman, M.; Scaiano, J. C. *J. Am. Chem. Soc.* **2009**, *131*, 4127. DOI: 10.1021/ja8094872. (b) Liu, J.; Liu, Q.; Yi, H.; Qin, C.; Bai, R.; Qi, X.; Lan, Y.; Lei, A. *Angew. Chem. Int. Ed. Engl.* **2014**, *53*, 502. DOI: 10.1002/anie.201308614. (c) Zuo, Z.; MacMillan, D. W. C. *J. Am. Chem. Soc.* **2014**, *136*, 5257. DOI: 10.1021/ja501621q. (d) Chu, L.; Lipshultz, J. M.; MacMillan, D. W. C. *Angew. Chem. Int. Ed. Engl.* **2015**, *54*, 7929. DOI: 10.1002/anie.201501908. (e) Huang, H.; Jia, K.; Chen, Y. *Angew. Chem. Int. Ed. Engl.* **2015**, *54*, 1881. DOI: 10.1002/anie.201410176. (f) Huang, X.; Liu, W.; Hooker, J. M.; Groves, J. T. *Angew. Chem. Int. Ed. Engl.* **2015**, *54*, 5241. DOI: 10.1002/anie.201500399. (g) Noble, A.; McCarver, S. J.; MacMillan, D. W. C. *J. Am. Chem. Soc.* **2015**, *137*, 624. DOI: 10.1021/ja511913h. (h) Vaillant, F. L.; Courant, T.; Waser, J. *Angew. Chem. Int. Ed. Engl.* **2015**, *54*, 11200. DOI: 10.1002/anie.201505111. (i) Ventre, S.; Petronijevic, F. R.; MacMillan, D. W. C. *J. Am. Chem. Soc.* **2015**, *137*, 5654. DOI: 10.1021/jacs.5b02244. (j) Zhou, Q.-Q.; Guo, W.; Ding, W.; Wu, X.; Chen, X.; Lu, L.-Q.; Xiao, W.-J. *Angew. Chem. Int. Ed. Engl.* **2015**, *54*, 11196. DOI: 10.1002/anie.201504559. (k) Zuo, Z.; Cong, H.; Li, W.; Choi, J.; Fu, G. C.; MacMillan, D. W. C. *J. Am. Chem. Soc.* **2016**, *138*, 1832. DOI: 10.1021/jacs.5b13211. (l) Cao, H.; Jiang, H.; Feng, H.; Kwan, J. M. C.; Liu, X.; Wu, J. *J. Am. Chem. Soc.* **2018**, *140*, 16360. DOI: 10.1021/jacs.8b11218. (m) Kautzky, J. A.; Wang, T.; Evans, R. W.; MacMillan, D. W. C. *J. Am. Chem. Soc.* **2018**, *140*, 6522. DOI: 10.1021/jacs.8b02650.

[7]   (a) Cleland, W. W. *Acc. Chem. Res.* **1999**, *32*, 862. DOI: 10.1021/ar990065a. (b) Tanaka, D.; Romeril, S. P.; Myers, A. G. *J. Am. Chem. Soc.* **2005**, *127*, 10323. DOI: 10.1021/ja052099l. (c) Zhang, S.-L.; Fu, Y.; Shang, R.; Guo, Q.-X.; Liu, L. *J. Am. Chem. Soc.* **2010**, *132*, 638. DOI: 10.1021/ja907448t. (d) Fromm, A.; van Wüllen, C.; Hackenberger, D.; Gooßen, L. J. *J. Am. Chem. Soc.* **2014**, *136*, 10007. DOI: 10.1021/ja503295x. (e) Kluger, R. *Acc. Chem. Res.* **2015**, *48*, 2843. DOI: 10.1021/acs.accounts.5b00306. (f) Samala, S.; Singh, G.; Kumar, R.; Ampapathi, R. S.; Kundu, B. *Angew. Chem. Int. Ed. Engl.* **2015**, *54*, 9564. DOI: 10.1002/anie.201504429. (g) Vandersteen, A. A.; Howe, G. W.; Lollar, B. S.; Kluger, R. *J. Am. Chem. Soc.* **2017**, *139*, 15049. DOI: 10.1021/jacs.7b07504. (h) Yu, J.-L.; Zhang, S.-Q.; Hong, X. *J. Am. Chem. Soc.* **2017**, *139*, 7224. DOI: 10.1021/jacs.7b00714.

[8]   (a) Mundle, S. O. C.; Kluger, R. *J. Am. Chem. Soc.* **2009**, *131*, 11674. DOI: 10.1021/ja905196n. (b) Mundle, S. O. C.; Lacrampe-Couloume, G.; Lollar, B. S.; Kluger, R. *J. Am. Chem. Soc.* **2010**, *132*, 2430. DOI: 10.1021/ja910608m.

[9]   Yu, X.; He, M.; Wu, J.; Zhou, C.; Feng, X.; Yamamoto, Y.; Bao, M. *Org. Lett.* **2018**, *20*, 6780. DOI: 10.1021/acs.orglett.8b02896.

[10]   Zhang, X.; Feng, X.; Zhou, C.; Yu, X.; Yamamoto, Y.; Bao, M. *Org. Lett.* **2018**, *20*, 7095. DOI: 10.1021/acs.orglett.8b03043.

[11]   (a) Allen, G. R. Jr. *Org. React.* **1973**, *20*, 337. (b) Baiocchi, L.; Giannangeli, M. *J. Heterocyclic Chem.* **1988**, *25*, 1905. DOI: 10.1002/jhet.5570250654. (c) Sakamoto, T.; Nagano, T.; Kondo, Y.; Yamanaka, H. *Synthesis* **1990**, *1990*, 215. DOI: 10.1055/s-1990-26835. (d) Kondo, Y.; Shiga, F.; Murata, N.; Sakamoto, T.; Yamanaka, H. *Tetrahedron* **1994**, *50*, 11803. DOI: 10.1016/S0040-4020(01)89295-4. (e) Yamazaki, K.; Nakamura, Y.; Kondo, Y. *J. Org. Chem.* **2003**, *68*, 6011. DOI: 10.1021/jo0340307. (f) Islam, M. S.; Brennan, C.; Wang, Q.; Hossain, M. M. *J. Org. Chem.* **2006**, *71*, 4675. DOI: 10.1021/jo0601821. (g) Söderberg, B. C. G.; Banini, S. R.; Turner, M. R.; Minter, A. R.; Arrington, A. K. *Synthesis* **2008**, *2008*, 903. DOI: 10.1055/s-2008-1032208.

[12]   (a) Walser, A.; Blount, J. F.; Fryer, R. I. *J. Org. Chem.* **1973**, *38*, 3077. DOI: 10.1021/jo00958a001. (b) Maehara, A.; Tsurugi, H.; Satoh, T.; Miura, M. *Org. Lett.* **2008**, *10*, 1159. DOI: 10.1021/ol8000602. (c) Yamashita, M.; Hirano, K.; Satoh, T.; Miura, M. *Org. Lett.* **2009**, *11*, 2337. DOI: 10.1021/ol900736s. (d) Hikawa, H.; Kotaki, F.; Kikkawa, S.; Azumaya, I. *J. Org. Chem.* **2019**, *84*, 1972. DOI: 10.1021/acs.joc.8b02947. (e) Zhang, Y.; Hu, Z.-Y.; Li, X.-C.; Guo, X.-X. *Synthesis* **2019**, *51*, 1803. DOI: 10.1055/s-0037-1611946.

[13]   Vandersteen, A. A.; Mundle, S. O. C.; Kluger, R. *J. Org. Chem.* **2012**, *77*, 6505. DOI: 10.1021/jo301032f.

[14]   Yue, H.; Guo, L.; Lee, S.-C.; Liu, X.; Rueping, M. *Angew. Chem. Int. Ed. Engl.* **2017**, *56*, 3972. DOI: 10.1002/anie.201612624.

[15]   Liu, C.; Qin, Z.-X.; Ji, C.-L.; Hong, X.; Szostak, M. *Chem. Sci.* **2019**, *10*, 5736. DOI: 10.1039/c9sc00892f.