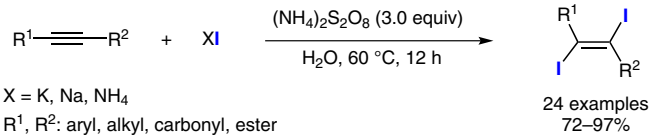
Synthesis Q. Jiang et al. Paper

$(NH_4)_2S_2O_8$-Mediated Diiodination of Alkynes with Iodide in Water: Stereospecific Synthesis of (*E*)-Diiodoalkenes

Qing Jiang
Jing-Yu Wang
Can-Cheng Guo*

College of Chemistry and Chemical Engineering, Hunan University, Changsha 410082, P. R. of China
ccguo@hnu.edu.cn



X = K, Na, NH_4
R^1, R^2: aryl, alkyl, carbonyl, ester

24 examples
72–97%

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Abstract A new approach to the stereospecific diiodination of alkynes under mild conditions has been developed. This protocol employs ammonium persulfate as an oxidant and iodide as an iodine source, and provides a highly efficient and general method for the preparation of a broad range of (*E*)-diiodoalkenes in water.

Key words persulfate salts, diiodination, alkenes, alkynes, water

Dihaloalkenes are valuable intermediates in organic synthesis and they are often employed for transition-metal-catalyzed cross-coupling reactions.[1,2] Among them, 1,2-diiodoalkenes have attracted attention because of their important roles in a wide variety of functional group transformations and direct coupling reactions for forming new carbon–carbon bonds, either involving organo-copper, organolithium, or metal-catalyzed cross-coupling reactions.[3] Despite the utility of vicinal diiodoalkenes, synthetic access to such compounds presents a challenge. Earlier studies have shown that they could be prepared stereospecifically by direct addition of iodine to alkynes.[4] However, the reactions proceeded very slowly and with low conversion. Later on, various additives such as alumina or CuI were included to improve the efficiency of the reaction; however, such approaches present additional problems in purification and environmental concerns.[5] Furthermore, hazardous I_2 or IX was used as an iodide, and harmful solvents such as dichloromethane, acetonitrile (MeCN), methanol, and petroleum ether were used in all cases.[6] In 2008, Stavber reported a sodium nitrite-catalyzed aerobic oxidative diiodination of alkynes with KI in the presence of H_2SO_4 in MeCN in which terminal alkynes were diiodinated in quantitative yield, but internal alkynes gave a mixture of *E*/*Z* isomers.[6g] Recently, Madabhushi developed an oxone-mediated diiodination of alkynes with KI in MeCN–H_2O; however, in most cases, mixtures of 1,2-diiodo alkenes and α,α-diiodoketones were obtained in moderate yields.[6h] Despite some advances, the quest for a simple and green method for the diiodination of alkynes with excellent functional group compatibility, high efficiency, broad substrate scope, and operational simplicity remains of considerable interest to synthetic organic chemists.

Water is inexpensive, safe, and an ideal green solvent, and can potentially provide benefits for chemical syntheses in terms of resource economy, energy efficiency, and health and environmental safety.[7] Furthermore, water has unique chemical and physical properties that allow reactivities to be realized that cannot be attained in organic solvents. Moreover, employing water as solvent can reduce the need for organic solvents, simplify the workup procedures, and allow mild conditions.[8] Despite the advantages that water offers, the development of organic reactions that run in pure water as reaction medium without the addition of any organic cosolvents is still much underdeveloped and remains both challenging and of great value.

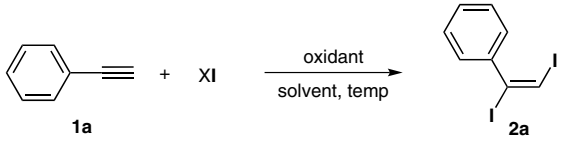
Herein, we wish to report a diiodination of alkynes with iodide in water in the presence of persulfate salt. This protocol provides a highly efficient and environmentally benign method for the preparation of a wide range of (*E*)-diiodoalkenes in water, and the method exhibits broad substrate scope and excellent functional group tolerance.

Recently, we developed the $K_2S_2O_8$-mediated oxybromination of alkenes with KBr in water,[9] and oxyhalogenation of alkynes with NaX in the presence of water.[10] When phenylacetylene was submitted to the mixture of KI and water in the presence of $K_2S_2O_8$, a diiodination, not the expected oxyiodination, occurred during the reaction to produce the (*E*)-1,2-diiodostyrene. This unexpected result prompted us to undertake further investigations. Initially, we chose phenylacetylene as a model reaction to test the reaction condi-

tions. Selected conditions in this study are listed in Table 1. When the reaction was carried out in the presence of KI (2.0 equiv) and $K_2S_2O_8$ (2.5 equiv) in water at 60 °C for 12 hours, the desired product **2a** was obtained in 92% yield (Table 1, entry 1). Control experiments showed that the reaction did not proceed in the absence of $K_2S_2O_8$ (Table 1, entry 2). The use of $(NH_4)_2S_2O_8$ and NH_4I as oxidant and iodine source, respectively, could afford the desired product in a yield of 84% (Table 1, entry 3). Remarkably, increasing the amount of $(NH_4)_2S_2O_8$ and NH_4I improved the yield to 95% (Table 1, entry 4), whereas further increase of the equivalent amount of $(NH_4)_2S_2O_8$ or NH_4I did not improve the yield further (Table 1, entries 5 and 6). The diiodination reaction afforded lower yield when performed at higher (80 °C) or lower (40 °C) temperature (Table 1, entries 7 and 8). We found that the use of organic solvent inhibited the reaction to some extent. Gratifyingly, other iodine sources, such as KI and NaI, gave comparable results (Table 1, entries 12 and 13). In addition, no (*Z*)-1,2-diiodostyrene was detected under any of the conditions tested. Finally, reaction of phenylacetylene with molecular iodine in water provided the product **2a** in 86% yield (Table 1, entry 14). Under these conditions, although the use of molecular iodine could deliver a good result, the post-treatment was generally troublesome, and it was difficult to completely remove the deep color from the reaction mixture.

With the establishment of the optimal conditions, the scope of this diiodination was then explored. The scope of the reaction with phenylacetylenes in the diiodination with NH_4I or KI was examined first (Table 2). With either electron-donating or electron-withdrawing groups such as alkyl (**2b**–**g**), alkoxyl (**2h**), and halide groups (**2i**–**k**) at the *para*- and *meta*-position of the phenyl ring, the reaction proceeded smoothly, affording the corresponding products in 88–97% yields (Table 2, entries 2–11). Moreover, aromatic internal alkynes also underwent diiodination efficiently to give the products in 87–96% yields (Table 2, entries 12–16).

Table 1 Optimization of the Reaction Conditions[a]

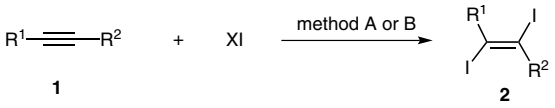


1a 2a

Entry	Oxidant (equiv)	XI (equiv)	Solvent	Temp (°C)	Yield (%)[b]
1	$K_2S_2O_8$ (2.5)	KI (2.0)	H_2O	60	92
2	none	KI (2.0)	H_2O	60	0
3	$(NH_4)_2S_2O_8$ (2.5)	NH_4I (2.0)	H_2O	60	84
4	$(NH_4)_2S_2O_8$ (3.0)	NH_4I (2.5)	H_2O	60	95
5	$(NH_4)_2S_2O_8$ (3.5)	NH_4I (2.0)	H_2O	60	93
6	$(NH_4)_2S_2O_8$ (3.0)	NH_4I (3.0)	H_2O	60	92
7	$(NH_4)_2S_2O_8$ (3.0)	NH_4I (2.5)	H_2O	80	32
8	$(NH_4)_2S_2O_8$ (3.0)	NH_4I (2.5)	H_2O	40	77
9	$(NH_4)_2S_2O_8$ (3.0)	NH_4I (2.5)	CH_3CN	60	38
10	$(NH_4)_2S_2O_8$ (3.0)	NH_4I (2.5)	EtOH	60	45
11	$(NH_4)_2S_2O_8$ (3.0)	NH_4I (2.5)	EtOH–H_2O[c]	60	78
12	$(NH_4)_2S_2O_8$ (3.0)	KI (2.5)	H_2O	60	98
13	$(NH_4)_2S_2O_8$ (3.0)	NaI (2.5)	H_2O	60	96
14	none	I_2 (2.5)	H_2O	60	86

[a] Reaction conditions: **1a** (0.5 mmol), solvent (1 mL), 12 h.
[b] Yield determined by GC analysis.
[c] Ratio 1:1.

Table 2 Scope of the Diiodination of Alkynes Mediated by $(NH_4)_2S_2O_8$[a]



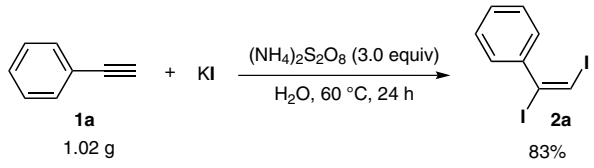
1 2

Entry	Product	R^1	R^2	Yield (method A)[b]	Yield (method B)[b]
1	**2a**	Ph	H	92	94
2	**2b**	4-MeC_6H_4	H	93	96
3	**2c**	3-MeC_6H_4	H	91	93
4	**2d**	4-EtC_6H_4	H	90	93
5	**2e**	4-PrC_6H_4	H	91	94
6	**2f**	4-BuC_6H_4	H	88	92
7	**2g**	4-$Me(CH_2)_4C_6H_4$	H	90	92
8	**2h**	4-$MeOC_6H_4$	H	94	97
9	**2i**	4-FC_6H_4	H	92	97
10	**2j**	4-ClC_6H_4	H	90	93
11	**2k**	4-BrC_6H_4	H	89	94
12	**2l**	Ph	Me	92	96
13	**2m**	Ph	Et	90	95
14	**2n**	Ph	Pr	91	94
15	**2o**	Ph	Bu	88	93
16	**2p**	Ph	Ph	89	90
17	**2q**	Pr	Pr	86	91
18	**2r**	$Me(CH_2)_4$	H	92	88
19	**2s**	$HO(CH_2)_2$	H	80	85
20	**2t**	$HO(CH_2)_3$	H	72	76
21	**2u**	$HO(CH_2)_4$	H	90	93
22	**2v**	Me	CO_2Me	84	89
23	**2w**	H	CO_2Me	82	86
24	**2x**	H	Ac	73	76

[a] Reaction conditions: Method A: alkyne (0.5 mmol), $(NH_4)_2S_2O_8$ (3.0 equiv), NH_4I (2.5 equiv), H_2O (1 mL), 60 °C, 12 h. Method B: alkyne (0.5 mmol), $(NH_4)_2S_2O_8$ (3.0 equiv), KI (2.5 equiv), H_2O (1 mL), 60 °C, 12 h.
[b] The cited yields are of material isolated by column chromatography.

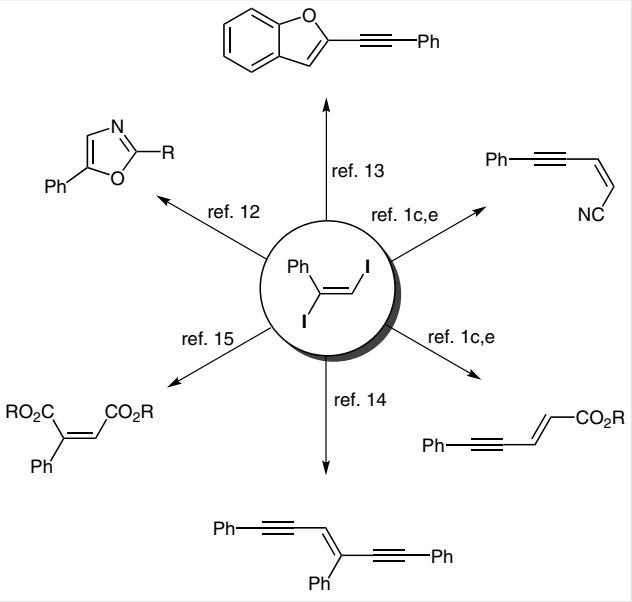
To our delight, besides aromatic alkynes, aliphatic alkynes could react with NH_4I or KI to provide the desired diiodination products in 72–91% yields (Table 2, entries 17–21). Conjugated alkynyl carboxylic acid derivatives and ketone also gave the desired products in 73–89% yield (Table 2, entries 22–24). As shown in Table 2, a variety of functional groups, including F, Cl, Br, ether, ester, ketone and hydroxyl, were tolerated under the reaction conditions, which enables potential applications in further functionalization.[11] It should be noted that the iodination reaction occurred exclusively through *anti*-addition to alkynes in all cases. Moreover, the stereochemistries of diiodoalkenes were confirmed by comparing NMR data with reported values. In addition, according to experimental observations, the present reaction is heterogeneous, and might exhibit an 'on water' effect.[7d,e]

To demonstrate the synthetic utility of this diiodination reaction, we conducted the reaction on a gram scale and obtained **2a** in 83% yield (Equation 1), thus demonstrating the scalability of this reaction.



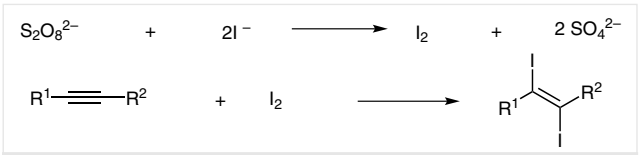
Equation 1

(*E*)-(1,2-diiodovinyl)benzenes can be converted into various useful heterocycles and valuable synthons, such as oxazoles,[12] 2-ethynylbenzofurans,[13] 2-en-4-ynenitriles,[1c,e] 2-en-4-ynoates,[1c,e] enediynes,[14] and maleic diesters[15] (Scheme 1). Among them, oxazoles and benzofurans are an important structural motif that is frequently found in natural and unnatural compounds,[16] enediynes and maleic diesters exhibit some biological properties such as antitumor activity,[17] and 1,3-enyne moieties are ubiquitous in many naturally occurring and biologically active compounds such as calichemicin γ_1, which is an effective antitumor antibiotic, and terbinafine, which is a potent drug for superficial fungal infections.[18]



Scheme 1 Transformations of (*E*)-(1,2-diiodovinyl)benzenes

Although the exact mechanism of this reaction is still not clear, on the basis of these preliminary results and on reported precedents,[3–7,19] a plausible reaction pathway is proposed (Scheme 2). Initially, oxidation of the iodide ion by the persulfate ion generates molecular iodine. The formation of I_2 has been confirmed by observation of a color change from red to deep-blue when starch was added into the solution. Finally, the molecular iodine undergoes electrophilic *anti*-addition onto the alkyne to give the corresponding (*E*)-1,2-diiodoakene.



Scheme 2 Possible reaction pathway

In summary, we have developed a novel protocol for the synthesis of (*E*)-diiodoalkenes by metal-free diiodination of alkynes under mild conditions. This transformation is environmentally benign in adoption of readily available ammonium persulfate as oxidant, nontoxic iodide as iodine resource, and water as solvent. The protocol exhibits broad substrate scope and high functional group tolerance. Our current efforts are directed toward the further application of the products and the further development of organic reactions in pure water.

All commercially available compounds were purchased from commercial suppliers and used without further purification unless otherwise noted. ^1H and ^{13}C NMR spectra were recorded on an Inova-400 (Varian) spectrometer operating at 400 MHz (^1H NMR) and 100 MHz (^{13}C NMR), in $CDCl_3$ or DMSO-d_6 using TMS as internal standard. Column chromatography was performed on 200–300 mesh silica gel. Thin-layer chromatography (TLC) was performed on Silicycle 250 mm silica gel F-254 plates. Multiplicities are indicated as s (singlet), d (doublet), t (triplet), q (quartet), and m (multiplet), and coupling constants (*J*) are reported in hertz. Petroleum ether (PE) refers to the hydrocarbon fraction boiling in the 60–90 °C range.

Diiodination of Alkynes; General Procedures

Method A: To a 25 mL Schlenck tube were added $(NH_4)_2S_2O_8$ (3.0 equiv), NH_4I (2.5 equiv), alkyne (0.5 mmol), and H_2O (1 mL). The reaction mixture was warmed to 60 °C (oil bath) and stirred for 12 h. The mixture was cooled to r.t., and EtOAc (5 mL) and H_2O (2 mL) were

added. The organic layer was separated, and the aqueous phase was extracted with EtOAc (2 × 10 mL). The combined organic layers were dried over anhydrous Na_2SO_4, filtered, and concentrated. The residue was purified by column chromatography to give the pure sample.

Method B: To a 25 mL Schlenck tube were added $(NH_4)_2S_2O_8$ (3.0 equiv), NH_4I (2.5 equiv), alkynes (0.5 mmol), and H_2O (1 mL). The reaction mixture was warmed to 60 °C (oil bath) and stirred for 12 h. The mixture was cooled to r.t., and EtOAc (5 mL) and H_2O (2 mL) were added. The organic layer was separated, and the aqueous phase was extracted with EtOAc (2 × 10 mL). The combined organic layers were dried over anhydrous Na_2SO_4, filtered, and concentrated. The residue was purified by column chromatography to give the pure sample.

(*E*)-(1,2-Diiodovinyl)benzene (2a)[6g]

[CAS Reg. No.: 71022-74-7]

Purified by flash chromatography (PE).

Yield: 163.8 mg (92%) (method A) or 167.3 mg (94%) (method B); colorless solid; mp 73–75 °C.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.26 (s, 1 H), 7.36 (s, 5 H).

^{13}C NMR (101 MHz, $CDCl_3$): δ = 80.8, 96.2, 128.4, 128.5, 129.0, 143.1.

HRMS (EI): *m*/*z* [M]$^+$ calcd for $C_8H_6I_2$: 355.8553; found: 355.8545.

(*E*)-1-(1,2-Diiodovinyl)-4-methylbenzene (2b)[6h]

[CAS Reg. No.: 219517-81-4]

Purified by flash chromatography (PE).

Yield: 172.1 mg (93%) (method A) or 177.6 mg (96%) (method B); red oil.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 2.35 (s, 2 H), 7.15 (d, *J* = 8.0 Hz, 2 H), 7.21 (s, 1 H), 7.26 (d, *J* = 8.0 Hz, 2 H).

^{13}C NMR (101 MHz, $CDCl_3$): δ = 21.5, 80.4, 96.8, 128.6, 129.2, 139.1, 140.2.

HRMS (EI): *m*/*z* [M]$^+$ calcd for $C_9H_8I_2$: 369.8710; found: 369.8697.

(*E*)-1-(1,2-Diiodovinyl)-3-methylbenzene (2c)

Purified by flash chromatography (PE).

Yield: 168.4 mg (91%) (method A) or 172.1 mg (93%) (method B); pale-yellow oil.

IR (neat): 3061, 2917, 2856, 1588, 1478, 1201, 1134, 1091, 795, 760, 698, 603 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 2.36 (s, 3 H), 7.11–7.15 (m, 3 H), 7.22–7.25 (m, 2 H).

^{13}C NMR (101 MHz, $CDCl_3$): δ = 21.5, 80.7, 96.6, 125.6, 128.4, 129.1, 129.8, 138.2, 143.0.

HRMS (EI): *m*/*z* [M]$^+$ calcd for $C_9H_8I_2$: 369.8710; found: 369.8700.

(*E*)-1-(1,2-Diiodovinyl)-4-ethylbenzene (2d)

Purified by flash chromatography (PE).

Yield: 172.8 mg (90%) (method A) or 178.6 mg (93%) (method B); orange oil.

IR (neat): 3063, 2962, 2927, 1608, 1498, 1454, 1240, 1150, 850, 828, 776, 595 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.25 (t, *J* = 8.0 Hz, 3 H), 2.65 (q, *J* = 8.0 Hz, 2 H), 7.18 (d, *J* = 6.8 Hz, 2 H), 7.21 (s, 1 H), 7.28–7.30 (m, 2 H).

^{13}C NMR (101 MHz, $CDCl_3$): δ = 15.3, 28.8, 80.3, 96.8, 127.9, 128.6, 140.6, 145.3.

HRMS (EI): *m*/*z* [M]$^+$ calcd for $C_{10}H_{10}I_2$: 383.8866; found: 383.8857.

(*E*)-1-(1,2-Diiodovinyl)-4-propylbenzene (2e)

Purified by flash chromatography (PE).

Yield: 181.1 mg (91%) (method A) or 187.1 mg (94%) (method B); red oil.

IR (neat): 3061, 2925, 2864, 1604, 1497, 1455, 1149, 819, 776, 595 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 0.96 (t, *J* = 8.0 Hz, 3 H), 1.61–1.70 (m, 2 H), 2.59 (t, *J* = 8.0 Hz, 2 H), 7.16 (d, *J* = 8.0 Hz, 2 H), 7.22 (s, 1 H), 7.29 (d, *J* = 8.0 Hz, 2 H).

^{13}C NMR (101 MHz, $CDCl_3$): δ = 14.0, 24.3, 37.9, 80.2, 96.8, 128.4, 128.5, 140.3, 143.8.

HRMS (EI): *m*/*z* [M]$^+$ calcd for $C_{11}H_{12}I_2$: 397.9023; found: 397.9032.

(*E*)-1-Butyl-4-(1,2-diiodovinyl)benzene (2f)

Purified by flash chromatography (PE).

Yield: 181.3 mg (88%) (method A) or 189.5 mg (92%) (method B); pale-yellow oil.

IR (neat): 3066, 2954, 2926, 2858, 1607, 1498, 1458, 1150, 829, 777, 597 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 0.94 (t, *J* = 6.8 Hz, 3 H), 1.34–1.42 (m, 2 H), 1.57–1.65 (m, 2 H), 2.61 (t, *J* = 8.0 Hz, 2 H), 7.16 (d, *J* = 8.0 Hz, 2 H), 7.22 (s, 1 H), 7.28 (t, *J* = 8.0 Hz, 2 H).

^{13}C NMR (101 MHz, $CDCl_3$): δ = 14.0, 22.5, 33.3, 35.6, 80.1, 96.8, 128.4, 128.5, 140.2, 144.1.

HRMS (EI): *m*/*z* [M]$^+$ calcd for $C_{12}H_{14}I_2$: 411.9179; found: 411.9175.

(*E*)-1-(1,2-Diiodovinyl)-4-pentylbenzene (2g)[6h]

[CAS Reg. No.: 1446467-81-7]

Purified by flash chromatography (PE).

Yield: 191.7 mg (90%) (method A) or 196.0 mg (92%) (method B); pale-yellow oil.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 0.90 (t, *J* = 6.8 Hz, 3 H), 1.33–1.34 (m, 4 H), 1.61–1.64 (m, 2 H), 2.60 (t, *J* = 8.0 Hz, 2 H), 7.15 (d, *J* = 8.0 Hz, 2 H), 7.21 (s, 1 H), 7.28 (d, *J* = 6.8 Hz, 2 H).

^{13}C NMR (101 MHz, $CDCl_3$): δ = 14.2, 22.6, 30.9, 31.6, 35.9, 80.2, 96.9, 128.4, 128.6, 140.2, 144.1.

HRMS (EI): *m*/*z* [M]$^+$ calcd for $C_{13}H_{16}I_2$: 425.9336; found: 425.9342.

(*E*)-1-(1,2-Diiodovinyl)-4-methoxybenzene (2h)

[CAS Reg. No.: 61926-36-1]

Purified by flash chromatography (PE–CH_2Cl_2, 7:1).

Yield: 181.4 mg (94%) (method A) or 187.2 mg (97%) (method B); pale-yellow oil.

IR (neat): 3051, 2922, 2837, 1601, 1504, 1299, 1254, 1177, 1026, 812, 763 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 3.81 (s, 3 H), 6.86 (d, *J* = 8.0 Hz, 2 H), 7.18 (s, 1 H), 7.33 (t, *J* = 12.0 Hz, 2 H).

^{13}C NMR (101 MHz, $CDCl_3$): δ = 55.4, 80.0, 96.7, 113.7, 130.3, 135.5, 159.8.

HRMS (EI): *m*/*z* [M]$^+$ calcd for $C_9H_8OI_2$: 385.8659; found: 385.8657.

(*E*)-1-(1,2-Diiodovinyl)-4-fluorobenzene (2i)

[CAS Reg. No.: 1041003-09-1]

Purified by flash chromatography (PE).

Yield: 172.0 mg (92%) (method A) or 181.4 mg (97%) (method B); orange oil.

IR (neat): 3062, 1597, 1500, 1220, 1153, 1095, 858, 833, 780, 594 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 7.05 (t, *J* = 8.0 Hz, 2 H), 7.27 (s, 1 H), 7.33–7.36 (m, 2 H).

^{13}C NMR (101 MHz, $CDCl_3$): δ = 81.6, 94.9, 115.6 (d, J_{C-F} = 22 Hz), 130.6 (d, J_{C-F} = 9.0 Hz), 139.1 (d, J_{C-F} = 4.0 Hz), 162.5 (d, J_{C-F} = 248 Hz).

HRMS (EI): *m*/*z* $[M]^+$ calcd for $C_8H_5FI_2$: 373.8459; found: 373.8464.

(*E*)-1-Chloro-4-(1,2-diiodovinyl)benzene (2j)

[CAS Reg. No.: 943032-01-7]

Purified by flash chromatography (PE).

Yield: 175.5 mg (90%) (method A) or 181.4 mg (93%) (method B); pale-yellow oil.

IR (neat): 2919, 1482, 1098, 1011, 852, 828, 781, 593 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 7.28–7.30 (m, 3 H), 7.33–7.35 (m, 2 H).

^{13}C NMR (101 MHz, $CDCl_3$): δ = 81.8, 94.6, 128.8, 130.0, 134.9, 141.5.

HRMS (EI): *m*/*z* $[M]^+$ calcd for $C_8H_5ClI_2$: 389.8164; found: 389.8164.

(*E*)-1-Bromo-4-(1,2-diiodovinyl)benzene (2k)

Purified by flash chromatography (PE).

Yield: 193.1 mg (89%) (method A) or 204.4 mg (94%) (method B); colorless solid; mp 62–64 °C.

IR (KBr): 3059, 1476, 1067, 1009, 844, 814, 771, 593 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 7.22 (d, *J* = 8.0 Hz, 2 H), 7.27 (s, 1 H), 7.49 (d, *J* = 12.0 Hz, 2 H).

^{13}C NMR (101 MHz, $CDCl_3$): δ = 82.0, 94.8, 123.2, 130.3, 131.8, 142.0.

HRMS (EI): *m*/*z* $[M]^+$ calcd for $C_8H_5BrI_2$: 433.7659; found: 433.7667.

(*E*)-1,2-Diiodo-1-phenyl-1-propene (2l)[6g]

[CAS Reg. No.: 268550-89-6]

Purified by flash chromatography (PE).

Yield: 170.2 mg (92%) (method A) or 177.6 mg (96%) (method B); red oil.

^1H NMR (400 MHz, $CDCl_3$): δ = 2.79 (s, 3 H), 7.22 (d, *J* = 8.0 Hz, 2 H), 7.27 (t, *J* = 8.0 Hz, 1 H), 7.34 (t, *J* = 8.0 Hz, 2 H).

^{13}C NMR (101 MHz, $CDCl_3$): δ = 40.3, 95.7, 96.5, 128.3, 128.4, 128.5, 148.1.

HRMS (EI): *m*/*z* $[M]^+$ calcd for $C_9H_8I_2$: 369.8710; found: 369.8714.

(*E*)-1-Phenyl-1,2-diiodo-1-butene (2m)[20]

[CAS Reg. No.: 64454-37-1]

Purified by flash chromatography (PE).

Yield: 172.8 mg (90%) (method A) or 182.4 mg (95%) (method B); pale-yellow oil.

^1H NMR (400 MHz, $CDCl_3$): δ = 1.17 (t, *J* = 8.0 Hz, 3 H), 2.87 (q, *J* = 8.0 Hz, 2 H), 7.20 (d, *J* = 8.0 Hz, 2 H), 7.27 (t, *J* = 8.0 Hz, 1 H), 7.33 (t, *J* = 8.0 Hz, 2 H).

^{13}C NMR (101 MHz, $CDCl_3$): δ = 13.1, 44.9, 93.8, 106.6, 128.2, 128.5, 128.6, 148.1.

HRMS (EI): *m*/*z* $[M]^+$ calcd for $C_{10}H_{10}I_2$: 383.8866; found: 383.8858.

(*E*)-1-Phenyl-1,2-diiodo-1-pentene (2n)

Purified by flash chromatography (PE).

Yield: 181.1 mg (91%) (method A) or 187.1 mg (94%) (method B); orange oil.

IR (neat): 2957, 2924, 2865, 1453, 1105, 751, 692, 583, 566 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 1.06 (t, *J* = 6.8 Hz, 3 H), 1.67–1.77 (m, 2 H), 2.84 (t, *J* = 8.0 Hz, 2 H), 7.20 (d, *J* = 8.0 Hz, 2 H), 7.28 (d, *J* = 8.0 Hz, 1 H), 7.34 (t, *J* = 8.0 Hz, 2 H).

^{13}C NMR (101 MHz, $CDCl_3$): δ = 13.0, 21.9, 52.1, 94.7, 105.2, 128.2, 128.4, 128.5, 148.3.

HRMS (EI): *m*/*z* $[M]^+$ calcd for $C_{11}H_{12}I_2$: 397.9023; found: 397.9017.

(*E*)-1-Phenyl-1,2-diiodo-1-hexene (2o)

Purified by flash chromatography (PE).

Yield: 181.3 mg (88%) (method A) or 191.6 mg (93%) (method B); pale-yellow oil.

IR (neat): 2962, 2926, 2861, 1486, 1446, 1111, 750, 692, 571, 638 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 1.01 (t, *J* = 6.8 Hz, 3 H), 1.42–1.51 (m, 2 H), 1.62–1.70 (m, 2 H), 2.85 (t, *J* = 8.0 Hz, 2 H), 7.19 (d, *J* = 8.0 Hz, 2 H), 7.26 (t, *J* = 8.0 Hz, 1 H), 7.33 (t, *J* = 8.0 Hz, 2 H).

^{13}C NMR (101 MHz, $CDCl_3$): δ = 14.8, 21.9, 30.6, 50.4, 94.5, 105.4, 128.4, 128.5, 131.6, 148.2.

HRMS (EI): *m*/*z* $[M]^+$ calcd for $C_{12}H_{14}I_2$: 411.9179; found: 411.9195.

(*E*)-1,2-Diiodo-1,2-diphenylethene (2p)[21]

[CAS Reg. No.: 20432-11-5]

Purified by flash chromatography (PE–EtOAc, 50:1).

Yield: 187.9 mg (87%) (method A) or 194.4 mg (90%) (method B); colorless solid; mp 181–183 °C.

^1H NMR (400 MHz, DMSO-d_6): δ = 7.33–7.6 (m, 6 H), 7.43–7.47 (m, 4 H).

^{13}C NMR (101 MHz, DMSO-d_6): δ = 99.7, 128.6, 128.8, 129.1, 148.2.

HRMS (EI): *m*/*z* $[M]^+$ calcd for $C_{14}H_{10}I_2$: 431.8866; found: 431.8866.

(*E*)-4,5-Diiodooct-4-ene (2q)[6f]

[CAS Reg. No.: 124471-41-6]

Purified by flash chromatography (PE).

Yield: 156.5 mg (86%) (method A) or 165.6 mg (91%) (method B); pale-yellow oil.

^1H NMR (400 MHz, $CDCl_3$): δ = 0.96 (t, *J* = 8.0 Hz, 3 H), 154–1.62 (m, 2 H), 2.68 (t, *J* = 8.0 Hz, 2 H).

^{13}C NMR (101 MHz, $CDCl_3$): δ = 12.9, 21.7, 52.6, 102.1.

HRMS (EI): *m*/*z* $[M]^+$ calcd for $C_8H_{14}I_2$: 363.9179; found: 363.9183.

(*E*)-1,2-Diiodohept-1-ene (2r)[6f]

[CAS Reg. No.: 192763-37-4]

Purified by flash chromatography (PE).

Yield: 143.5 mg (82%) (method A) or 154.0 mg (88%) (method B); colorless oil.

^1H NMR (400 MHz, $CDCl_3$): δ = 0.92 (t, *J* = 6.8 Hz, 3 H), 1.31–1.40 (m, 4 H), 1.51–1.58 (m, 2 H), 2.50 (t, *J* = 8.0 Hz, 2 H), 6.80 (s, 1 H).

^{13}C NMR (101 MHz, $CDCl_3$): δ = 14.0, 22.5, 27.9, 30.4, 44.7, 79.0, 104.5.

HRMS (EI): *m*/*z* [M]$^+$ calcd for $C_7H_{12}I_2$: 349.9023; found: 349.9022.

(*E*)-3,4-Diiodobut-3-en-1-ol (2s)[13]

[CAS Reg. No.: 1126638-97-8]

Purified by flash chromatography (PE–EtOAc, 7:1).

Yield: 129.6 mg (80%) (method A) or 137.7 mg (85%) (method B); orange oil.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 2.14–2.50 (br s, 1 H), 2.80–2.83 (m, 2 H), 3.83 (t, *J* = 8.0 Hz, 2 H), 7.02 (s, 1 H).

^{13}C NMR (101 MHz, $CDCl_3$): δ = 47.5, 60.7, 82.2, 99.0.

HRMS (EI): *m*/*z* [M]$^+$ calcd for $C_4H_6I_2O$: 323.8503; found: 323.8496.

(*E*)-4,5-Diiodopent-4-en-1-ol (2t)

Purified by flash chromatography (PE–EtOAc, 6:1).

Yield: 121.7 mg (72%) (method A) or 128.4 mg (76%) (method B); orange oil.

IR (neat): 3325, 3066, 2943, 2873, 1436, 1213, 1175, 1060, 768, 565 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.18 (br s, 1 H), 1.71–1.78 (m, 2 H), 2.58 (t, *J* = 8.0 Hz, 2 H), 3.62 (t, *J* = 6.8 Hz, 2 H), 6.79 (s, 1 H).

^{13}C NMR (101 MHz, $CDCl_3$): δ = 31.0, 41.5, 61.1, 79.8, 103.3.

HRMS (EI): *m*/*z* [M]$^+$ calcd for $C_5H_8I_2O$: 337.8659; found: 337.8645.

(*E*)-5,6-Diiodohex-5-en-1-ol (2u)

Purified by flash chromatography (PE–EtOAc, 6:1).

Yield: 158.4 mg (90%) (method A) or 163.7 mg (93%) (method B); orange oil.

IR (neat): 3318, 3067, 2918, 2862, 1447, 1210, 1062, 770, 630, 565 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.61–1.62 (m, 4 H), 2.43 (br s, 1 H), 2.55 (t, *J* = 8.0 Hz, 2 H), 2.67 (t, *J* = 6.8 Hz, 2 H), 6.85 (s, 1 H).

^{13}C NMR (101 MHz, $CDCl_3$): δ = 24.6, 31.1, 44.4, 62.5, 79.8, 104.0.

HRMS (EI): *m*/*z* [M]$^+$ calcd for $C_6H_{10}I_2O$: 351.8816; found: 351.8806.

(*E*)-Methyl 2,3-Diiodobut-2-enoate (2v)[6b]

[CAS Reg. No.: 500912-97-0]

Purified by flash chromatography (PE–EtOAc, 10:1).

Yield: 147.8 mg (84%) (method A) or 156.6 mg (89%) (method B); pale-yellow oil.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 2.68 (s, 3 H), 3.84 (s, 3 H).

^{13}C NMR (101 MHz, $CDCl_3$): δ = 38.6, 53.4, 84.7, 97.6, 166.5.

HRMS (EI): *m*/*z* [M]$^+$ calcd for $C_5H_6I_2O_2$: 351.8452; found: 351.8456.

(*E*)-Methyl 2,3-Diiodoacrylate (2w)[6f]

[CAS Reg. No.: 71264-45-4]

Purified by flash chromatography (PE–EtOAc, 10:1).

Yield: 138.6 mg (82%) (method A) or 145.3 mg (86%) (method B); pale-yellow oil.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 3.87 (s, 3 H), 7.78 (s, 1 H).

^{13}C NMR (101 MHz, $CDCl_3$): δ = 53.5, 87.8, 129.7, 164.1.

HRMS (EI): *m*/*z* [M]$^+$ calcd for $C_4H_4I_2O_2$: 337.8295; found: 337.8289.

(*E*)-3,4-Diiodobut-3-en-2-one (2x)

Purified by flash chromatography (PE–EtOAc, 15:1).

Yield: 117.5 mg (73%) (method A) or 122.4 mg (76%) (method B); pale-yellow oil.

IR (neat): 3055, 2955, 2917, 1700, 1525, 1353, 1230, 1152, 971, 781, 604 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 2.43 (s, 3 H), 7.19 (s, 1 H).

^{13}C NMR (101 MHz, $CDCl_3$): δ = 27.4, 80.0, 95.6, 197.8.

HRMS (EI): *m*/*z* [M]$^+$ calcd for $C_4H_4I_2O$: 321.8346; found: 321.8351.

Gram-Scale Reaction; General Procedure

To a 25 mL Schlenck tube were added $(NH_4)_2S_2O_8$ (30 mmol, 3.0 equiv), KI (25 mmol, 2.5 equiv), phenylacetylene (10 mmol), and H_2O (15 mL). The reaction mixture was warmed to 60 °C (oil bath) and stirred for 24 h. The mixture was cooled to r.t., and EtOAc (30 mL) was added. The organic layer was separated, and the aqueous phase was extracted with EtOAc (3 × 30 mL). The combined organic layers were dried over anhydrous Na_2SO_4, filtered, and concentrated. The residue was purified by column chromatography to give desired product (*E*)-(1,2-diiodovinyl)benzene (2.95 g, 83%).

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Supporting Information

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References

(1) For selective application of *vic*-dihaloalkene, see: (a) Poulsen, T. B.; Dickmeiss, G.; Overgaard, J.; Jorgensen, K. A. *Angew. Chem. Int. Ed.* **2008**, *47*, 4687. (b) Jiang, B.; Tian, H.; Huang, Z.-G.; Xu, M. *Org. Lett.* **2008**, *10*, 2737. (c) Ranu, B. C.; Adak, L.; Chattopadhyay, K. *J. Org. Chem.* **2008**, *73*, 5609. (d) Simard-Mercier, J.; Jiang, J. L.; Ho, M. L.; Flynn, A. B.; Ogilvie, W. W. *J. Org. Chem.* **2008**, *73*, 5899. (e) Ranu, B. C.; Chattopadhyay, K. *Org. Lett.* **2007**, *9*, 2409. (f) Lemay, A. B.; Vulic, K. S.; Ogilvie, W. W. *J. Org. Chem.* **2006**, *71*, 3615. (g) Sun, C.; Camp, J. E.; Weinreb, S. M. *Org. Lett.* **2006**, *8*, 1779. (h) Negishi, E.; Alimardanov, A.; Xu, C. *Org. Lett.* **2000**, *2*, 65. (i) Bellina, F.; Colzi, F.; Mannina, L.; Rossi, R.; Viel, S. *J. Org. Chem.* **2003**, *68*, 10175. (j) Ghosh, A. K.; Bilcer, G.; Schiltz, G. *Synthesis* **2001**, 2203. (k) List, B.; Castello, C. *Synlett* **2001**, 1687.

(2) For selective application of *gem*-dihaloalkene, see: (a) Coste, A.; Karthikeyan, G.; Couty, F.; Evano, G. *Angew. Chem. Int. Ed.* **2009**, *48*, 4381. (b) Coste, A.; Couty, F.; Evano, G. *Org. Lett.* **2009**, *11*, 4454. (c) Okutani, M.; Mori, Y. *J. Org. Chem.* **2009**, *74*, 442. (d) Tan, Z.; Negishi, E. *Angew. Chem. Int. Ed.* **2006**, *45*, 762. (e) Zeng, X.; Qian, M.; Hu, Q.; Negishi, E. *Angew. Chem. Int. Ed.* **2004**, *43*, 2259. (f) Ogasawara, M.; Ikeda, H.; Hayashi, T. *Angew. Chem. Int. Ed.* **2000**, *39*, 1042. (g) Xu, J.; Burton, D. J. *J. Org. Chem.* **2006**, *71*, 3743. (h) Zeng, X.; Hu, Q.; Qian, M.; Negishi, E. *J. Am.*

Chem. Soc. **2003**, *125*, 13636. (i) Hwang, G. T.; Son, H. S.; Ku, J. K.; Kim, B. H. *J. Am. Chem. Soc.* **2003**, *125*, 11241. (j) Shen, W.; Kunzer, A. *Org. Lett.* **2002**, *4*, 1315.

(3) (a) Barluenga, J.; Montserrat, J. M.; Flórez, J. *J. Org. Chem.* **1993**, *58*, 5976. (b) Staab, H. A.; Shin, H. J. *Chem. Ber.* **1977**, *110*, 631. (c) Huynh, C.; Linstrumelle, G. *Tetrahedron* **1988**, *44*, 6337. (d) Wright, M. E.; Lowe-Ma, C. K. *Organometallics* **1990**, *9*, 347. (e) Hénaff, N.; Whiting, A. *J. Chem. Soc., Perkin Trans. 1* **2000**, 395; and references therein.

(4) (a) Hollins, R. A.; Campos, M. P. A. *J. Org. Chem.* **1979**, *44*, 3931. (b) Heasley, V. L. D.; Shellhamer, F.; Heasley, L. E.; Yaeger, D. B. *J. Org. Chem.* **1980**, *45*, 4649. (c) Raffa, G.; Belot, S.; Balme, G.; Monteiro, N. *Org. Biomol. Chem.* **2011**, *9*, 1474.

(5) (a) Larson, S.; Luidhardt, T.; Kabalka, G. W.; Pagni, R. M. *Tetrahedron Lett.* **1988**, *29*, 35. (b) Hondrogiannis, G.; Lee, L. C.; Kabalka, G. W.; Pagni, R. M. *Tetrahedron Lett.* **1989**, *30*, 2069. (c) Pagni, R. M.; Kabalka, G. W.; Boothe, R.; Gaetano, K.; Stewart, L. J.; Conaway, R.; Dial, C.; Gray, D.; Larson, S.; Luidhard, T. *J. Org. Chem.* **1988**, *53*, 4477. (d) Duan, J.; Dolbier, W. R. Jr.; Chen, Q.-Y. *J. Org. Chem.* **1998**, *63*, 9486.

(6) For some selected examples, see: (a) Jereb, M.; Zupan, M.; Stavber, S. *Chem. Commun.* **2004**, 2614. (b) Li, J.-H.; Xie, Y.-X.; Yin, D.-L. *Green Chem.* **2002**, *4*, 505. (c) Pavlinac, J.; Zupan, M.; Stavber, S. *Org. Biomol. Chem.* **2007**, *5*, 699. (d) Hiegel, G. A.; Bayne, C. D.; Ridley, B. *Synth. Commun.* **2003**, *33*, 1997. (e) Li, J.-H.; Xie, Y.-X.; Yin, D.-L.; Jiang, H.-F. *Chin. J. Org. Chem.* **2003**, *21*, 714. (f) Terent'ev, A. O.; Borisov, D. A.; Krylov, I. B.; Nikishin, G. I. *Synth. Commun.* **2007**, *37*, 3151. (g) Stavber, G.; Iskra, J.; Zupan, M.; Stavber, S. *Adv. Synth. Catal.* **2008**, *350*, 2921. (h) Madabhushi, S.; Jillella, R.; Mallu, K. K. R.; Godala, K. R.; Vangipuram, V. S. *Tetrahedron Lett.* **2013**, *54*, 3993.

(7) For reviews, see: (a) Li, C.-J. *Chem. Rev.* **1999**, *93*, 2023. (b) Li, C.-J. *Chem. Rev.* **2005**, *105*, 3095. (c) Herrerías, C. I.; Yao, X.; Li, Z.; Li, C.-J. *Chem. Rev.* **2007**, *107*, 2546. (d) Chanda, A.; Fokin, V. V. *Chem. Rev.* **2009**, *109*, 725. (e) Butler, R. N.; Coyne, A. G. *Chem. Rev.* **2010**, *110*, 6302. (f) Li, C.-J.; Chen, L. *Chem. Soc. Rev.* **2006**, *35*, 68.

(8) (a) Li, C.-J.; Chen, L. *Chem. Soc. Rev.* **2006**, *35*, 68. (b) Chanda, A.; Fokin, V. V. *Chem. Rev.* **2009**, *109*, 725. (c) Butler, R. N.; Coyne, A. G. *Chem. Rev.* **2010**, *110*, 6302. (d) Lindström, U. M. *Organic Reactions in Water*; Blackwell: Oxford, **2007**. (e) Li, C.-J.; Chen, L. *Chem. Soc. Rev.* **2006**, *35*, 68. (f) Uozumi, Y.; Yamada, Y. M. A. *Chem. Rec.* **2009**, *9*, 51. (g) Raj, M.; Singh, V. K. *Chem. Commun.* **2009**, 6687. (h) Chanda, A.; Fokin, V. V. *Chem. Rev.* **2009**, *109*, 725.

(9) Jiang, Q.; Sheng, W.; Guo, C. *Green Chem.* **2013**, *15*, 2175.

(10) Wang, J.-Y.; Jiang, Q.; Guo, C.-C. *Synth. Commun.* **2014**, *44*, 3130.

(11) (a) Negishi, E. In *Handbook of Organopalladium Chemistry for Organic Synthesis*; Vol. I; Negishi, E., Ed.; Wiley-Interscience: New York, **2002**, 213–1119. (b) *Metal-Catalyzed Cross-Coupling Reactions*; de Meijere, A.; Diederich, F., Eds.; Wiley-VCH: New York, **2004**, ; and references therein. (c) Yu, D.-G.; Li, B.-J.; Shi, Z.-J. *Acc. Chem. Res.* **2010**, *43*, 1486.

(12) Schuh, K.; Glorius, F. *Synthesis* **2007**, 2297.

(13) Liang, Y.; Tao, L.-M.; Zhang, Y.-H.; Li, J.-H. *Synthesis* **2008**, 3988.

(14) Kimura, T.; Nishimura, Y.; Ishida, N.; Momochi, H.; Yamashita, H.; Satoh, T. *Tetrahedron Lett.* **2013**, *54*, 1049.

(15) Li, J.-H.; Tang, S. *Synth. Commun.* **2005**, *35*, 105.

(16) (a) Jin, Z. *Nat. Prod. Rep.* **2006**, *23*, 464. (b) Yeh, V. S. C. *Tetrahedron* **2004**, *60*, 11995. (c) Donelly, D. M. X.; Meegan, M. J. In *Comprehensive Heterocyclic Chemistry*; Vol. 4; Katrikzky, A. R.; Rees, C. W., Eds.; Pergamon: Oxford, **1984**, 657–712. (d) Mahmoud, M. M.; Ali, H. I.; Ahn, K. H.; Damaraju, A.; Samala, S.; Pulipati, V. K.; Kolluru, S.; Kendall, D. A.; Lu, D. *J. Med. Chem.* **2013**, *56*, 7965.

(17) (a) Nicolaou, K. C.; Smith, A. L.; Yue, E. W. *Proc. Natl. Acad. Sci. U.S.A.* **1993**, *90*, 5881. (b) Kar, M.; Basak, A. *Chem. Rev.* **2007**, *107*, 2861. (c) Vanghn, T. H. *Union Carbide Corp., Belg.* **1963**, *631*, 355.

(18) (a) Rudi, A.; Schleyer, M.; Kashman, Y. *J. Nat. Prod.* **2000**, *63*, 1434. (b) El-Jaber, N.; Estevez-Braun, A.; Ravelo, A. G.; Munoz-Munoz, O.; Rodriguez-Afonso, A.; Murguia, J. R. *J. Nat. Prod.* **2003**, *66*, 722. (c) Zein, N.; Sinha, A. M.; McGahren, W. J.; Ellestad, G. A. *Science* **1988**, *240*, 1198. (d) Iverson, S. L.; Uetrecht, J. P. *Chem. Res. Toxicol.* **2001**, *14*, 175.

(19) Podgoršek, A.; Zupan, M.; Iskra, J. *Angew. Chem. Int. Ed.* **2009**, *48*, 8424.

(20) Ide, M.; Yauchi, Y.; Shiogai, R.; Iwasawa, T. *Tetrahedron* **2014**, *70*, 8532.

(21) Luo, L.; Resch, D.; Wilhelm, C.; Young, C. N.; Halada, G. P.; Gambino, R. J.; Grey, C. P.; Goroff, N. S. *J. Am. Chem. Soc.* **2011**, *133*, 19274.