Pyridine/Potassium *tert*-Butoxide Catalyzed Benzannulation of β-Diketones with Dimethyl Acetylenedicarboxylate

Bin Hu, Ling-Guo Meng, Yan-Ling Liu, Mao Liang, Song Xue*

Department of Applied Chemistry, Tianjin University of Technology, Tianjin 300384, P. R. of China
Fax +86(22)60214250; E-mail: xuesong@ustc.edu.cn

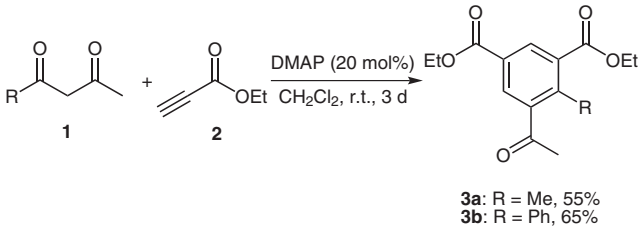
Received 23 July 2009; revised 17 August 2009

Abstract: A benzannulation reaction of β-diketones with dimethyl acetylenedicarboxylate catalyzed by pyridine and potassium *tert*-butoxide is described. Fully substituted benzenes are synthesized from simple and commercially available starting materials under mild conditions in high yields.

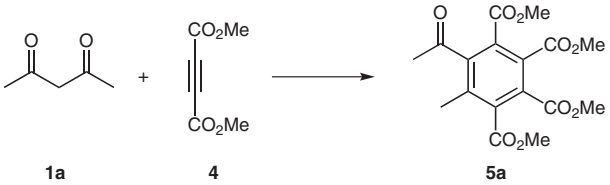
Key words: benzannulation, dimethyl acetylenedicarboxylate, pyridine, β-diketones, potassium *tert*-butoxide

Highly substituted benzenes are important synthetic intermediates in organic chemistry. Great efforts have been made to develop new methods for the synthesis of these highly substituted aromatic compounds.[1] There are famous aromatic annulations including transition-metal-catalyzed cycloaddition,[2,3] the Dötz reaction,[4] the Reppe reaction,[5] carbonyl condensation reaction,[6] and electrocyclic reaction.[7] Nevertheless, regiochemistry and available starting materials limit the application of these reactions. It is still a challenge to develop new methods for the synthesis of highly substituted benzenes.

Recently, reaction based on nucleophilic catalysis via conjugate addition of N- and P-nucleophiles has proven to be useful in the development of cycloaddition providing various carbo-[8] and heterocycles.[9] We reported earlier a benzannulation reaction of 1,3-dicarbonyl compounds **1** with ethyl propiolate (**2**) for the synthesis of substituted aromatic compounds.[10] The reaction catalyzed by 4-(dimethylamino)pyridine (DMAP) under mild conditions afforded tetrasubstituted benzenes **3** in moderate yields (Scheme 1). Acetylenic ketones, in place of ethyl propiolate, showed higher reactivity in benzannulation reaction and gave 1,3,5-trisubstituted benzenes in excellent yields in the presence of DMAP and β-diketones.[11] Our ongoing interest in the chemistry of zwitterionic species prompted us to investigate the benzannulation reaction of dimethyl acetylenedicarboxylate (**4**) with β-diketones. Previously, Nair et al. had described an efficient protocol for the synthesis of fully substituted benzenes from the reaction of dimethyl acetylenedicarboxylate with β-keto esters.[12] During the course of our investigation on the reaction of dimethyl acetylenedicarboxylate (**4**) with β-diketones (Scheme 2), it was found that potassium *tert*-butoxide is crucial for this benzannulation reaction. Herein, we wish to report this procedure to synthesize fully substituted benzenes from the reaction of dimethyl acetylenedicarboxylate (**4**) with β-diketones in the presence of pyridine and potassium *tert*-butoxide under mild conditions.



Scheme 1 DMAP-catalyzed benzannulation of ethyl propiolate with β-diketones



Scheme 2 Reaction of pentane-2,4-dione (**1a**) with dimethyl acetylenedicarboxylate (**4**)

Our studies were initiated by the addition of 25 mol% DMAP to a solution of pentane-2,4-dione (**1a**) and dimethyl acetylenedicarboxylate (**4**) in dimethoxyethane (DME). However, only 18% yield of the benzannulation product **5a** was obtained after stirring the mixture at room temperature for 48 hours (Table 1). Pyridine as catalyst could give the product **5a** in 35% yield. The yield of **5a** increased to 52% when 25 mol% of potassium *tert*-butoxide was added to the reaction mixture in the presence of pyridine. The yield was not improved by further increasing the amount of potassium *tert*-butoxide or pyridine to 50 mol%. In the absence of pyridine, potassium *tert*-butoxide (50 mol%) gave only 15% yield of the desired product. The choice of solvent has an effect on the reaction yield. Acetonitrile as solvent gave the product in 68% yield. Using tetrahydrofuran, toluene, or DME as solvent, the desired product was produced in a relatively lower yield. Shortening the reaction time to 12 hours generated 72% yield of the product. However, the yield decreased significantly when the reaction time was shortened to 6 hours. Pyridine is the most suitable organic catalyst. DMAP, Et_3N, and PPh_3 instead of pyridine afforded the product **5a**

SYNTHESIS 2009, No. 24, pp 4137–4142
Advanced online publication: 12.10.2009
DOI: 10.1055/s-0029-1217035; Art ID: F14509SS

in 51%, 27%, and 38% yield, respectively. On the other hand, NaH and NaOMe as additive in place of potassium *tert*-butoxide could give the product **5a** in 45% and 56% yield, respectively. When zeolite 4A (120 mg) was used as additive, the desired product was obtained in 42% yield.

Table 1 Benzannulation of Pentane-2,4-dione (**1a**) with Dimethyl Acetylenedicarboxylate (**4**)

Entry	Lewis base (mol%)	Additive (mol%)	Solvent	Time (h)	Yield (%)[a]
1	DMAP (25)	–	DME	48	18
2	pyridine (25)	–	DME	24	35
3	pyridine (25)	KO*t*-Bu (25)	DME	24	52
4	pyridine (25)	KO*t*-Bu (50)	DME	24	53
5	pyridine (50)	KO*t*-Bu (25)	DME	24	50
6	pyridine (0)	KO*t*-Bu (50)	DME	24	15
7	pyridine (25)	KO*t*-Bu (25)	CH_2Cl_2	24	63
8	pyridine (25)	KO*t*-Bu (25)	THF	24	59
9	pyridine (25)	KO*t*-Bu (25)	DMF	24	59
10	pyridine (25)	KO*t*-Bu (25)	toluene	24	46
12	pyridine (25)	KO*t*-Bu (25)	MeCN	24	68
13	pyridine (25)	KO*t*-Bu (25)	MeCN	12	72
14	pyridine (25)	KO*t*-Bu (25)	MeCN	6	54
15	DMAP (25)	KO*t*-Bu (25)	MeCN	12	51
16	Et_3N (25)	KO*t*-Bu (25)	MeCN	24	27
17	PPh_3 (25)	KO*t*-Bu (25)	MeCN	24	38
18	pyridine (25)	NaH (25)	MeCN	18	45
19	pyridine (25)	NaOMe(25)	MeCN	18	56
20	pyridine (25)	Zeolite 4A	MeCN	18	42

[a] Isolated yield.

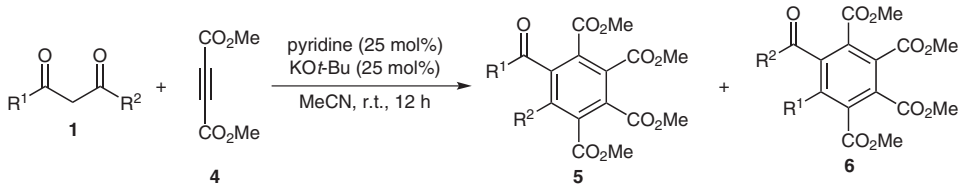
By using conditions optimized for the formation of **5a**, a variety of β-diketones has been examined (Scheme 3), and the representative results are shown in Table 2. It was found that aromatic β-diketones afforded the corresponding products in good to excellent yields. For example, treatment of 1-phenylbutane-1,3-dione (**1b**) with dimethyl acetylenedicarboxylate (**4**) in the presence of pyridine and potassium *tert*-butoxide gave a 2.7:1 mixture of two benzannulation isomers **5b** and **6b** in 86% yield.

Table 2 Benzannulation of β-Diketones **1** with Dimethyl Acetylenedicarboxylate (**4**) Catalyzed by Pyridine and KO*t*-Bu

Entry	R^1	R^2	Product	Yield (%)[a]
1	Me	Me	**5a**	72
2	Ph	Me	**5b/6b** (2.7:1)[b]	86
3	4-MeC_6H_4	Me	**5c**	83
4	4-$MeOC_6H_4$	Me	**5d**	87
5	4-FC_6H_4	Me	**5e/6e** (1.3:1)[b]	89
6	4-ClC_6H_4	Me	**5f/6f** (1:1.6)[b]	86
7	4-BrC_6H_4	Me	**5g/6g** (1.3:1)[b]	87
8	4-$O_2NC_6H_4$	Me	**5h/6h** (1:5.2)[b]	93
9	3-BrC_6H_4	Me	**5i/6i** (1:4.1)[b]	88
10	2-$MeOC_6H_4$	Me	**5j/6j** (4.5:1)[b]	86
11	thiophen-2-yl	Me	**5k**	93
12	2-naphthyl	Me	**5l/6l** (2.6:1)[b]	91
13	3,4-$(MeO)_2C_6H_3$	Et	**5m/6m** (1:1.1)[b]	85
14	Ph	Ph	**5n**	97
15	4-MeC_6H_4	4- MeC_6H_4	**5o**	96
16	4-$MeOC_6H_4$	Ph	**5p**	98
17	(*E*)-PhCH=CH	(*E*)-PhCH=CH	**5r**	77

[a] Isolated yield.
[b] Determined by ^1H NMR analysis.

The two isomers could not be separated by column chromatography, but their structures were easily assigned on the basis of NMR spectra. The ^{13}C carbon signal of methyl group (R^2) in the isomer **5b**, in which methyl group was directly attached to the benzene ring, was at about δ = 17.1, whereas the ^{13}C carbon signal of methyl group (R^2) in the isomer **6b** was positioned at about δ = 31.8. The substituents on the benzene ring have no obvious influence on the reaction yield, but have remarkable effect on the selectivity for isomers **5** and **6**. As can be seen from Table 2, an aromatic β-diketone containing an electron-donating group at *para* position of its benzene ring preferred to form the isomer **5**. For example, substrate with methyl group on the aromatic ring afforded the corre-



Scheme 3

sponding product **5c** as a colorless crystalline solid in 83% yield, and its isomer **6c** was not observed. The structure of **5c** was characterized based on the spectral data and further confirmed unambiguously using single crystal X-ray analysis (Figure 1).[13] On the other hand, the aromatic β-diketone bearing an electron-withdrawing group, such as a nitro group, at the benzene ring *para* position afforded the isomer **6h** as the major product. It is notable that these results are in contrast to our previous observation (Scheme 1).[10] In the course of the benzannulation reaction of aromatic β-diketones with ethyl propiolate (**2**), tetrasubstituted benzenes **3** were generated to form a biaryl derivative, in which the aromatic group is directly attached on benzene ring. In addition, aromatic β-diketone containing methoxy or methyl group on its aromatic ring gave no or poor yield of the four-substituted benzene.

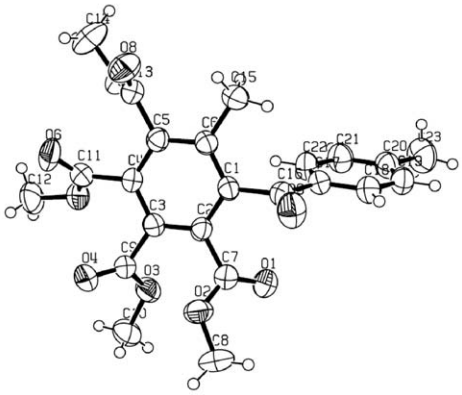


Figure 1 X-ray crystal structure of **5c**

The heteroaromatic β-diketone, such as 1-(thiophen-2-yl)butane-1,3-dione, subjected to this benzannulation reaction gave the product **5k** in 93% yield and its isomer **6k** was not observed. When R^1 was an aromatic group, and R^2 was changed from a methyl group to an aromatic group, the benzannulation reaction proceeded smoothly and afforded the corresponding products **5n–p** in excellent yields.

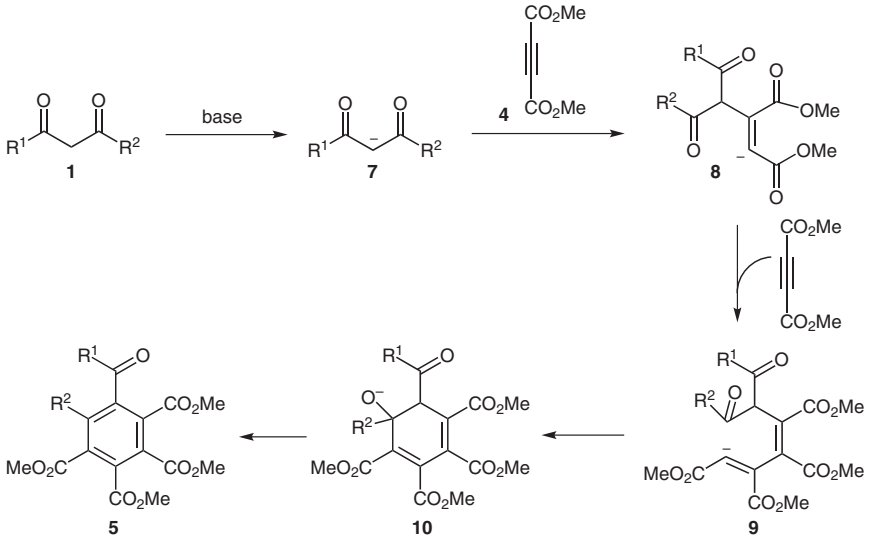
Based on the work of Nair et al.,[12] a plausible mechanism of the benzannulation reaction of β-diketone with dimethyl acetylenedicarboxylate is shown in Scheme 4. Pyridine and potassium *tert*-butoxide might act as base to deprotonate the active methylene of β-diketone to generate the anion **7**, which adds to dimethyl acetylenedicarboxylate (**4**) to give the intermediate **8**. The intermediate **8** reacts with another molecule of dimethyl acetylenedicarboxylate (**4**) to give the intermediate **9**, followed by intramolecular nucleophilic addition to form **10**. The selectivity for isomers **5** and **6** was determined in this step based on the electronic effect and steric effect. Subsequently, the intermediate **10** underwent proton transfer and dehydration to give product **5**.

In summary, we have described a benzannulation reaction of β-diketones **1** with dimethyl acetylenedicarboxylate (**4**) catalyzed by pyridine and potassium *tert*-butoxide under mild conditions. This methodology supplies a facile way to synthesize fully substituted benzenes with high yields from simple and commercially available starting materials. The presented procedure leads to building blocks and potential intermediates in organic synthesis.

^{1}H NMR (300 MHz) and ^{13}C NMR (75 MHz) spectra were recorded on a Bruker AC 300 spectrometer using TMS as an internal standard. High-resolution mass spectra were obtained with a Micromass GCT TOF mass spectrometer. IR spectra were recorded on a Perkin-Elmer FT210 spectrophotometer. Chromatographic purification was performed on silica gel (100–200 mesh) and analytical TLC on silica gel 60-F_{254} was detected by fluorescence. Petroleum ether (PE) used for chromatography was of the fraction boiling in the range 60–90 °C.

Benzannulation of β-Diketones 1 with Dimethyl Acetylenedicarboxylate (4); General Procedure

To a stirred solution of the desired β-diketone **1** (0.30 mmol) in MeCN (2 mL) was added dimethyl acetylenedicarboxylate (**4**; 107 mg, 0.75 mmol) followed by pyridine (6 mg, 0.075 mmol) and



Scheme 4 Possible mechanism for the reaction of β-diketones with dimethyl acetylenedicarboxylate (**4**)

KO*t*-Bu (9 mg, 0.075 mmol). The reaction mixture was stirred at r.t. for 12 h. The solvent was removed under reduced pressure, and the residue was purified by column chromatography on silica gel using PE–EtOAc (10:1) as eluent to afford the desired product (Table 2).

5a
Yield: 79 mg (72%); oil.

IR (neat): 1733 cm^{-1}.

^1H NMR (300 MHz, $CDCl_3$): δ = 3.93 (s, 3 H), 3.90 (s, 3 H), 3.88 (s, 3 H), 3.85 (s, 3 H), 2.53 (s, 3 H), 2.31 (s, 3 H).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 203.0, 167.1, 166.7, 165.6, 146.3, 137.6, 133.6, 132.5, 130.4, 128.8, 53.3, 53.1, 53.0, 31.8, 16.5.

HRMS (ESI): *m*/*z* calcd for $C_{17}H_{18}O_9$ + Na [M + Na]$^+$: 389.0843; found: 389.0845.

5b and 6b
Yield: 111 mg (86%); colorless crystalline solid mixture of **5b** and **6b** (2.7:1). Spectral data are given for the obtained mixture of **5b** and **6b**.

IR (KBr): 1736, 1678 cm^{-1}.

^1H NMR (300 MHz, $CDCl_3$): δ = 7.76–7.73 (m, 2 H), 7.64–7.58 (m, 1 H), 7.50–7.48 (m, 2 H), 3.91–3.88 (m, 9 H), 3.55 (s, 3 H), 3.50 (s, 3 H for **6b**), 2.19 (s, 3 H), 1.91 (s, 3 H for **6b**).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 195.4, 167.3, 166.8, 165.8, 165.3, 143.7, 138.7, 137.4, 135.9, 134.3, 132.5, 131.0, 129.3, 129.2, 128.9, 53.5, 53.3, 53.2, 53.0, 52.8, 14.3.

HRMS (ESI): *m*/*z* calcd for $C_{22}H_{20}O_9$ + Na [M + Na]$^+$: 451.0999; found: 451.1007.

5c
Yield: 110 mg (83%); colorless crystalline solid; mp 140–141 °C.

IR (KBr): 1739 cm^{-1}.

^1H NMR (300 MHz, $CDCl_3$): δ = 7.63 (d, *J* = 7.5 Hz, 2 H), 7.26 (d, *J* = 7.5 Hz, 2 H), 3.91 (s, 3 H), 3.90 (s, 3 H), 3.88 (s, 3 H), 3.56 (s, 3 H), 2.42 (s, 3 H), 2.19 (s, 3 H).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 194.9, 167.3, 166.8, 165.8, 165.3, 145.3, 143.8, 137.2, 135.8, 134.2, 132.3, 130.6, 129.8, 129.4, 53.3, 53.1, 53.0, 52.8, 21.9, 17.0.

HRMS (ESI): *m*/*z* calcd for $C_{23}H_{22}O_9$ + Na [M + Na]$^+$: 465.1156; found: 465.1157.

5d
Yield: 124 mg (87%); colorless crystalline solid; mp 124–125 °C.

IR (KBr): 1752, 1734 cm^{-1}.

^1H NMR (300 MHz, $CDCl_3$): δ = 7.72–7.70 (d, *J* = 9.0 Hz, 2 H), 6.95–6.92 (d, *J* = 9.0 Hz, 2 H), 3.92 (s, 3 H), 3.90 (s, 3 H), 3.88 (s, 3 H), 3.87 (s, 3 H), 3.57 (s, 3 H), 2.19 (s, 3 H).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 193.8, 167.3, 166.9, 165.9, 165.5, 164.5, 143.8, 137.2, 135.9, 132.2, 131.8, 130.7, 130.5, 129.7, 114.4, 55.8, 53.4, 53.2, 53.1, 53.0, 17.1.

HRMS (ESI): *m*/*z* calcd for $C_{23}H_{22}O_{10}$ + Na [M + Na]$^+$: 481.1105; found: 481.1101.

5e and 6e
Yield: 119 mg (89%); colorless crystalline solid mixture of **5e** and **6e** (1.3:1). Spectral data are given for the obtained mixture of **5e** and **6e**.

IR (KBr): 1752, 1734 cm^{-1}.

^1H NMR (300 MHz, $CDCl_3$): δ = 7.81–7.77 (s, 2 H), 7.23–7.15 (m, 2 H), 3.93–3.87 (m, 9 H), 3.59 (s, 3 H), 3.55 (s, 3 H for **6e**), 2.18 (s, 3 H), 1.96 (s, 3 H for **6e**).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 202.9, 193.8, 166.7, 165.9, 165.7, 145.5, 143.3, 137.4, 135.7, 133.1, 131.0, 130.8, 130.7, 130.5, 116.6, 115.31, 53.4, 53.3, 53.1, 52.9, 31.3, 17.1.

HRMS (ESI): *m*/*z* calcd for $C_{22}H_{19}FO_9$ + Na [M + Na]$^+$: 469.0905; found: 469.0907.

5f and 6f
Yield: 119 mg (86%); colorless crystalline solid mixture of **5f** and **6f** (1:1.6). Spectral data are given for the obtained mixture of **5f** and **6f**.

IR (KBr): 1733, 1674 cm^{-1}.

^1H NMR (300 MHz, $CDCl_3$): δ = 7.70 (d, *J* = 8.1 Hz, 2 H), 7.44 (d, *J* = 8.1 Hz, 2 H), 7.42 (d, *J* = 6.3 Hz, 2 H for **6f**), 7.14 (d, *J* = 6.3 Hz, 2 H for **6f**), 3.95–3.82 (m, 9 H), 3.59 (s, 3 H), 3.56 (s, 3 H for **6f**), 2.17 (s, 3 H), 1.97 (s, 3 H for **6f**).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 202.7, 194.2, 167.1, 166.7, 166.2, 165.8, 165.7, 165.6, 165.2, 145.5, 143.2, 140.9, 137.5, 137.2, 136.7, 135.8, 135.7, 134.9, 133.8, 133.2, 131.1, 130.6, 130.3, 129.6, 129.2, 128.6, 53.4, 53.3, 53.1, 52.9, 31.4, 17.1.

HRMS (ESI): *m*/*z* calcd for $C_{22}H_{19}ClO_9$ + Na [M + Na]$^+$: 485.0610; found: 485.0603.

5g and 6g
Yield: 132 mg (87%); colorless crystalline solid mixture of **5g** and **6g** (1.3:1). Spectral data are given for the obtained mixture of **5g** and **6g**.

IR (KBr): 1752, 1734 cm^{-1}.

^1H NMR (300 MHz, $CDCl_3$): δ = 7.62–7.59 (m, 2 H), 7.11–7.07 (m, 2 H), 3.93–3.91 (m, 9 H), 3.60 (s, 3 H), 3.56 (s, 3 H for **6g**), 2.18 (s, 3 H), 1.98 (s, 3 H for **6g**).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 202.5, 194.4, 167.0, 166.5, 166.5, 166.2, 165.8, 165.7, 165.5, 165.2, 145.4, 143.1, 137.4, 137.2, 136.7, 135.7, 135.4, 133.3, 132.5, 132.1, 131.5, 131.1, 130.9, 130.6, 129.6, 123.9, 53.3, 53.2, 53.1, 52.9, 31.4, 17.0.

HRMS (ESI): *m*/*z* calcd for $C_{22}H_{19}BrO_9$ + Na [M + Na]$^+$: 529.0105; found: 529.0100.

5h and 6h
Yield: 133 mg (93%); colorless crystalline solid mixture of **5h** and **6h** (1:5.2). Spectral data are given for the obtained mixture of **5h** and **6h**.

IR (KBr): 1752, 1734 cm^{-1}.

^1H NMR (300 MHz, $CDCl_3$): δ = 8.33–8.31(m, 2 H), 7.60–7.58 (m, 2 H), 3.93–3.78 (m, 9 H), 3.63 (s, 3 H for **5h**), 3.58 (s, 3 H), 2.18 (s, 1 H for **5h**), 2.01(s, 3 H).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 201.8, 166.0, 165.5, 165.2, 165.0, 148.3, 148.1, 145.6, 137.9, 137.0, 135.8, 135.0, 134.7, 134.2, 131.2, 130.6, 129.9, 129.4, 128.2, 124.1, 123.9, 123.4, 53.2, 53.0, 31.6, 17.1.

HRMS (ESI): *m*/*z* calcd for $C_{22}H_{19}NO_{11}$ + Na [M + Na]$^+$: 496.0850; found: 496.0846.

5i and 6i
Yield: 134 mg (88%); colorless crystalline solid mixture of **5i** and **6i** (1:4.1). Spectral data are given for the obtained mixture of **5i** and **6i**.

IR (KBr): 1752, 1734 cm^{-1}.

^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.59–7.56 (m, 1 H), 7.38 (s, 1 H), 7.37–7.27 (m, 2 H), 3.93–3.82 (m, 9 H), 3.61 (s, 3 H for **5i**), 3.58 (s, 3 H), 2.18 (s, 3 H for **5i**), 1.99 (s, 3 H).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 202.5, 166.4, 166.2, 165.8, 165.5, 145.3, 138.2, 137.3, 137.1, 136.9, 136.7, 135.7, 133.3, 132.5, 132.0, 131.6, 131.2, 130.9, 130.8, 130.4, 128.1, 122.9, 53.5, 53.3, 53.22, 52.9, 31.4, 17.1.

HRMS (ESI): *m*/*z* calcd for $C_{22}H_{19}BrO_9$ + Na [M + Na]$^+$: 529.0105; found: 529.0103.

5j and 6j

Yield: 111 mg (86%); colorless crystalline solid mixture of **5j** and **6j** (4.5:1). Spectral data are given for the obtained mixture of **5j** and **6j**.

IR (KBr): 1736, 1662 cm^{-1}.

^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.91–7.89 (m, 1 H), 7.57–7.51 (m, 1 H), 7.09–7.04 (m, 1 H), 6.99–6.91 (m, 1 H), 3.93–3.85 (m, 9 H), 3.58 (s, 3 H), 3.55 (s, 3 H), 2.21 (s, 3 H), 1.95 (s, 3 H for **6j**).

^{13}C NMR (75 MHz,$CDCl_3$): δ = 193.6, 167.5, 167.0, 166.0, 165.7, 159.8, 156.4, 147.2, 137.0, 135.7, 134.9, 131.9, 131.4, 131.1, 129.5, 129.3, 126.2, 121.1, 120.9, 112.6, 111.0, 56.0, 55.5, 53.2, 53.0, 52.9, 52.7, 30.3, 16.8.

HRMS (ESI): *m*/*z* calcd for $C_{23}H_{22}O_{10}$ + Na [M + Na]$^+$: 481.1105; found: 481.1104.

5k

Yield: 121 mg (93%); colorless crystalline solid; mp 106–108 °C.

IR (KBr): 1752, 1734 cm^{-1}.

^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.79–7.77 (m, 1 H), 7.27–7.25 (m, 1 H), 7.12–7.09 (m, 1 H), 3.93–3.88 (m, 9 H), 3.61 (s, 3 H), 2.30 (s, 3 H).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 187.2, 167.2, 166.7, 165.8, 165.4, 143.9, 142.7, 137.3, 136.1, 135.1, 132.2, 130.7, 128.7, 53.5, 53.3, 53.2, 17.0.

HRMS (ESI): *m*/*z* calcd for $C_{20}H_{18}O_9S$ + Na [M + Na]$^+$: 457.0564; found: 457.0561.

5l and 6l

Yield: 131 mg (91%); colorless crystalline solid mixture of **5l** and **6l** (2.6:1). Spectral data are given for the obtained mixture of **5l** and **6l**.

IR (KBr): 1736, 1674 cm^{-1}.

^{1}H NMR (300 MHz, $CDCl_3$): δ = 8.08 (s, 1 H), 7.97–7.88 (m, 3 H), 7.68–7.56 (m, 3 H), 3.93–3.85 (m, 9 H), 3.49 (s, 3 H), 3.43 (s, 3 H for **6l**), 2.22 (s, 3 H), 1.87 (s, 3 H for **6l**).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 195.4, 167.3, 166.9, 165.9, 165.3, 145.5, 143.8, 137.4, 136.2, 136.1, 133.9, 133.2, 132.7, 130.7, 130.1, 129.3, 129.0, 128.8, 128.5, 128.1, 127.4, 127.3, 126.2, 123.8, 53.5, 53.3, 53.2, 53.0, 31.3, 15.5.

HRMS (ESI): *m*/*z* calcd for $C_{26}H_{22}O_9$ + Na [M + Na]$^+$: 501.1156; found: 501.1151.

5m and 6m

Yield: 128 mg (85%); colorless crystalline solid mixture of **5m** and **6m** (1:1.1). Spectral data are given for the obtained mixture of **5m** and **6m**.

IR (KBr): 1752, 1734 cm^{-1}.

^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.61–7.59 (m, 1 H), 6.90–6.89 (m, 2 H), 3.96–3.83 (m, 15 H), 3.58 (s, 3 H), 3.54 (s, 3 H), 2.73–2.68 (m, 1 H), 2.49–2.45 (m, 1 H), 2.23–2.21 (m, 2 H for **6m**), 1.21 (t, *J* = 6.9 Hz, 3 H), 0.83 (t, *J* = 7.2 Hz, 3 H for **6m**).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 206.7, 193.4, 167.3, 167.2, 166.8, 166.4, 166.1, 165.9, 165.6, 154.4, 149.7, 149.6, 149.1, 145.2, 142.9, 142.5, 138.4, 136.7, 132.3, 131.8, 131.3, 131.1, 130.0, 127.8, 125.7, 122.0, 112.4, 111.2, 110.3, 110.0, 56.3, 56.1, 56.0, 53.4, 53.2, 53.1, 53.0, 37.1, 22.8, 14.3, 7.7.

HRMS (ESI): *m*/*z* calcd for $C_{25}H_{26}O_{11}$ + Na [M + Na]$^+$: 525.1367; found: 525.1369.

5n

Yield: 143 mg (97%); light yellow solid; mp 49–50 °C.

IR (KBr): 1739, 1676 cm^{-1}.

^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.48–7.40 (m, 3 H), 7.27–7.24 (m, 2 H), 7.13–7.10 (m, 3 H), 7.02–6.98 (m, 2 H), 3.92 (s, 3 H), 3.91 (s, 3 H), 3.62 (s, 3 H), 3.47 (s, 3 H).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 195.2, 166.9, 166.5, 165.8, 165.7, 143.3, 140.5, 136.9, 135.2, 133.4, 133.0, 131.8, 131.2, 129.2, 128.9, 128.6, 128.4, 128.1, 53.5, 53.4, 53.1, 52.7.

HRMS (ESI): *m*/*z* calcd for $C_{27}H_{22}O_9$ + Na [M + Na]$^+$: 513.1156; found: 513.1149.

5o

Yield: 149 mg (96%); colorless crystalline solid; mp 217–219 °C.

IR (KBr): 1752, 1734 cm^{-1}.

^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.39 (d, *J* = 7.8 Hz, 2 H), 7.25 (d, *J* = 8.7 Hz, 2 H), 6.94–6.90 (m, 4 H), 3.89 (s, 3 H), 3.88 (s, 3 H), 3.57 (s, 3 H), 3.49 (s, 3 H), 2.31 (s, 3 H), 2.20 (s, 3 H).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 194.5, 166.9, 166.5, 165.8, 165.6, 144.3, 143.4, 140.7, 138.3, 137.1, 134.6, 132.7, 132.3, 131.7, 131.0, 129.4, 129.1, 128.7, 53.4, 53.2, 52.9, 52.6, 21.8, 21.2.

HRMS (ESI): *m*/*z* calcd for $C_{29}H_{26}O_9$ + Na [M + Na]$^+$: 541.1469; found: 541.1463.

5p

Yield: 153 mg (98%); colorless crystalline solid; mp 142–143 °C.

IR (KBr): 1752, 1734 cm^{-1}.

^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.47 (d, *J* = 8.7 Hz, 2 H), 7.16–7.12 (m, 5 H), 6.73 (d, *J* = 8.7 Hz, 2 H), 3.92 (s, 3 H), 3.91 (s, 3 H), 3.79 (s, 3 H), 3.62 (s, 3 H), 3.48 (s, 3 H).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 193.5, 167.0, 166.6, 165.9, 165.8, 163.9, 143.4, 140.5, 137.0, 135.4, 133.4, 132.9, 131.7, 131.1, 130.1, 129.2, 128.6, 128.4, 128.1, 113.8, 55.6, 53.5, 53.4, 53.1, 52.8.

HRMS (ESI): *m*/*z* calcd for $C_{28}H_{24}O_{10}$ + Na [M + Na]$^+$: 543.1262; found: 543.1254.

5r

Yield: 125 mg (77%); colorless crystalline solid; mp 199–201 °C.

IR (KBr): 1752, 1734 cm^{-1}.

^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.48–7.46 (m, 2 H), 7.38–7.23 (m, 3 H), 7.36–7.33 (m, 4 H), 7.26–7.25 (m, 2 H), 6.93 (d, *J* = 16.5 Hz, 1 H), 6.88 (d, *J* = 13.2 Hz, 1 H), 6.73 (d, *J* = 16.5 Hz, 1 H), 3.91 (s, 6 H), 3.84 (s, 3 H), 3.78 (s, 3 H).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 194.5, 167.3, 166.4, 165.9, 146.7, 142.2, 138.8, 137.0, 136.1, 135.5, 134.2, 132.4, 131.9, 131.8, 131.3, 129.2, 128.9, 128.8, 127.1, 122.2, 53.5, 53.4, 53.3.

HRMS (ESI): *m*/*z* calcd for $C_{31}H_{26}O_9$ + Na [M + Na]$^+$: 565.1469; found: 565.1461.

Acknowledgment

We are grateful to the National Natural Science Foundation of China (20772116) and the Tianjin Natural Science Foundation (09JCZDJC24400) for financial support.

References

(1) (a) *Modern Arene Chemistry*; Astruc, D., Ed.; Wiley-VCH: Weinheim, **2002**. (b) Eyley, S. C. In *Comprehensive Organic Synthesis*, Vol. 2; Trost, B. M.; Fleming, I., Eds.; Pergamon: New York, **1991**, 707.

(2) (a) Kotha, T.; Brahmachary, E.; Lahiri, K. *Eur. J. Org. Chem.* **2005**, 4741. (b) Saito, S.; Yamamoto, Y. *Chem. Rev.* **2000**, *100*, 2901. (c) Vollhardt, K. P. C. *Ang. Chem., Int. Ed. Engl.* **1984**, *23*, 539.

(3) (a) Xi, Z.; Sato, K.; Gao, Y.; Lu, J.; Takahashi, T. *J. Am. Chem. Soc.* **2003**, *125*, 9568. (b) Takahashi, T.; Ishikawa, M.; Huo, S. *J. Am. Chem. Soc.* **2002**, *124*, 388. (c) Langer, P.; Bose, G. *Angew. Chem. Int. Ed.* **2003**, *42*, 4033. (d) Katritzky, A. R.; Li, J.; Xie, L. *Tetrahedron* **1999**, *55*, 8263.

(4) Dötz, K. H.; Tomuschat, P. *Chem. Soc. Rev.* **1999**, *28*, 187.

(5) Suzuki, D.; Urabe, H.; Sato, F. *J. Am. Chem. Soc.* **2001**, *123*, 7925.

(6) (a) Tius, M. A.; Gomez-Galeno, J. *Tetrahedron Lett.* **1986**, *27*, 2571. (b) Chan, T. H.; Prasad, C. V. C. *J. Org. Chem.* **1986**, *51*, 3012.

(7) (a) Serra, S.; Fuganti, C.; Moro, A. *J. Org. Chem.* **2001**, *66*, 7883. (b) Turnbull, P.; Moore, H. W. *J. Org. Chem.* **1995**, *60*, 644.

(8) (a) Zhang, C.; Lu, X. *J. Org. Chem.* **1995**, *60*, 2906. (b) Lu, X.; Zhang, C.; Xu, Z. *Acc. Chem. Res.* **2001**, *34*, 535. (c) Du, Y.; Lu, X.; Yu, Y. *J. Org. Chem.* **2002**, *67*, 8901. (d) Cowen, B. J.; Miller, S. J. *J. Am. Chem. Soc.* **2007**, *129*, 10988. (e) Ye, L.-W.; Sun, X.-L.; Wang, Q.-G.; Tang, Y. *Angew. Chem. Int. Ed.* **2007**, *46*, 5951. (f) Ye, L.-W.; Han, X.; Sun, X.-L.; Tang, Y. *Tetrahedron* **2008**, *64*, 1487. (g) Denmark, S. E.; Beutner, G. L. *Angew. Chem. Int. Ed.* **2008**, *47*, 1560. (h) Ye, L.-W.; Zhou, J.; Tang, Y. *Chem. Soc. Rev.* **2008**, *37*, 1140.

(9) (a) Lu, C.; Lu, X. *Org. Lett.* **2002**, *4*, 4677. (b) Shi, Y.-L.; Shi, M. *Chem. Eur. J.* **2006**, *12*, 3374. (c) Gabillet, S.; Lecerclé, D.; Loreau, O.; Carboni, M.; Dézard, S.; Gomis, J.-M.; Taran, F. *Org. Lett.* **2007**, *9*, 3925. (d) Zhu, X.-F.; Henry, C. E.; Wang, J.; Dudding, T.; Kwon, O. *Org. Lett.* **2005**, *7*, 1387. (e) Zhu, X.-F.; Schaffner, A.-P.; Li, R. C.; Kwon, O. *Org. Lett.* **2005**, *7*, 2977. (f) Wurz, R. P.; Fu, G. C. *J. Am. Chem. Soc.* **2005**, *127*, 12234. (g) Nair, V.; Menon, R. S.; Sreekanth, A. R.; Abhilash, N.; Biju, A. T. *Acc. Chem. Res.* **2006**, *39*, 520. (h) Fang, Y.-Q.; Jacobsen, E. N. *J. Am. Chem. Soc.* **2008**, *130*, 5660.

(10) Zhou, Q.-F.; Yang, F.; Guo, Q.-X.; Xue, S. *Synlett* **2007**, 2073.

(11) Zhou, Q.-F.; Yang, F.; Guo, Q.-X.; Xue, S. *Synlett* **2007**, 215.

(12) Nair, V.; Vidya, N.; Biju, A. T.; Deepthi, A.; Abhilash, K. G.; Suresh, E. *Tetrahedron* **2006**, *62*, 10136.

(13) X-ray data of **5c** have been deposited at CCDC as deposition number CCDC 727040. Empirical Formula: $C_{23}H_{22}O_9$; Formula Weight: 442.41; Crystal color, Habit: colorless, prismatic; Crystal Dimensions: $0.12 \times 0.10 \times 0.08$ mm; Crystal System: monoclinic; Lattice Type: primitive; Lattice Parameters: a = 13.259 (3) Å, b = 6.2983 (13)Å, c = 26.596 (5) Å, β = 98.07 (3)°, V = 2199.0(8) Å^3; Space group: $P2(1)/c$; Z value = 4; Dcalc = 1.336 g/cm^3; $F000$ = 928; Residuals: R, Rw: 0.0597, 0.1465.