JOC The Journal of Organic Chemistry

Article

pubs.acs.org/joc

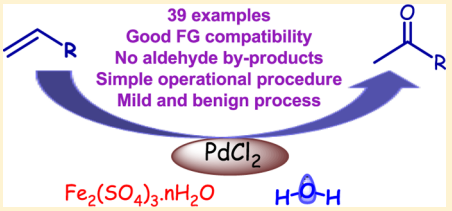
Iron(III) Sulfate as Terminal Oxidant in the Synthesis of Methyl Ketones via Wacker Oxidation

Rodney A. Fernandes* and Dipali A. Chaudhari

Department of Chemistry, Indian Institute of Technology Bombay, Powai, Mumbai 400076, Maharashtra, India

Supporting Information

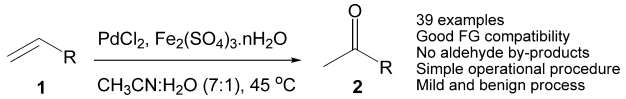
ABSTRACT: An efficient and environmentally benign method using Fe(III) sulfate as a terminal oxidant in the synthesis of methyl ketones from terminal olefins via the Wacker process is developed. The methodology offers high selectivity for a Markonikov product, shows good functional group compatibility, involves mild reaction conditions, and is operationally simple. $Fe_2(SO_4)_3$ is the sole terminal oxidant in this process. The method holds potential for future applications in organic synthesis.



INTRODUCTION

Many natural products have a methyl ketone moiety, and their cumulative biological history over many years firmly establishes that this moiety is of natural origin. Of the several approaches to introduce methyl ketone unit such as hydration of alkynes,[1] Friedel–Crafts acylation,[2] Dakin–West reaction,[3] and Weinreb ketone synthesis,[4] the Wacker oxidation[5−11] is the most familiar approach. The Cu-mediated conventional Wacker process is well established on an industrial scale. However, the process suffers from certain limitations mainly derived from the use of $CuCl_2$ as a Pd-reoxidant which leads to corrosive reaction media and forms chlorinated byproducts. The Wacker process for higher olefins sometimes results in slower reaction, chlorinated byproducts, and double bond isomerized compounds.[12] The catalytic $CuCl_2$ version requires pressurization of oxygen. To overcome these limitations many modifications are directed toward developing an alternative reoxidant.[9,13] The direct O_2 coupled Wacker oxidation along with coordinating solvents (DMF, DMA, NMP, or ethylene carbonate) offered a good alternative.[13z,ad] Co-catalysts[13d,e,g,i,w,ae,af] and/or solvents,[13q−t,ab] nitrogen based ligands,[13n,p,y] organic oxidants (benzoquinone),[9,13f,h,j,af] organic peroxides,[13a,c,x,ac] nitrites,[13o,af] H_2O_2,[13b] $KBrO_3$,[13ae] O_2/TFA,[13ag] and CrO_3[13ah] were also explored. While many of these modifications offer a wider scope to Wacker-type oxidation, there is still a need to develop a cost-effective, mild, environmentally benign, and operationally simpler method. In 1988, Bäckvall and Hopkins developed an iron(II) phthalocyanine based multicomponent catalytic system for the oxidation of terminal olefins.[14a] However, acidic media and tedious workup for removal of polar aprotic solvent DMF could be disadvantageous. Acid sensitive functionalities also become an issue. Formation of palladium nanoparticles in olefin oxidation with iron(III) aqua ions in the presence of the $Pd/ZrO_2/SO_4$ metallic catalyst has been investigated.[14b] However, only limited examples have been explored. Use of iron compounds in natural olefin oxidation is also documented.[14c,d] From careful investigation of various available iron salts as oxidants, we found, to our delight, $Fe_2(SO_4)_3$ offered an efficient Pd-catalyzed oxidation of terminal olefins to methyl ketones in an environmentally benign process (Scheme 1). No aldehyde formation or olefin isomerization was observed. $Fe_2(SO_4)_3$ is freely soluble in the CH_3CN/H_2O (7:1) solvent system, making this method advantageous and operationally simple.

Scheme 1. Oxidation of Terminal Olefins to Methyl Ketones (FG = functional group)



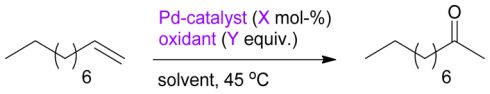
RESULTS AND DISCUSSION

We first examined various Pd-catalysts and Fe-salts for oxidation of 1-decene (**1b**) as a model substrate (Table 1). With the use of $PdCl_2$ (5 mol %) in a mixture of CH_3CN/H_2O (7:1) with $Fe_2(SO_4)_3{\cdot}nH_2O$ (1.5 equiv)[15] at 45 °C under N_2, the reaction was complete within 1.5 h giving decan-2-one (**2b**) as the sole product in 95% yield (Table 1, entry 1). No trace of aldehyde was formed. The purification process was mere filtration of the reaction mixture through a pad of silica gel to remove water and inorganic byproducts delivering the ketone product after filtrate concentration in virtually pure form. $Fe(NO_3)_3{\cdot}9H_2O$ also worked well delivering **2b** in 87% yield (Table 1, entry 2). Other iron based salts and complexes such as $Fe(C_2O_4){\cdot}2H_2O$, $Fe(OAc)_2$, $Fe(BF_4)_2{\cdot}6H_2O$, $Fe(ClO_4)_2{\cdot}xH_2O$, K_3FeCN_6, and $FeSO_4$ showed oxidation, however in lower yields (Table 1, entries 3−8). The normal Fe-oxides such as Fe_2O_3 and Fe_3O_4 (nanoparticles) were unsuccessful for this oxidation (Table 1, entries 9 and 10). The Fe(II) compounds are not oxidants but in the reaction media (H_2O, 45 °C) may become oxidized to Fe(III) and then act as terminal oxidants.

Received: April 26, 2014

   dx.doi.org/10.1021/jo500921j | J. Org. Chem. XXXX, XXX, XXX−XXX

Table 1. Optimization of Reaction Conditions for Oxidation of 1-Decene[a]



1b 2b

entry	Pd-catalyst (mol %)	oxidant (equiv)	solvent	t (h)	yield (%)
1	**$PdCl_2$ (5)**	**$Fe_2(SO_4)_3$·nH_2O[b] (1.5)**	**CH_3CN/H_2O (7:1)**	**1.5**	**95**
2	$PdCl_2$ (5)	$Fe(NO_3)_3$·$9H_2O$ (1.5)	CH_3CN/H_2O (7:1)	1.5	87
3	$PdCl_2$ (5)	$Fe(C_2O_4)$·$2H_2O$ (1.5)	CH_3CN/H_2O (7:1)	16	52
4	$PdCl_2$ (5)	$Fe(OAc)_2$ (1.5)	CH_3CN/H_2O (7:1)	35	48
5	$PdCl_2$ (5)	$Fe(BF_4)_2$·$6H_2O$ (1.5)	CH_3CN/H_2O (7:1)	15	62
6	$PdCl_2$ (5)	$Fe(ClO_4)_2$·xH_2O (1.5)	CH_3CN/H_2O (7:1)	2.5	72
7	$PdCl_2$ (5)	K_3FeCN_6 (1.5)	CH_3CN/H_2O (7:1)	27	25
8	$PdCl_2$ (5)	$FeSO_4$ (1.5)	CH_3CN/H_2O (7:1)	20	52
9	$PdCl_2$ (5)	Fe_2O_3 (1.5)	CH_3CN/H_2O (7:1)	23	43
10	$PdCl_2$ (5)	Fe_3O_4 (NP) (1.5)	CH_3CN/H_2O (7:1)	51	46
11	$Pd(OAc)_2$ (5)	$Fe_2(SO_4)_3$·nH_2O (1.5)	CH_3CN/H_2O (7:1)	3.5	71
12	$Pd(CF_3CO_2)_2$ (5)	$Fe_2(SO_4)_3$·nH_2O (1.5)	CH_3CN/H_2O (7:1)	4	86
13	$Pd(dba)_2$ (5)	$Fe_2(SO_4)_3$·nH_2O (1.5)	CH_3CN/H_2O (7:1)	8	81
14	$Pd(PPh_3)_4$ (5)	$Fe_2(SO_4)_3$·nH_2O (1.5)	CH_3CN/H_2O (7:1)	10	37
15	–	$Fe_2(SO_4)_3$·nH_2O (1.5)	CH_3CN/H_2O (7:1)	18	NR[d]
16[c]	$PdCl_2$ (5)	$Fe_2(SO_4)_3$·nH_2O (1.5)	CH_3CN/H_2O (7:1)	30	75
17	$PdCl_2$ (5)	$Fe_2(SO_4)_3$·nH_2O (1.5)	DMF/H_2O (7:1)	29	81
18	$PdCl_2$ (5)	$Fe_2(SO_4)_3$·nH_2O (1.5)	THF/H_2O (7:1)	32	24
19	$PdCl_2$ (5)	$Fe_2(SO_4)_3$·nH_2O (1.5)	DMA/H_2O (7:1)	36	76
20	$PdCl_2$ (5)	$Fe_2(SO_4)_3$·nH_2O (1.5)	CH_3CN/H_2O (3:1)	1.5	71
21	$PdCl_2$ (5)	$Fe_2(SO_4)_3$·nH_2O (1.5)	CH_3CN/H_2O (1:1)	1.5	71
22	$PdCl_2$ (5)	$Fe_2(SO_4)_3$·nH_2O (1.0)	CH_3CN/H_2O (7:1)	18	68
23	$PdCl_2$ (5)	$Fe_2(SO_4)_3$·nH_2O (2.0)	CH_3CN/H_2O (7:1)	1	90
24	$PdCl_2$ (2)	$Fe_2(SO_4)_3$·nH_2O (1.5)	CH_3CN/H_2O (7:1)	19	71
25	$PdCl_2$ (10)	$Fe_2(SO_4)_3$·nH_2O (1.5)	CH_3CN/H_2O (7:1)	2.5	81

[a]All reactions were performed with olefin (0.5 mmol), Fe-source (1.0–2.0 equiv., 0.5–1.0 mmol), Pd-catalyst (2–10 mol %, 0.01–0.05 mmol), at 45 °C in solvent (4 mL) under N_2. [b]$Fe_2(SO_4)_3$·nH_2O is a hydrate obtained from Aldrich Chem. Co. with unspecified water molecules. The amount used is based on $Fe_2(SO_4)_3$ anhydrous mol wt. Hence the actual amount of $Fe_2(SO_4)_3$ present in reaction media would be less than 1.5 equiv. NP = Nanoparticles. [c]Reaction carried out in the presence of air. [d]NR = No reaction.

Changing the Pd-catalyst did not prove better (Table 1, entries 11–14). When no catalyst was used, the reaction did not work (Table 1, entry 15). Surprisingly, the reaction was rather slow when carried out in the presence of air (open flask) and took 30 h to complete giving **2b** in 75% yield (entry 16). Screening different solvents for this oxidation (Table 1, entries 17–21) revealed that CH_3CN/H_2O (7:1) was the best solvent mixture (entry 1). Keeping the $PdCl_2$ catalyst loading at 5 mol % and changing the concentration of oxidant $Fe_2(SO_4)_3$·nH_2O showed that the optimum requirement was 1.5 equiv (Table 1, entries 22 and 23). Similarly, with 1.5 equiv of oxidant the optimum catalyst loading required was 5 mol % (Table 1, entry 1 vs entries 24 and 25). The optimized oxidation conditions which include the use of $PdCl_2$ (5 mol %), $Fe_2(SO_4)_3$·nH_2O (1.5 equiv)[15] in CH_3CN/H_2O (7:1) at 45 °C gave the methyl ketones in good to excellent yields. With these optimized conditions and operationally simple procedure, we evaluated the scope and limitations of this method (Table 2).

The long chain inactivated olefins 1-octene, 1-decene, and 1-tetradecene gave the methyl ketones (**2a–c**, entries 1–3, Table 2) in 92–95% yields. Terminal dienes also showed comparable reactivity and gave methyl diketones **2d** and **2e** in good yields (entries 4 and 5). The oxidation was compatible with diverse functional groups: hydroxyl, halide, benzoate, MOM, silyl, ester, and acid were all tolerated giving the methyl ketone products with complete Markonikov selectivity in good yields (**2f–n**, entries 6–14). No OH group oxidation or deprotection of acid labile groups was observed. Styrenes are masked precursors for aryl methyl ketones synthesis through olefin oxidation. Various aryl substituted styrenes with electron-donating or -withdrawing groups reacted under the present protocol to give aryl methyl ketones (**2o–t**, entries 15–20) in good yields. Hydroxyl allylated salicylic acid delivered the methyl ketone **2u** in 70% yield (entry 21). Similarly bis-allylated salicylic acids (with ester and ether functionality) gave the diketones **2v** and **2w** in 74% and 70% yields, respectively (entries 22 and 23). Menthyl allyl ether efficiently gave **2x** in 66% yield (entry 24).

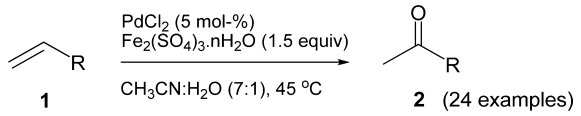
Classically difficult substrates such as protected allyl and homoallyl alcohols show a possible coordination of the neighboring oxygen atom to the Lewis acidic palladium causing water attack through multiple pathways.[13ac,16] Under the developed procedure these compounds also reacted successfully (Table 3). Primary allyl alcohols with various protecting groups: phenyl, benzyl, 4-*tert*-butylphenyl, 2-naphthyl, 4-methylbenzoyl, and nitrobenzoyl gave methyl ketones (**4a–g**, entries 1–7) in good yields. The acyloin products (**4h–j**, entries 8–10) were obtained in good yields without the formation of otherwise competitive aldehydes due to heteroatom directed effects. Homoallyl alcohols delivered the protected β-hydroxy ketone products (**4k–o**, entries 11–15) in good yields with complete Markonikov selectivity.

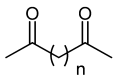
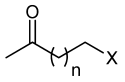
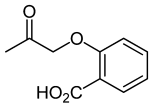
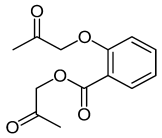
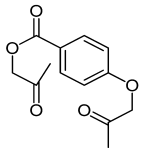
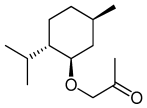
CONCLUSION

In summary, we have found a mild, efficient, general, and environmentally benign method to access methyl ketones from terminal olefins without the use of Cu-salts and molecular oxygen. Various long chain terminal olefins, dienes, substituted styrenes, and protected allyl and homoallyl alcohols have been explored (39 examples). A wide spectrum of functional-group tolerance, mild reaction conditions, complete Markonikov selectivity, and use of commercially available $Fe_2(SO_4)_3$·nH_2O as the sole oxidant are key features of this methodology. Since it is a mild process with operational simplicity and exclusive ketone delivery, we expect this method to find broad application in synthetic chemistry.

dx.doi.org/10.1021/jo500921j | J. Org. Chem. XXXX, XXX, XXX–XXX

Table 2. Synthesis of Methyl Ketones from Terminal Olefins[a]



Entry	Product		t (h)	Yield %
1		**2a**, R = nC_6H_{13}	2	92
2		**2b**, R = nC_8H_{17}	1.5	95
3		**2c**, R = $nC_{12}H_{25}$	1	94
4[b]		**2d**, n = 6	2	74
5[b]		**2e**, n = 8	2	77
6		**2f**, X = OH, n = 8	3	85
7		**2g**, X = CH(OH)CH_3, n = 12	4	78
8		**2h**, X = Br, n = 7	4	76
9		**2i**, X = OBz, n = 3	6.5	75
10		**2j**, X = OMOM, n = 8	4	81
11		**2k**, X = OTBDPS, n = 0	4.5	90
12		**2l**, X = CO_2Et, n = 0	2.5	87
13		**2m**, X = CO_2H, n = 1	12	82
14		**2n**, X = CO_2H, n = 2	14	81
15		**2o**, Ar = Ph	2	85
16		**2p**, Ar = 4-OMe-phenyl	1.5	65
17		**2q**, Ar = 4-*t*Bu-phenyl	3	78
18		**2r**, Ar = 2-naphthyl	4	58
19		**2s**, Ar = 4-Ph-phenyl	4	65
20		**2t**, Ar = 4-NO_2-phenyl	14	55
21		**2u**	12	70
22[b]		**2v**	11.5	74
23[b]		**2w**	11	70
24		**2x**	14	66

[a]Reaction conditions: Substrate (0.5 mmol), $PdCl_2$ (5 mol %, 0.025 mmol), $Fe_2(SO_4)_3{\cdot}nH_2O$ (1.5 equiv, 0.75 mmol), CH_3CN (3.5 mL), H_2O (0.5 mL), at 45 °C under N_2. [b]Substrate (0.5 mmol), $PdCl_2$ (10 mol %, 0.05 mmol), $Fe_2(SO_4)_3{\cdot}nH_2O$ (3.0 equiv, 1.5 mmol), CH_3CN (3.5 mL), H_2O (0.5 mL), at 45 °C under N_2.

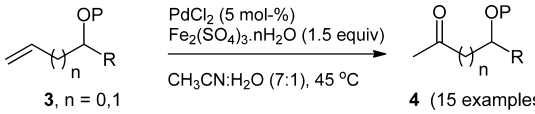
EXPERIMENTAL SECTION

General Information. Solvents and reagents were purified by standard methods. Thin-layer chromatography was performed on EM 250 Kieselgel 60 F254 silica gel plates. The spots were visualized by staining with $KMnO_4$ or under a UV lamp. ^1H and ^{13}C NMR were recorded with a spectrometer operating at 500 or 400 and 125 or 100 MHz for proton and carbon nuclei, respectively. The chemical shifts are based on the TMS peak at δ = 0.00 pm for proton NMR and the $CDCl_3$ peak at δ = 77.00 ppm (t) in carbon NMR. IR spectra were obtained on an FT−IR spectrometer, and samples were prepared by evaporation from $CHCl_3$ on CsBr plates. High-resolution mass spectra (HRMS) were obtained using positive electrospray ionization by the TOF method. The ^1H and ^{13}C NMR anaylses of **2w** were at 400 and 125 MHz, respectively.

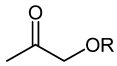
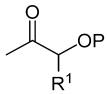
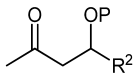
General Procedure for Oxidation of Terminal Olefins. To a stirred solution of olefin (0.5 mmol) in CH_3CN (3.5 mL) and H_2O (0.5 mL) were added $PdCl_2$ (4.4 mg, 0.025 mmol, 5 mol %) and $Fe_2(SO_4)_3{\cdot}nH_2O$ (600 mg, 1.5 mmol, 1.5 equiv) at room temperature. The reaction mixture was warmed to 45 °C and stirred for a specified time (see Tables 2 and 3) under N_2. The reaction mixture was then filtered through a small pad of silica gel and washed with EtOAc, and

dx.doi.org/10.1021/jo500921j | J. Org. Chem. XXXX, XXX, XXX−XXX

Table 3. Oxidation of Protected Allyl and Homoallyl Alcohols[a]



3, n = 0,1 **4** (15 examples)

Entry	Product		t (h)	Yield (%)
1		**4a**, R = Ph	6.5	76
2		**4b**, R = Bn	7	80
3		**4c**, R = 4-*t*Bu-phenyl	8.5	68
4		**4d**, R = 2-naphthyl	9.5	81
5		**4e**, R = 4-methylbenzoyl	11.5	76
6		**4f**, R = 4-nitrobenzoyl	14	64
7		**4g**, R = 3,5-dinitrobenzoyl	21	61
8		**4h**, P = TBDPS, R^1 = Ph	4.5	78
9		**4i**, P = Ac, R^1 = nC_6H_{13}	4	65
10		**4j**, P = Ac, R^1 = Ph	2.5	74
11		**4k**, P = Ac, R^2 = nC_5H_{11}	4.5	75
12		**4l**, P = Ac, R^2 = Ph	8	71
13		**4m**, P = Ac, R^2 = 4-OMe-phenyl	9	84
14		**4n**, P = Bz, R^2 = 1-naphthyl	13	77
15		**4o**, P = Bn, R^2 = 4-NO_2-phenyl	17	61

[a]Reaction conditions: Substrate (0.5 mmol), $PdCl_2$ (5 mol %, 0.025 mmol), $Fe_2(SO_4)_3{\cdot}nH_2O$ (1.5 equiv, 0.75 mmol), CH_3CN (3.5 mL), H_2O (0.5 mL), at 45 °C under N_2.

the filtrate was concentrated. The residue in some cases contained virtually pure compound, and no further purification was necessary (for compounds **2a–c** and **2f–h**). In other cases the residue was purified by silica gel column chromatography using petroleum ether/EtOAc as an eluent to afford the methyl ketones.

*Octan-2-one (**2a**):*[17] Yield (59 mg, 92%). Colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$/TMS): δ = 2.41 (t, J = 7.5 Hz, 2H), 2.13 (s, 3H), 1.59–1.52 (m, 2H), 1.32–1.21 (m, 6H), 0.87 (t, J = 6.9 Hz, 3H); ^{13}C {^{1}H} NMR (100 MHz, $CDCl_3$): δ = 209.5, 43.8, 31.6, 29.8, 28.8, 23.8, 22.5, 14.0.

*Decan-2-one (**2b**):*[13i] Yield (74.2 mg, 95%). Colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$/TMS): δ = 2.40 (t, J = 7.5 Hz, 2H), 2.11 (s, 3H), 1.55–1.52 (m, 2H), 1.30–1.22 (m, 10H), 0.86 (t, J = 6.9 Hz, 3H); ^{13}C {^{1}H} NMR (100 MHz, $CDCl_3$): δ = 209.4, 43.8, 31.8, 29.8, 29.3, 29.14, 29.1, 23.8, 22.6, 14.1.

*Tetradecan-2-one (**2c**):*[20] Yield (99.3 mg, 94%). Colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$/TMS): δ = 2.42 (t, J = 7.5 Hz, 2H), 2.14 (s, 3H), 1.58–1.55 (m, 4H), 1.36–1.19 (m, 16H), 0.88 (t, J = 6.8 Hz, 3H); ^{13}C {^{1}H} NMR (100 MHz, $CDCl_3$): δ = 209.3, 43.7, 31.8, 29.7, 29.6, 29.53, 29.5, 29.4, 29.3, 29.25, 29.1, 23.7, 22.6, 14.0.

*Decane-2,9-dione (**2d**):*[21a] Yield (63 mg, 74%). Colorless oil; IR ($CHCl_3$): ν_{max} = 3019, 2933, 2858, 1717, 1409, 1363, 1168, 1048, 967, 927, 667 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$/TMS): δ = 2.41 (t, J = 7.4 Hz, 4H), 2.12 (s, 6H), 1.61–1.52 (m, 4H), 1.31–1.25 (m, 4H); ^{13}C {^{1}H} NMR (100 MHz, $CDCl_3$): δ = 209.2, 43.6, 29.9, 28.9, 23.5; HRMS (ESI-TOF) calcd for $[C_{10}H_{18}O_2 + Na]^+$ 193.1199, found 193.1198.

*Dodecane-2,11-dione (**2e**):*[21b] Yield (76.3 mg, 77%). Colorless oil; IR ($CHCl_3$): ν_{max} = 3017, 2916, 1704, 1406, 1379, 1284, 1165, 1131, 1018, 949, 717, 667 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$/TMS): δ = 2.40 (t, J = 7.4 Hz, 4H), 2.12 (s, 6H), 1.63–1.51 (m, 4H), 1.28–1.23 (m, 8H); ^{13}C {^{1}H} NMR (100 MHz, $CDCl_3$): δ = 209.2, 43.6, 29.7, 29.1, 28.9, 23.6; HRMS (ESI-TOF) calcd for $[C_{12}H_{22}O_2 + Na]^+$ 221.1512, found 221.1512.

*11-Hydroxyundecan-2-one (**2f**):*[17] Yield (79.2 mg, 85%). Colorless oil; IR ($CHCl_3$): ν_{max} = 3415, 2929, 2855, 1712, 1465, 1363, 1169, 1055, 912 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$/TMS): δ = 3.59 (t, J = 6.7 Hz, 2H), 2.38 (t, J = 7.4 Hz, 2H), 2.10 (s, 3H), 1.54–1.50 (m, 4H), 1.37–1.20 (m, 10H); ^{13}C {^{1}H} NMR (100 MHz, $CDCl_3$): δ = 209.6, 63.0, 43.8, 32.7, 29.4, 29.3, 29.27, 29.1, 25.7, 23.8; HRMS (ESI-TOF) calcd for $[C_{11}H_{22}O_2 + Na]^+$ 209.1512, found 209.1510.

*16-Hydroxyheptadecane-2-one (**2g**).* Yield (105.3 mg, 78%). White solid, mp 55–57 °C; IR ($CHCl_3$): ν_{max} = 3402, 2916, 2849, 1709, 1464, 1372, 1163, 1124, 1038, 910, 667 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$/TMS): δ = 3.78–3.75 (m, 1H), 2.38 (t, J = 7.4 Hz, 2H), 2.10 (s, 3H), 1.55–1.51 (m, 2H), 1.39–1.38 (m, 2H), 1.35–1.22 (m, 20H), 1.15 (d, J = 6.2 Hz, 3H); ^{13}C {^{1}H} NMR (100 MHz, $CDCl_3$): δ = 209.4, 68.0, 43.7, 39.3, 29.8, 29.6, 29.5, 29.5, 29.4, 29.3, 29.1, 25.7, 23.8, 23.4; HRMS (ESI-TOF) calcd for $[C_{17}H_{34}O_2 + Na]^+$ 293.2451, found 293.2455.

*10-Bromodecan-2-one (**2h**):*[22a] Yield (89.4 mg, 76%). Colorless oil; IR ($CHCl_3$): ν_{max} = 2931, 2856, 1717, 1459, 1439, 1359, 1259, 1224, 1166, 948, 721, 644 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$/TMS): δ = 3.39 (t, J = 6.8 Hz, 2H), 2.41 (t, J = 7.4 Hz, 2H), 2.13 (s, 3H), 1.87–1.78 (m, 2H), 1.59–1.51 (m, 2H), 1.42–1.38 (m, 2H), 1.29–1.23 (m, 6H); ^{13}C {^{1}H} NMR (100 MHz, $CDCl_3$): δ = 209.3, 43.7, 34.0, 32.7, 29.8, 29.2, 29.0, 28.5, 28.0, 23.7; HRMS (ESI-TOF) calcd for $[C_{10}H_{19}BrO + Na]^+$ 257.0511, found 257.0511.

*5-Oxohexyl Benzoate (**2i**):*[22b] Yield (82.6 mg, 75%). Colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$/TMS): δ = 8.04–8.02 (m, 2H), 7.58–7.53 (m, 1H), 7.46–7.40 (m, 2H), 4.36 (t, J = 6.1 Hz, 2H), 2.51 (t, J = 6.9 Hz, 2H), 2.15 (s, 3H), 1.82–1.70 (m, 4H); ^{13}C {^{1}H} NMR (100 MHz, $CDCl_3$): δ = 208.5, 166.6, 132.9, 130.3, 129.5, 128.3, 64.5, 43.0, 29.9, 28.1, 20.2; HRMS (ESI-TOF) calcd for $[C_{13}H_{16}O_3 + Na]^+$ 243.0992, found 243.0989.

*11-(Methoxymethoxy)undecan-2-one (**2j**):*[22c] Yield (93.3 mg, 81%). Colorless oil; IR ($CHCl_3$): ν_{max} = 3014, 2929, 2856, 1716, 1465, 1410, 1361, 1145, 1111, 1043, 919, 667 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$/TMS): δ = 4.61 (s, 2H), 3.51 (t, J = 6.6 Hz, 2H), 3.35 (s, 3H), 2.41 (t, J = 7.5 Hz, 2H), 2.13 (s, 3H), 1.60–1.54 (m, 2H), 1.28–1.27 (m, 12H); ^{13}C {^{1}H} NMR (100 MHz, $CDCl_3$): δ = 209.3, 96.3, 67.8, 55.0, 43.7, 29.8, 29.7, 29.3, 29.1, 26.1, 23.8; HRMS (ESI-TOF) calcd for $[C_{13}H_{26}O_3 + Na]^+$ 253.1774, found 253.1778.

dx.doi.org/10.1021/jo500921j | J. Org. Chem. XXXX, XXX, XXX–XXX

*1-(tert-Butyldiphenylsilyloxy)propan-2-one (**2k**):*[22d] Yield (140.6 mg, 90%). Colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$/TMS): δ = 7.65 (dd, J = 7.2, 0.7 Hz, 4H), 7.44−7.38 (m, 6H), 4.16 (s, 2H), 2.20 (s, 3H), 1.10 (s, 9H); ^{13}C {^{1}H} NMR (100 MHz, $CDCl_3$): δ = 208.5, 135.5, 132.6, 130.0, 127.8, 69.9, 26.7, 26.3, 19.2.

*Ethyl 3-Oxobutanoate (**2l**):*[13aa] Yield (56.6 mg, 87%). Colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$/TMS): δ = 4.16 (q, J = 7.2 Hz, 2H), 3.40 (s, 2H), 2.23 (s, 3H), 1.25 (t, J = 7.1 Hz, 3H); ^{13}C {^{1}H} NMR (100 MHz, $CDCl_3$): δ = 200.6, 167.1, 61.3, 50.1, 30.1, 14.0.

*4-Oxopentanoic Acid (**2m**):*[22e] Yield (47.6 mg, 82%). Colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$/TMS): δ = 2.73 (t, J = 7.2 Hz, 2H), 2.61 (t, J = 7.2 Hz, 2H), 2.18 (s, 3H); ^{13}C {^{1}H} NMR (100 MHz, $CDCl_3$): δ = 206.6, 178.2, 37.7, 29.8, 27.7.

*5-Oxohexanoic Acid (**2n**):*[22e] Yield (52.7 mg, 81%). Colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$/TMS): δ = 2.53 (t, J = 7.2 Hz, 2H), 2.39 (t, J = 7.2 Hz, 2H), 2.15 (s, 3H), 1.94−1.84 (m, 2H); ^{13}C {^{1}H} NMR (100 MHz, $CDCl_3$): δ = 208.0, 178.7, 42.3, 32.8, 29.9, 18.5.

*Acetophenone (**2o**):*[17] Yield (51 mg, 85%). Pale yellow oil; ^{1}H NMR (400 MHz, $CDCl_3$/TMS): δ = 7.97−7.92 (m, 2H), 7.57−7.51 (m, 1H), 7.48−7.41 (m, 2H), 2.60 (s, 3H).

*4-Methoxyacetophenone (**2p**):*[13ab] Yield (48.8 mg, 65%). Colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$/TMS) δ = 7.94 (d, J = 8.6 Hz, 2H), 6.94 (d, = 8.6 Hz, 2H), 3.87 (s, 3H), 2.56 (s, 3H).

*4-tert-Butylacetophenone (**2q**):*[18] Yield (68.6 mg, 78%). Colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$/TMS): δ = 7.90 (d, J = 8.7 Hz, 2H), 7.48 (d, J = 8.7 Hz, 2H), 2.58 (s, 3H), 1.34 (s, 9H); ^{13}C {^{1}H} NMR (100 MHz, $CDCl_3$): δ = 197.9, 156.8, 134.5, 128.3, 125.5, 35.1, 31.0, 26.5.

*2-Acetylnaphthalene (**2r**):*[23a] Yield (49.3 mg, 58%). Colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$/TMS): δ = 8.48 (s, 1H), 8.04 (dd, J = 8.7, 1.7 Hz, 1H), 7.97 (d, J = 8.2 Hz, 1H), 7.92−7.86 (m, 2H), 7.66−7.53 (m, 2H), 2.73 (s, 3H); ^{13}C {^{1}H} NMR (100 MHz, $CDCl_3$): δ = 198.2, 135.6, 134.5, 132.5, 130.2, 129.5, 128.6, 128.5, 127.8, 126.8, 123.9, 26.7.

*4-Phenylacetophenone (**2s**):*[23b] Yield (63.7 mg, 65%). White solid, mp 115−117 °C; IR ($CHCl_3$): ν_{max} = 3019, 2923, 1679, 1599, 1404, 1359, 1267, 1119, 1078, 1044, 957, 927, 842, 694, 669 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$/TMS): δ = 8.04 (d, J = 8.6 Hz, 2H), 7.69 (d, J = 8.6 Hz, 2H), 7.63 (d, J = 7.0 Hz, 2H), 7.50−7.41 (m, 3H), 2.65 (s, 3H); ^{13}C {^{1}H} NMR (100 MHz, $CDCl_3$): δ = 197.8, 145.8, 139.9, 135.8, 128.94, 128.9, 128.2, 127.3, 127.2, 26.6; HRMS (ESI-TOF) calcd for $[C_{14}H_{12}O + Na]^+$ 219.0780, found 219.0783.

*4-Nitrophenylacetophenone (**2t**):*[18] Yield (45.4 mg, 55%). Pale yellow solid, mp 76−78 °C; ^{1}H NMR (400 MHz, $CDCl_3$/TMS): δ = 8.32 (d, J = 8.8 Hz, 2H), 8.11 (d, J = 8.8 Hz, 2H), 2.68 (s, 3H); ^{13}C {^{1}H} NMR (100 MHz, $CDCl_3$): δ = 196.3, 150.7, 141.6, 129.3, 123.9, 27.0.

*2-(2-Oxopropoxy)benzoic Acid (**2u**).* Yield (68 mg, 70%). Colorless oil; IR ($CHCl_3$): ν_{max} = 3212, 2919, 1781, 1717, 1600, 1485, 1458, 1418, 1341, 1295, 1252, 1184, 1165, 1095, 1058, 1036, 958, 862, 829, 798, 684, 646 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$/TMS): δ = 8.18 (dd, J = 7.8, 1.4 Hz, 1H), 7.53 (t, J = 7.2 Hz, 1H), 7.18 (t, J = 7.6 Hz, 1H), 6.91 (d, J = 8.2 Hz, 1H), 4.89 (s, 2H), 2.30 (s, 3H); ^{13}C {^{1}H} NMR (100 MHz, $CDCl_3$): δ = 201.2, 165.4, 156.3, 134.8, 133.1, 123.0, 118.9, 112.9, 73.6, 26.0; HRMS (ESI-TOF) calcd for $[C_{10}H_{10}O_4 + Na]^+$ 217.0471, found 217.0472.

*2-Oxopropyl 2-(2-Oxopropoxy)benzoate (**2v**).* Yield (92.6 mg, 74%). White solid, mp 62−64 °C; IR ($CHCl_3$): ν_{max} = 3020, 2928, 2846, 1728, 1603, 1586, 1491, 1457, 1420, 1364, 1306, 1253, 1180, 1168, 1134, 1097, 1060, 1012, 964, 884, 828, 703, 668 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$/TMS): δ = 7.96 (dd, J = 7.8, 1.8 Hz, 1H), 7.51−7.48 (m, 1H), 7.1 (td, J = 7.6, 0.8 Hz, 1H), 6.84 (d, J = 8.3 Hz, 1H), 4.88 (s, 2H), 4.60 (s, 2H), 2.35 (s, 3H), 2.23 (s, 3H); ^{13}C {^{1}H} NMR (100 MHz, $CDCl_3$): δ = 205.7, 201.7, 164.7, 157.6, 134.3, 132.4, 121.5, 119.5, 113.6, 73.9, 68.6, 26.9, 26.2; HRMS (ESI-TOF) calcd for $[C_{13}H_{14}O_5 + Na]^+$ 273.0733, found 273.0731.

*2-Oxopropyl 4-(2-Oxopropoxy)benzoate (**2w**).* Yield (87.5 mg, 70%). White solid, mp 80−82 °C; IR ($CHCl_3$): ν_{max} = 3021, 2928, 1721, 1607, 1583, 1509, 1420, 1371, 1314, 1276, 1170, 1115, 1070, 1008, 966, 883, 848, 696, 667 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$/TMS): δ = 8.03 (d, J = 9.0 Hz, 2H), 6.91 (d, J = 9.0 Hz, 2H), 4.82 (s, 2H), 4.61 (s, 2H), 2.28 (s, 3H), 2.21 (s, 3H); ^{13}C {^{1}H} NMR (100 MHz, $CDCl_3$): δ = 204.3, 201.9, 165.3, 161.7, 132.1, 122.6, 114.3, 72.8, 68.6, 26.5, 26.2; HRMS (ESI-TOF) calcd for $[C_{13}H_{14}O_5 + Na]^+$ 273.0733, found 273.0734.

*1-[(1R,2S,5R)-2-Isopropyl-5-methylcyclohexyloxy]propan-2-one (**2x**).* Yield (70 mg, 66%). Colorless oil; $[\alpha]_D^{25}$ = −73.3 (c = 1.0, $CHCl_3$); IR ($CHCl_3$): ν_{max} = 3020, 2958, 2928, 2872, 1720, 1457, 1370, 1116, 1015, 938, 842, 668 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$/TMS): δ = 4.14 (d, J = 16.8 Hz, 1H), 3.93 (d, J = 16.8 Hz, 1H), 3.11 (td, J = 10.6, 4.1 Hz, 1H), 2.28−2.24 (m, 1H), 2.18 (s, 3H), 2.06−2.00 (m, 1H), 1.68−1.61 (m, 2H), 1.37−1.28 (m, 2H), 1.01−0.84 (m, 8H), 0.78 (d, J = 7.0 Hz, 4H); ^{13}C {^{1}H} NMR (125 MHz, $CDCl_3$): δ = 208.0, 80.3, 74.3, 48.0, 40.0, 34.4, 31.4, 26.6, 25.6, 23.2, 22.2, 20.9, 16.1; HRMS (ESI-TOF) calcd for $[C_{13}H_{24}O_2 + Na]^+$ 235.1669, found 235.1666.

*1-Phenoxypropan-2-one (**4a**):*[24a] Yield (57.1 mg, 76%). Colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$/TMS): δ = 7.33−7.28 (m, 2H), 7.02−6.98 (m, 1H), 6.91−6.88 (m, 2H), 4.54 (s, 2H), 2.28 (s, 3H); ^{13}C {^{1}H} NMR (100 MHz, $CDCl_3$): δ = 205.9, 157.6, 129.6, 121.7, 114.4, 72.9, 26.6.

*1-(Benzyloxy)propan-2-one (**4b**):*[24b] Yield (65.7 mg, 80%). Colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$/TMS): δ = 7.38−7.25 (m, 5H), 4.58 (s, 2H), 4.07 (s, 2H), 2.16 (s, 3H); ^{13}C {^{1}H} NMR (100 MHz, $CDCl_3$): δ = 206.8, 137.0, 128.5, 127.9, 127.0, 75.2, 73.3, 26.4.

*1-[4-(tert-Butyl)phenoxy]propan-2-one (**4c**).* Yield (64.7 mg, 68%). Colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$/TMS): δ = 7.32 (d, J = 8.9 Hz, 2H), 6.82 (d, J = 8.9 Hz, 2H), 4.52 (s, 2H), 2.28 (s, 3H), 1.30 (s, 9H); ^{13}C {^{1}H} NMR (100 MHz, $CDCl_3$): δ = 206.4, 155.5, 144.5, 126.5, 114.0, 73.2, 34.1, 31.5, 26.6; HRMS (ESI-TOF) calcd for $[C_{13}H_{18}O_2 + Na]^+$ 229.1199, found 229.1199.

*1-(Napthalen-2-yloxy)propan-2-one (**4d**):*[24c] Yield (130.6 mg, 81%). White solid, mp 64−66 °C; IR ($CHCl_3$): ν_{max} = 3028, 3056, 2924, 2850, 1732, 1631, 1600, 1509, 1470, 1432, 1390, 1358, 1272, 1259, 1222, 1173, 1122, 1071, 978, 950, 908, 875, 838, 819, 777, 638 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$/TMS): δ = 7.79 (d, J = 8.8 Hz, 2H), 7.72 (d, J = 8.2 Hz, 1H), 7.48−7.44 (m, 1H), 7.39−7.35 (m, 1H), 7.22 (dd, J = 9.0, 2.6 Hz, 1H), 7.03 (d, J = 2.5 Hz, 1H), 4.66 (s, 2H), 2.33 (s, 3H); ^{13}C {^{1}H} NMR (100 MHz, $CDCl_3$): δ = 205.9, 155.6, 134.2, 129.9, 129.3, 127.7, 126.8, 126.6, 124.2, 118.5, 106.9, 73.0, 26.7; HRMS (ESI-TOF) calcd for $[C_{13}H_{12}O_2 + Na]^+$ 223.0730, found 223.0729.

*2-Oxopropyl 4-Methylbenzoate (**4e**).* Yield (73 mg, 76%). Colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$/TMS): δ = 7.97 (d, J = 8.2 Hz, 2H), 7.26 (d, J = 8.1 Hz, 2H), 4.86 (s, 2H), 2.40 (s, 3H), 2.22 (s, 3H); ^{13}C {^{1}H} NMR (100 MHz, $CDCl_3$): δ = 202.1, 165.9, 144.2, 129.9, 129.2, 126.3, 68.6, 26.2, 21.6; HRMS (ESI-TOF) calcd for $[C_{11}H_{12}O_3 + Na]^+$ 215.0679, found 215.0675.

*2-Oxopropyl 4-Nitrobenzoate (**4f**).* Yield (67.6 mg, 64%). White solid, mp 102−104 °C; ^{1}H NMR (400 MHz, $CDCl_3$/TMS): δ = 8.28 (d, J = 9.1 Hz, 2H), 8.23 (d, J = 9.1 Hz, 2H), 4.97 (s, 2H), 2.23 (s, 3H); ^{13}C {^{1}H} NMR (100 MHz, $CDCl_3$): δ = 200.3, 164.0, 150.7, 134.6, 131.0, 123.6, 69.1, 26.1; HRMS (ESI-TOF) calcd for $[C_{10}H_9O_5N + Na]^+$ 246.0373, found 246.0379.

*2-Oxopropyl 3,5-Dinitrobenzoate (**4g**):*[19] Yield (81.8 mg, 61%). White solid, mp 139−141 °C; IR ($CHCl_3$): ν_{max} = 3093, 3020, 2923, 1735, 1630, 1599, 1547, 1462, 1418, 1345, 1285, 1157, 1075, 1035, 923, 905, 669 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$/TMS): δ = 9.27−9.25 (m, 1H), 9.24−9.20 (m, 2H), 5.05 (s, 2H), 2.27 (s, 3H); ^{13}C {^{1}H} NMR (100 MHz, $CDCl_3$): δ = 199.1, 161.9, 148.7, 132.9, 129.7, 122.8, 69.6, 25.9; HRMS (ESI-TOF) calcd for $[C_{10}H_8O_7N_2 + Na]^+$ 291.0224, found 291.0230.

*1-(tert-Butyldiphenylsilyloxy)-1-phenylpropan-2-one (**4h**):*[24d] Yield (151.3 mg, 78%). Colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$/TMS): δ = 7.66−7.64 (m, 2H), 7.47−7.42 (m, 3H), 7.40−7.32 (m, 5H), 7.31−7.27 (m, 5H), 5.08 (s, 1H), 2.02 (s, 3H), 1.13 (m, 9H); ^{13}C {^{1}H} NMR (100 MHz, $CDCl_3$): δ = 207.7, 138.2, 135.7, 135.6, 132.8, 132.6, 130.0, 129.8, 128.5, 128.1, 127.8, 127.6, 126.2, 81.7, 26.9,

dx.doi.org/10.1021/jo500921j | J. Org. Chem. XXXX, XXX, XXX−XXX

24.3, 19.3; HRMS (ESI-TOF) calcd for $[C_{25}H_{28}O_2Si + Na]^+$ 411.1751, found 411.1755.

2-Oxononan-3-yl Acetate (4i):[24e] Yield (65.1 mg, 65%). Colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$/TMS): δ = 4.98 (dd, J = 8.2, 4.6 Hz, 1H), 2.16 (s, 3H), 2.15 (s, 3H), 1.76−1.71 (m, 2H), 1.54−1.25 (m, 8H), 0.88 (t, J = 6.8 Hz, 3H); ^{13}C {^{1}H} NMR (100 MHz, $CDCl_3$): δ = 205.5, 170.7, 78.7, 31.5, 30.2, 28.9, 26.1, 25.1, 22.5, 20.7, 14.0.

2-Oxo-1-phenylpropyl Acetate (4j):[24e] Yield (71 mg, 74%). Colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$/TMS): δ = 7.44−7.38 (m, 5H), 5.97 (s, 1H), 2.20 (s, 3H), 2.12 (s, 3H); ^{13}C {^{1}H} NMR (100 MHz, $CDCl_3$): δ = 201.7, 170.3, 133.1, 129.4, 129.1, 128.1, 80.9, 26.1, 20.7.

2-Oxononan-4-yl Acetate (4k):[24f] Yield (75.1 mg, 75%). Colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$/TMS): δ = 5.22−5.16 (m, 1H), 2.70 (dd, J = 16.2, 7.4 Hz, 1H), 2.57 (dd, J = 16.2, 5.3 Hz, 1H), 2.13 (s, 3H), 2.01 (s, 3H), 1.54−1.51 (m, 2H), 1.32−1.21 (m, 6H), 0.86 (t, J = 6.8 Hz, 3H); ^{13}C {^{1}H} NMR (100 MHz, $CDCl_3$): δ = 205.8, 170.5, 70.3, 48.0, 34.1, 31.5, 30.4, 24.8, 22.5, 21.1, 14.0.

3-Oxo-1-phenylbutyl Acetate (4l):[24g] Yield (73.2 mg, 71%). Colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$/TMS): δ = 7.37−7.28 (m, 5H), 6.18 (dd, J = 8.7, 4.9 Hz, 1H), 3.12 (dd, J = 16.6, 8.7 Hz, 1H), 2.82 (dd, J = 16.7, 4.9 Hz, 1H), 2.15 (s, 3H), 2.04 (s, 3H); ^{13}C {^{1}H} NMR (100 MHz, $CDCl_3$): δ = 204.7, 169.8, 139.6, 128.6, 128.2, 126.4, 71.6, 49.8, 30.4, 21.0.

1-(4-Methoxyphenyl)-3-oxobutyl Acetate (4m). Yield (99.2 mg, 84%). Colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$/TMS): δ = 7.29 (d, J = 8.7 Hz, 2H), 6.86 (d, J = 8.7 Hz, 2H), 6.13 (dd, J = 8.5, 5.3 Hz, 1H), 3.78 (s, 3H), 3.10 (dd, J = 16.5, 8.5 Hz, 1H), 2.81 (dd, J = 16.5, 5.3 Hz, 1H), 2.14 (s, 3H), 2.01 (s, 3H); ^{13}C {^{1}H} NMR (100 MHz, $CDCl_3$): δ = 204.8, 169.9, 159.5, 131.6, 128.0, 113.9, 71.3, 55.2, 49.6, 30.4, 21.1; HRMS (ESI-TOF) calcd for $[C_{13}H_{16}O_4 + Na]^+$ 259.0941, found 259.0948.

1-(Naphthalen-1-yl)-3-oxobutyl Benzoate (4n). Yield (122.2 mg, 77%). Colorless oil; IR ($CHCl_3$): ν_{max} = 3062, 3009, 2925, 2854, 1719, 1601, 1584, 1510, 1492, 1451, 1417, 1398, 1363, 1315, 1270, 1176, 1110, 1070, 1058, 1026, 975, 938, 862, 798, 713, 686 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$/TMS): δ = 8.25 (d, J = 8.4 Hz, 1H), 8.10−8.07 (m, 2H), 7.88 (d, J = 7.6 Hz, 1H), 7.80 (d, J = 8.2 Hz, 1H), 7.64−7.42 (m, 7H), 7.21 (dd, J = 9.0, 4.0 Hz, 1H), 3.40 (dd, J = 16.9, 8.6 Hz, 1H), 3.13 (dd, J = 16.9, 4.1 Hz, 1H), 2.23 (s, 3H); ^{13}C {^{1}H} NMR (100 MHz, $CDCl_3$): δ = 204.6, 165.3, 135.6, 133.9, 133.1, 129.9, 129.8, 129.6, 129.0, 128.9, 128.7, 126.6, 125.8, 125.3, 123.7, 122.9, 69.9, 49.6, 30.4; HRMS (ESI-TOF) calcd for $[C_{21}H_{18}O_3 + Na]^+$ 341.1148, found 341.1148.

4-(Benzyloxy)-4-(4-nitrophenyl)butan-2-one (4o). Yield (91.3 mg, 61%). Colorless oil; IR ($CHCl_3$): ν_{max} = 3066, 3032, 3008, 2865, 1716, 1606, 1521, 1497, 1415, 1347, 1162, 1096, 1075, 1028, 884, 857, 699 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$/TMS): δ = 8.15 (d, J = 8.8 Hz, 2H), 7.48 (d, J = 8.7 Hz, 2H), 7.27−7.21 (m, 5H), 4.93 (dd, J = 8.4, 4.6 Hz, 1H), 4.32 (d, J = 11.3 Hz, 1H), 4.27 (d, J = 11.3 Hz, 1H), 2.99 (dd, J = 16.5, 8.5 Hz, 1H), 2.57 (dd, J = 16.5, 4.6 Hz, 1H), 2.10 (s, 3H); ^{13}C {^{1}H} NMR (100 MHz, $CDCl_3$): δ = 205.3, 148.9, 147.6, 137.2, 128.4, 127.9, 127.9, 127.5, 123.9, 76.5, 71.5, 51.5, 31.0; HRMS (ESI-TOF) calcd for $[C_{17}H_{17}NO_4 + Na]^+$ 322.1050, found 322.1049.

■ ASSOCIATED CONTENT

Supporting Information

Spectra for compounds **2a−2x** and **4a−4o**. This material is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: rfernand@chem.iitb.ac.in.

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This work is financially supported by the Council of Scientific and Industrial Research (CSIR) New Delhi [Grant No. 02(0158)/13/EMR-II], India. D.A.C. thanks CSIR for a research fellowship India.

■ REFERENCES

(1) For representative reviews, see: (a) Beller, M.; Seayad, J.; Tillack, A.; Jiao, H. *Angew. Chem., Int. Ed.* **2004**, *43*, 3368. (b) Alonso, F.; Beletskaya, I. P.; Yus, M. *Chem. Rev.* **2004**, *104*, 3079. (c) Hintermann, L.; Labonne, A. *Synthesis* **2007**, 1121. (d) Brenzovich, W. E. *Angew. Chem., Int. Ed.* **2012**, *51*, 8933.

(2) (a) Heaney, H. In *Comprehensive Organic Synthesis*; Trost, B. M., Fleming, I., Eds.; Pergamon Press: Oxford, U.K., 1991; Vol. 2, p 733. (b) Olah, G. A. *Friedel-Crafts Chemistry*; Wiley: New York, 1973. (c) Olah, G. A.; Krishnamurti, R.; Prakash, G. K. S. *Comprehensive Organic Synthesis*, 1st ed.; Pergamon: New York, 1991; Vol. 3, pp 293−339. (d) Bandini, M.; Melloni, A.; Umani-Ronchi, A. *Angew. Chem., Int. Ed.* **2004**, *43*, 550.

(3) (a) Dakin, H. D.; West, R. *J. Biol. Chem.* **1928**, *78*, 91. (b) Buchanan, G. L. *Chem. Soc. Rev.* **1988**, *17*, 91. (c) Tran, K.-V.; Bickar, D. *J. Org. Chem.* **2006**, *71*, 6640.

(4) Nahm, S.; Weinreb, S. M. *Tetrahedron Lett.* **1981**, *22*, 3815.

(5) (a) Smidt, J.; Hafner, W.; Jira, R.; Sedlmeier, J.; Sieber, R.; Rüttinger, R.; Kojer, K. *Angew. Chem.* **1959**, *71*, 176. (b) Smidt, J.; Hafner, W.; Jira, R.; Sieber, R.; Sedlmeier, J.; Sabel, A. *Angew. Chem., Int. Ed.* **1962**, *1*, 80. (c) Jira, R. *Angew. Chem., Int. Ed.* **2009**, *48*, 9034.

(6) Tsuji, J. *Palladium Reagents and Catalysts*; Wiley: Chichester, 2004.

(7) Akermark, B.; Zetterberg, K. In *Handbook of Organopalladium Chemistry for Organic Synthesis*, Vol. 2; Negishi, E., Ed.; Wiley: New York, 2002; p 1875.

(8) Henry, P. M. In *Handbook of Organopalladium Chemistry for Organic Synthesis*, Vol. 2; Negishi, E., Ed.; Wiley: New York, 2002; p 2119.

(9) Clement, W. H.; Selwitz, C. M. *J. Org. Chem.* **1964**, *29*, 241.

(10) Tsuji, J. *Synthesis* **1984**, 369.

(11) Takacs, J. M.; Jiang, X. *Curr. Org. Chem.* **2003**, *7*, 369.

(12) Aguado, J.; Serrano, D. P.; Van Grieken, R.; Escola, J. M.; García R.; Carretero, S. Modified Wacker of long chain terminal olefins. In *Book of extended abstracts of the Fourth World Congress on Oxidation Catalysis*; Berlin, Potsdam, Germany, 2001; pp 493−497.

(13) (a) Tsuji, J.; Nagashima, H.; Hori, K. *Chem. Lett.* **1980**, *9*, 257. (b) Roussel, M.; Mimoun, H. *J. Org. Chem.* **1980**, *45*, 5387. (c) Mimoun, H.; Charpentier, R.; Mitschler, A.; Fischer, J.; Weiss, R. *J. Am. Chem. Soc.* **1980**, *102*, 1047. (d) Davison, S. F.; Mann, B. E.; Maitlis, P. M. *J. Chem. Soc., Dalton Trans.* **1984**, 1223. (e) Ogawa, H.; Fujinami, H.; Taya, K.; Teratani, S. *Bull. Chem. Soc. Jpn.* **1984**, *57*, 1908. (f) Clark, G. R.; Thiensathit, S. *Tetrahedron Lett.* **1985**, *26*, 2503. (g) Bäckvall, J.-E.; Awasthi, A. K.; Renko, Z. D. *J. Am. Chem. Soc.* **1987**, *109*, 4750. (h) Nokami, J.; Ogawa, H.; Miyamoto, S.; Mandai, T.; Wakabayasi, S.; Tsuji, J. *Tetrahedron Lett.* **1988**, *29*, 5181. (i) Bäckvall, J.-E.; Hopkins, R. B.; Grennberg, H.; Mader, M. M.; Awasthi, A. K. *J. Am. Chem. Soc.* **1990**, *112*, 5160. (j) Miller, D. G.; Wayner, D. D. *J. Org. Chem.* **1990**, *55*, 2924. (k) Tang, H.-G.; Sherrington, D. C. *J. Catal.* **1993**, *142*, 540. (l) Tang, H.-G.; Sherrington, D. C. *Polymer* **1993**, *34*, 2821. (m) Ahn, J.-H.; Sherrington, D. C. *Macromolecules* **1996**, *29*, 4164. (n) ten Brink, G.-J.; Arends, I. W. C. E.; Papadogianakis, G.; Sheldon, R. A. *Chem. Commun.* **1998**, 2359. (o) Uchiumi, S.; Ataka, K.; Matsuzaki, T. *J. Organomet. Chem.* **1999**, *576*, 279. (p) ten Brink, G.-J.; Arends, I. W. C. E.; Papadogianakis, G.; Sheldon, R. A. *Appl. Catal. A: General* **2000**, *194*, 435. (q) Jiang, H.; Jia, L.; Li, J. *Green Chem.* **2000**, *2*, 161. (r) Namboodiri, V. V.; Varma, R. S.; Sahle-Demessie, E.; Pillai, U. R. *Green Chem.* **2002**, *4*, 170. (s) Hou, Z.; Han, B.; Gao, L.; Jiang, T.; Liu, Z.; Chang, Y.; Zhang, X.; He, J. *New J. Chem.* **2002**, *26*, 1246. (t) Haimov, A.; Neumann, R. *Chem. Commun.* **2002**, 876. (u) Stahl, S. S. *Angew. Chem., Int. Ed.* **2004**, *43*, 3400. (v) Stahl, S. S. *Science* **2005**, *309*, 1824. (w) Wang, Z.-

Y.; Jiang, H.-F.; Qi, C.-R.; Wang, Y.-G.; Dong, Y.-S.; Liu, H.-L. *Green Chem.* **2005**, *7*, 582. (x) Cornell, C. N.; Sigman, M. S. *J. Am. Chem. Soc.* **2005**, *127*, 2796. (y) Cornell, C. N.; Sigman, M. S. *Org. Lett.* **2006**, *8*, 4117. (z) Mitsudome, T.; Umetani, T.; Nosaka, N.; Mori, K.; Mizugaki, T.; Ebitani, K.; Kaneda, K. *Angew. Chem., Int. Ed.* **2006**, *45*, 481. (aa) Cornell, C. N.; Sigman, M. S. *Inorg. Chem.* **2007**, *46*, 1903. (ab) Wang, J.-Q.; Cai, F.; Wang, E.; He, L.-N. *Green Chem.* **2007**, *9*, 882. (ac) Michel, B. W.; Camelio, A. M.; Cornell, C. N.; Sigman, M. S. *J. Am. Chem. Soc.* **2009**, *131*, 6076. (ad) Wang, J.-L.; He, L.-N.; Miao, C.-X.; Li, Y.-N. *Green Chem.* **2009**, *11*, 1317. (ae) Kulkarni, M. G.; Shaikh, Y. B.; Borhade, A. S.; Chavhan, S. W.; Dhondge, A. P.; Gaikwad, D. D.; Desai, M. P.; Birhade, D. R.; Dhatrak, N. R. *Tetrahedron Lett.* **2013**, *54*, 2293. (af) Zhang, G.; Xie, X.; Wang, Y.; Wen, X.; Zhao, Y.; Ding, C. *Org. Biomol. Chem.* **2013**, *11*, 2947. (ag) Wang, Y.-F.; Gao, Y.-R.; Mao, S.; Zhang, Y.-L.; Guo, D.-D.; Yan, Z.-L.; Guo, S.-H.; Wang, Y.-Q. *Org. Lett.* **2014**, *16*, 1610. (ah) Fernandes, R. A.; Bethi, V. *Tetrahedron* **2014**, DOI: 10.1016/j.tet.2014.05.022.

(14) (a) Bäckvall, J.-E.; Hopkins, R. B. *Tetrahedron Lett.* **1988**, *29*, 2885. (b) Potekhin, V. V.; Matsura, V. A. *Russ. Chem. Bull., Int. Ed.* **2006**, *55*, 650. (c) Ferreira de Paula, F. G.; Berllini, L.; José da Silva, M. *Catal. Commun.* **2013**, *42*, 129. (d) Carari, D. M.; José da Silva, M. *Catal. Lett.* **2014**, *144*, 615.

(15) $Fe_2(SO_4)_3{\cdot}nH_2O$ is a hydrate obtained from Aldrich Chem. Co. with unspecified water molecules. The amount used is based on $Fe_2(SO_4)_3$ anhydrous mol wt. Hence the actual amount of $Fe_2(SO_4)_3$ present in reaction media would be less than 1.5 equiv.

(16) Muzart, J. *Tetrahedron* **2007**, *63*, 7505.

(17) Naik, A.; Meina, L.; Zabel, M.; Reiser, O. *Chem.—Eur. J.* **2010**, *16*, 1624.

(18) Moriyama, K.; Takemura, M.; Togo, H. *Org. Lett.* **2012**, *14*, 2414.

(19) Kulkarni, M. G.; Bagale, S. M.; Shinde, M. P.; Gaikwad, D. D.; Borhade, A. S.; Dhondge, A. P.; Chavhan, S. W.; Shaikh, Y. B.; Ningdale, V. B.; Desai, M. P.; Birhade, D. R. *Tetrahedron Lett.* **2009**, *50*, 2893.

(20) Mitsudo, K.; Kaide, T.; Nakamoto, E.; Yoshida, K.; Tanaka, H. *J. Am. Chem. Soc.* **2007**, *129*, 2246.

(21) (a) Aulenta, F.; Hölemann, A.; Reißig, H. U. *Eur. J. Org. Chem.* **2006**, 1733. (b) Iuchi, Y.; Hyotanishi, M.; Miller, B. E.; Maeda, K.; Obora, Y.; Ishii, Y. *J. Org. Chem.* **2010**, *75*, 1803.

(22) (a) Lermer, L.; Neeland, E. G.; Ounsworth, J. P.; Sims, R. J.; Tischler, S. A.; Weiler, L. *Can. J. Chem.* **1992**, *70*, 1427. (b) Tachinami, T.; Nishimura, T.; Ushimaru, R.; Noyori, R.; Naka, H. *J. Am. Chem. Soc.* **2013**, *135*, 50. (c) Rodríguez, S.; Camps, F.; Gemma; Fabriás, G. *J. Org. Chem.* **2001**, *66*, 8052. (d) Nemoto, H.; Ishibashi, H.; Nagamochi, M.; Fukumoto, K. *J. Org. Chem.* **1992**, *57*, 1707. (e) Alemán, J.; Solar, V.; Cubo, L.; Quiroga, A. G.; Ranninger, C. N. *Dalton Trans.* **2010**, *39*, 10601.

(23) (a) Dohi, T.; Fukushima, K.-I.; Kamitanaka, T.; Morimoto, K.; Takenaga, N.; Kita, Y. *Green Chem.* **2012**, *14*, 1493. (b) Liu, C.; Rao, X.; Zhang, Y.; Li, X.; Qiu, J.; Jin, Z. *Eur. J. Org. Chem.* **2013**, 4345.

(24) (a) Bobbitt, J. M.; Bartelson, A. L.; Bailey, W. F.; Hamlin, T. A.; Christopher, B.; Kelly, C. B. *J. Org. Chem.* **2014**, *79*, 1055. (b) Ishikawa, T.; Aikawa, T.; Ohata, E.; Iseki, T.; Maeda, S.; Matsuo, T.; Tatsuo, F. T.; Saito, S. *J. Org. Chem.* **2007**, *72*, 435. (c) Mereyala, H. B.; Lingannagaru, S. R. *Tetrahedron* **1997**, *53*, 17501. (d) Bach, T.; Jödicke, K.; Birgit, W. *Tetrahedron* **1996**, *52*, 10861. (e) Ghosh, N.; Nayak, S.; Sahoo, A. K. *J. Org. Chem.* **2011**, *76*, 500. (f) McCombs, J. R.; Michel, B. W.; Sigman, M. S. *J. Org. Chem.* **2011**, *76*, 3609. (g) Denmark, S. E.; Beutner, G. L.; Wynn, T.; Martin, D.; Eastgate, M. D. *J. Am. Chem. Soc.* **2005**, *127*, 3774.