JOC The Journal of Organic Chemistry

NOTE

pubs.acs.org/joc

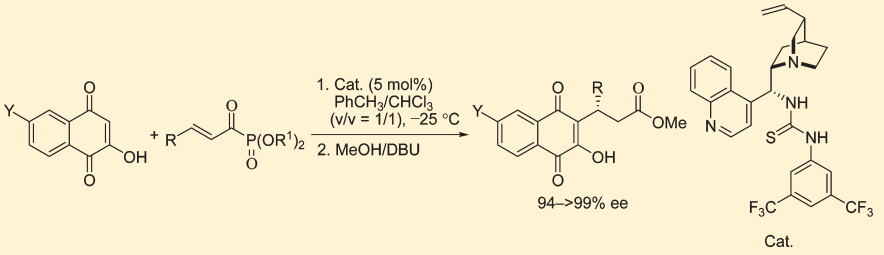
Organocatalyzed Enantioselective Michael Addition of 2-Hydroxy-1, 4-naphthoquinone to β,γ-Unsaturated α-Ketophosphonatesθ

Tao Liu, Youming Wang,* Guiping Wu, Haibin Song, Zhenghong Zhou,* and Chuchi Tang

State Key Laboratory of Elemento-Organic Chemistry, Institute of Elemento-Organic Chemistry, Nankai University, Tianjin 300071, People's Republic of China

Supporting Information

ABSTRACT:



By employing a cinchonine-based thiourea as catalyst, highly enantioselective Michael addition reactions of 2-hydroxy-1,4-naphthoquinone to β,γ-unsaturated α-ketophosphonates were realized. The reaction afforded the corresponding β-substituted carboxylates in excellent yields with high levels of enantioselectivities (94−>99% ee) upon quenching the generated parent structures with DBU and MeOH as a second nucleophile.

The Michael addition reaction represents one of the most important and fundamental methods for construction of a carbon−carbon bond in organic synthesis.[1] As a result, with the explosive development of organocatalysis during the past two decades, considerable effort has been directed to the development of the organocatalytic asymmetric version of these processes, and a number of successful organocatalytic asymmetric Michael additions have been reported. However, the Michael acceptors employed in these asymmetric Michael additions generally have been restricted to enals, enones, and nitroalkenes.[2] The application of the efficient organocatalyst for Michael addition of such acceptors to α,β-unsaturated esters seems to be difficult because of the poorer nature of the α,β-unsaturated ester as a Michael acceptor. Therefore, the development of general and highly enantioselective versions of the reactions of α,β-unsaturated acid derivatives still remains a challenging goal. An in-direct, but equally efficient, strategy to encounter this problem is the use of activated ester surrogates as masked equivalents of the desired products. Various α,β-unsaturated carbonyl compounds have been used as activated ester surrogates in the catalytic enantioselective Michael reactions to give products in which the desired carboxylates could be unveiled in a subsequent step. Notable examples of such compounds include α,β-unsaturated *N*-acylpyrazoles,[3] alkenoyl pyrroles,[4] styryloxazoles,[5] α,β-unsaturated imides,[6] and most recently α,β-unsaturated acylphosphonates.[7,8] Among these activated ester surrogates, α,β-unsaturated acylphosphonates especially deserve to be noticed owning to their unique characteristics: (i) The electron-withdrawing capability of the phosphonate group will enhance activation of the substrate toward nucleophilic attack. (ii) Preferential binding between the catalyst and the phosphoryl and carbonyl oxygens will lead to further activation of the substrate and also constrains it to a well-defined orientation required for asymmetric induction. (iii) The facile nucleophilic cleavage of the P−C bond enables the desired β-branched optically active carboyxlates to be accessed in a one-pot fashion under mild conditions. For example, using chiral H-donor catalysts then oxazolones,[8a] indoles,[8a,b] and cyclic 1,3-dicarbonyl compounds[8a] were successfully introduced with enantioselectivities up to 93%, 92%, and 95% ee, respectively. Herein, we report another Michael donor, 2-hydroxy-1, 4-naphthaquinone,[9] participated in the asymmetric Michael addition to α,β-unsaturated acylphosphonates, generating the corresponding β-(3-hydroxy-1,4-dioxo-1,4-dihydronaphthalen-2-yl)-substituted carboxylates in excellent yields with high levels of enantioselectivities (94−>99% ee). Since naphthoquinones are considered privileged structures in medicinal chemistry,[10] the organocatalytic additions of these valuable skeletons to electron-deficient alkenes may provide an alternative process for some novel optically active chemicals with potent pharmacological properties.

First, a series of cinchona alkaloid derivatives **1**−**2** and bifunctional thioureas **3**−**7** bearing different chiral diamine skeletons were chosen as the catalyst candidates (Figure 1) and the conjugate addition of 2-hydroxy-1,4-naphthaquinone (**8a**) to (*E*)-dimethyl

Received: February 9, 2011
Published: April 05, 2011

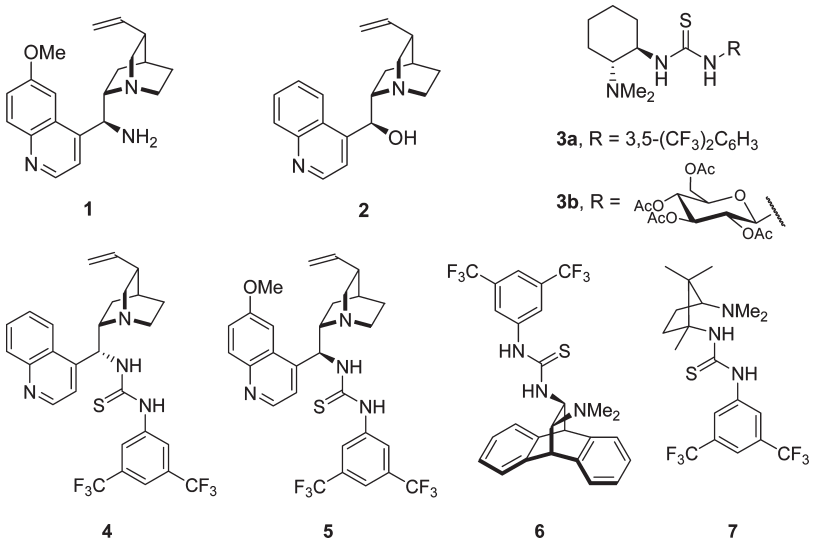
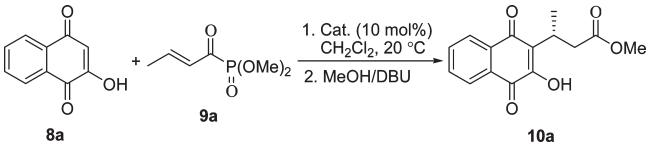


Figure 1. Hydrogen bonding organocatalysts.

Table 1. Catalyst Screening [a]



entry	catalyst	time	yield (%)[b]	ee (%)[c]
1	**1**	84 h	52	36
2	**2**	4 h	50	21
3	**3a**	5 min	40	80
4	**3b**	72 h	56	52
5	**4**	5 min	74	82
6	**5**	5 min	56	80
7	**6**	28 h	48	77
8	**7**	96 h	61	0

[a] Reaction conditions: (*E*)-dimethyl but-2-enoylphosphonate (**9a**) (0.2 mmol), 2-hydroxy-1,4-naphthoquinone (**8a**) (0.2 mmol), in 2 mL of methylene chloride at 20 °C in the presence of 10 mol % of catalyst. [b] Yield of the isolated product after chromatography on silica gel. [c] Determined by chiral HPLC analysis.

but-2-enoylphosphonate (**9a**) was selected as a model reaction. The experimental results are summarized in Table 1.

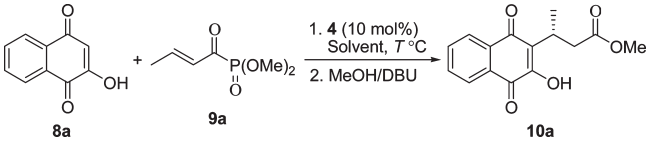
As shown in Table 1, The reaction of (*E*)-dimethyl but-2-enoylphosphonate (**9a**) with 2-hydroxy-1,4-naphthoquinone (**8a**) in the presence of catalyst **1** in methylene chloride as solvent at 20 °C afforded the desired C-2 addition product **10a** in 36% ee upon quenching with DBU and MeOH as a second nucleophile (Table 1, entry 1).[11] The replacement of **1** with cinchonine (**2**) as the catalyst resulted in a dramatic rate acceleration with slight erosion in enantioselectivity (Table 1, entry 2 vs entry 1). The observed rate acceleration may attribute to the hydrogen bond interaction between the more acidic hydroxy group and the phosphoryl and carbonyl oxygens of (*E*)-dimethyl but-2-enoylphosphonate which activate it toward nucleophilic addition. In general, bifunctional thioureas are promising catalysts for this transformation. However, the chiral diamine backbone of these thioureas plays a crucial role on both the catalytic efficacy and chiral induction ability (Table 1, entries 3−8). Takemoto's thiourea **3a**[12] and cinchona alkaloid-based thioureas **4** and **5**[13] proved to be highly efficient for this reaction. The reaction was complete within 5 min, giving the corresponding conjugate addition product **10a** with enantioselectivities of 80%, 82%, and 80% ee, respectively (Table 1, entries 3, 5, and 6). The use of catalyst **3b** derived from (1*R*,2*R*)-cyclohexane-1,2-diamine bearing a glucosyl scaffold[14] and catalyst **6** containing a (*R*,*R*)-11,12-diamino-9,10-dihydro-9,10-ethanonanthracene skeleton led to a significant decrease in both reaction rate and enantioselectivity (Table 1, entries 4 and 7). Moreover, it is quite surprising that racemic product was obtained when thiourea **7** derived from (+)-*cis*-1,2,2-trimethylcyclopentane-1,3-diamine was employed as the catalyst. These results demonstrated that cinchonine-based thiourea **4** was the best choice as the catalyst for the model reaction.

Having confirmed thiourea **4** as the optimum catalyst for the reaction, other factors, such as solvent, catalyst loading, and reaction temperature, influencing the reaction were thoroughly investigated employing the reaction between (*E*)-dimethyl but-2-enoylphosphonate (**9a**) and 2-hydroxy-1,4-naphthoquinone (**8a**) as the model. The results are listed in Table 2.

With 10 mol % of **4** as the catalyst at 20 °C, various solvents have been examined for this reaction (Table 2, entries 1−6). Except for methanol in which no reaction occurred, the asymmetric Michael addition could be carried out smoothly in several conventional solvents such as methylene chloride (82% ee), chloroform (85% ee), THF (77% ee), ethyl acetate (83% ee), and toluene (83% ee). The use of chloroform resulted in the highest enantioselectivity of 85% ee albeit in low yield (Table 2, entry 2). The conjugate addition product **10a** was obtained in high yield but with a slight loss of sterercontrol in toluene (Table 2, entry 5). Thus, further screening indicated that the reaction conducted in a mixture of $CHCl_3$/$PhCH_3$ (v/v, 1:1) offered the best result (Table 2, entry 7). Adjusting the catalyst loading demonstrated only little influence on the outcome of the enantioselectivity of the reaction. The use of 5 mol % of catalyst led to a slight improvement on enantioselectivity (Table 2, entry 8, 87% ee). The reaction proceeds well even at 2.5 mol % catalyst

dx.doi.org/10.1021/jo2002825 |*J. Org. Chem.* 2011, 76, 4119–4124

Table 2. Optimization of the Reaction Conditions [a]



8a 9a 10a

entry	solvent	temp (°C)	time	yield (%)[b]	ee (%)[c]
1	CH_2Cl_2	20	5 min	74	82
2	$CHCl_3$	20	5 min	55	85
3	THF	20	10 min	63	77
4	AcOEt	20	5 min	46	83
5	$PhCH_3$	20	10 min	72	83
6	MeOH	20	24 h	NR	
7	$CHCl_3/PhCH_3$[d]	20	10 min	72	85
8[e]	$CHCl_3/PhCH_3$[d]	20	20 min	67	87
9[f]	$CHCl_3/PhCH_3$[d]	20	20 h	69	88
10[e]	$CHCl_3/PhCH_3$[d]	0	15 h	96	96
11[e]	$CHCl_3/PhCH_3$[d]	−25	35 h	99	98
12[e]	$CHCl_3/PhCH_3$[d]	−40	4.5 d	98	99

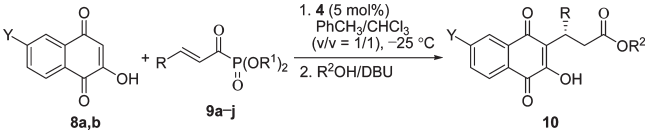
[a] Reaction conditions: (*E*)-dimethyl but-2-enoylphosphonate (**9a**) (0.2 mmol), 2-hydroxy-1,4-naphthoquinone (**8a**) (0.2 mmol) in 2 mL of solvent in the presence of 10 mol % of catalyst **4**. [b] Yield of the isolated product after chromatography on silica gel. [c] Determined by chiral HPLC analysis. [d] v/v = 1/1. [e] The reaction was conducted in the presence of 5 mol % of catalyst. [f] The reaction was conducted in the presence of 2.5 mol % of catalyst.

loading at the expense of reaction time, without any erosion in the observed ee value (Table 2, entry 9, 88% ee). It was gratifying that decreasing the reaction temperature had a markedly positive effect on the enantioselectivity of the reaction with a catalyst loading of 5 mol % (Table 2, entries 8 and 10−12). Lowering the temperature from 20 to −25 °C led to a sharp increase in enantioselectivity (Table 2, entry 8, 87% ee vs entry 11, 98% ee). Although almost perfect enantioselectivity was achieved, the reaction became quite sluggish by further lowering the temperature to −40 °C (Table 2, entry 12).

With a set of optimized reaction conditions in hand (5 mol % of **4** as the catalyst, at −25 °C in a 1:1 mixture of chloroform and toluene), we then investigated the scope and limitations of this asymmetric Michael addition reaction. The results are collected in Table 3.

As shown in Table 3, in the case of 2-hydroxy-1,4-naphthoquinone (**8a**), the reaction tolerated both aliphatic and aromatic substituents R on the α,β-unsaturated acyl phosphonates (Table 3, entries 1−11), affording the desired optically active β-(3-hydroxy-1,4-dioxo-1,4-dihydronaphthalen-2-yl)-substituted carboxylates **10a**−**i** in 50−99% yield and 94−>99% ee. With respect to the alkyl-substituted α,β-unsaturated acyl phosphonates, generally, the introduction of bulky alkyl substituent to some extent favored the enantioselectivity of the reaction. For example, the reaction of a linear alkyl group, such as propyl and butyl, substituted substrates led to the addition product with 97% and 94% ee, respectively (Table 3, entries 6 and 8). However, the use of the corresponding branched alkyl group, such as isopropyl, isobutyl, and second butyl, substituted ones resulted in obviously improved enantioselectivities (Table 3, entries 7, 9, and 10, 98%, 97%, and 99% ee, respectively).

Table 3. Chiral Thiourea 4 Catalyzed Asymmetric Michael Addition of 2-Hydroxy-1,4-naphthoquinones 8 to α,β-Unsaturated Acylphosphonates 9[a]



8a,b 9a–j 10

entry	**10** (Y, R, R^1, R^2)	time (h)	yield (%)[b]	ee (%)[c]
1	**10a** (H, Me, Me, Me)	35	99	98
2	**10a** (H, Me, Et, Me)	7	95	98
3	**10b** (H, Me, Me, Et)	35	82	97
4	**10c** (H, Et, Me, Me)	2	81	96
5	**10c** (H, Et, Et, Me)	48	85	98
6	**10d** (H, Pr, Me, Me)	1	96	97
7	**10e** (H, ^{i}Pr, Me, Me)	24	90	98
8	**10f** (H, Bu, Me, Me)	144	50	94
9	**10g** (H, ^{i}Bu, Me, Me)	1	88	97
10	**10h** (H, ^{s}Bu, Me, Me)	144	58	99 (96)[d]
11	**10i** (H, Ph, Me, Me)	108	99	>99
12	**10j** (MeO, Me, Me, Me)	96	95	99
13	**10k** (MeO, Pr, Me, Me)	120	62	96
14	**10l** (MeO, ^{i}Pr, Me, Me)	96	59	99
15	**10m** (MeO, Bu, Me, Me)	144	65	94
16	**10n** (MeO, ^{i}Bu, Me, Me)	96	92	99

[a] Reaction conditions: acyl phosphonates **9** (0.2 mmol), 2-hydroxy-1,4-naphthoquinones **8** (0.2 mmol), in 2 mL of $CHCl_3/PhCH_3$ (v/v = 1:1) at −25 °C in the presence of 5 mol % of catalyst **4**. [b] Yield of the isolated product after chromatography on silica gel. [c] Determined by chiral HPLC analysis. [d] The ratio of the two diastereomers is 72/28. Data in parentheses is the enantiomeric excess value of the minor diastereomer.

Moreover, the use of ethanol instead of methanol as the quenching nucleophile also led to the corresponding ethyl ester adduct **10b** with almost the same level of enantioselectivity (Table 3, entry 3 vs entry 1). Diethyl acylphosphonates rather than dimethyl acylphosphonates also worked well to furnish the desired product with unaltered or even improved ee values (Table 3, entries 2, 5 vs entries 1, 4). In addition, a substituted 2-hydroxy-1,4-naphthoquinone, such as 2-hydroxy-6-methoxyl-1,4-naphthoquinone (**8b**), was also proved to be a suitable reaction partner with different aliphatic α,β-unsaturated acyl phosphonates, furnishing the desired products **10j**−**n** with 94−99% ee albeit with decreased yields and prolonged reaction times (Table 3, entries 12−16). Similarly, a bulkier substituent on the β-position of α,β-unsaturated acyl phosphonates means the higher ee values of the desired product (Table 3, entry 14 vs entry 13; entry 16 vs entry 15).

The absolute configuration of the product **10a** is unequivocally established to be *R* by X-ray analysis (see the Supporting Information, the absolute configuration of compound **10a** was determined by the Flack parameter −0.20(19), and further examination was done by BijvoetPair check in platon) and the remaining configurations are assumed by analogy.

To account for the observed high enantioselectivity of the reaction, a ternary complex of thiourea catalyst **4**, 1,4-dioxo-1,

dx.doi.org/10.1021/jo2002825 |*J. Org. Chem.* 2011, 76, 4119–4124

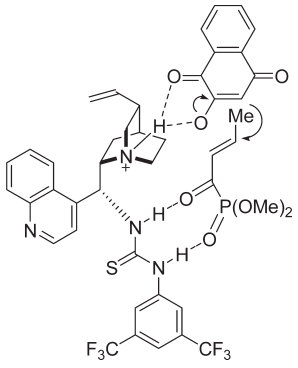


Figure 2. Proposed transition state.

4-dihydronaphthalen-2-olate, and (*E*)-dimethyl but-2-enoylphosphonate is proposed as a plausible transition state for this transformation (Figure 2). In the proposed transition state, 1,4-dioxo-1,4-dihydronaphthalen-2-olate and (*E*)-dimethyl but-2-enoylphosphonate coordinate to the thiourea moiety and tertiary amino group of catalyst **4** by hydrogen bonding interaction, respectively. Then nucleophilic attack of the 1,4-dioxo-1,4-dihydronaphthalen-2-olate from the *Re*-face of (*E*)-dimethyl but-2-enoylphosphonate leads to the formation of the (*R*)-enantiomer as the major product.

In conclusion, cinchonine-based thiourea **4** has proven to be an efficient catalyst for the asymmetric Michael addition of 2-hydroxy-1,4-naphthoquinones to α,*β*-unsaturated acylphosphonates. Subsequent treatment of the resulting conjugate addition product with methanol in the presence of DBU afforded *β*-(3-hydroxy-1,4-dioxo-1,4-dihydronaphthalen-2-yl)-substituted carboxylates in excellent yields and enantioselectivities (up to >99% ee). The presented approach allows for an efficient route to formal *β*-functionalization of simple esters.

EXPERIMENTAL SECTION

All reagents and solvents were commercial grade and purified prior to use when necessary. NMR spectra were acquired on either a 300 or 400 MHz instrument. Chemical shifts are measured relative to residual solvent peaks as an internal standard set to δ 7.26 and 77.0 ($CDCl_3$). Enantiomeric excesses were determined on a HPLC instrument (chiral column; mobile phase: hexane/*i*-PrOH). Column chromatography was performed on silica gel (200−300 mesh).

Preparation of Thioureas 6 and 7. To a solution of chiral parent diamine (2 mmol) in methylene chloride (4 mL) was added dropwise a solution of the 3,5-bis(trifluoromethyl)phenyl isothiocyanate (0.54 g, 2 mmol) in methylene chloride (4 mL) under a nitrogen atmosphere. The resulting mixture was stirred at room temperature until total consumption of the isothiocyanate (monitored by TLC). After removal of solvent, the residue was purified through column chromatography on silica gel (200−300 mesh, eluted with ethyl acetate/petroleum ether: 1/2) to give the thiourea catalyst as a white solid.

For **6**: white solid, 1.06 g, 99% yield, mp 116−117 °C, $[\alpha]^{20}_D$ +48.4 (*c* 1.0, $CHCl_3$); ^{1}H NMR ($CDCl_3$, 400 MHz) δ 2.29 (s, 6 H), 3.00 (s, 1 H), 3.86 (s, 1 H), 4.29 (s, 1 H), 4.62 (s, 1 H), 6.23 (s, 1 H), 7.16−7.22 (m, 4 H), 7.32−7.40 (m, 4 H), 7.58 (s, 1 H), 7.98 (s, 2 H), 12.04 (s, 1 H); ^{13}C NMR ($CDCl_3$, 100.6 MHz) δ 41.4, 42.9, 48.4, 57.9, 72.9, 117.9 (br signal, *J* = 3.2 Hz), 122.8, 123.1 (q, *J* = 273.3 Hz), 123.6, 125.8, 126.0, 126.7, 126.9, 127.4, 131.7 (q, *J* = 33.5 Hz), 137.5, 140.2, 140.4, 141.7, 142.7, 181.3; HRMS (ESI) *m*/*z* calcd for $C_{27}H_{23}F_6N_3S$ $[M - H]^-$ 534.1444, found 534.1446.

For **7**: white solid, 0.66 g, 75% yield, mp 166−167 °C, $[\alpha]^{20}_D$ −46.7 (*c* 0.3, $CHCl_3$); ^{1}H NMR ($CDCl_3$, 400 MHz) δ 0.89 (s, 3 H), 1.02 (s, 3 H), 1.66 (s, 3 H), 1.77−1.86 (m, 9 H), 2.23−2.27 (m, 1 H), 2.87 (br s, 1 H), 7.64 (s, 1 H), 7.69 (s, 2 H), 8.83 (br s, 2 H); ^{13}C NMR ($CDCl_3$, 100.6 MHz) δ 18.5, 24.3, 25.4, 33.2, 45.0, 49.4, 69.5, 74.6, 118.5 (br signal, *J* = 3.6 Hz), 122.8 (q, *J* = 272.7 Hz), 124.1, 132.7 (q, *J* = 33.6 Hz), 139.7, 179.4; HRMS (ESI) *m*/*z* calcd for $C_{19}H_{25}F_6N_3S$ $[M - H]^-$ 440.1601, found 440.1606.

General Procedure for the Catalytic Asymmetric Addition of 2-Hydroxy-1,4-naphthoquinones to *β*,*γ*-Unsaturated α-Ketophophonates. A 10 mL Schlenk tube was charged with *β*,*γ*-unsaturated α-ketophophonate **9** (0.2 mmol), thiourea catalyst **4** (5 mol %), and a mixture of $PhCH_3/CHCl_3$ (2 mL, v/v = 1/1). After 30 min of stirring at −25 °C, 2-hydroxy-1,4-naphthonuinone (**8**, 0.2 mmol) was added in one portion. The stirring was maintained at the same temperature until the total consumption of 2-hydroxy-1,4-naphthonuinone (**8**) (monitored by TLC). Upon completion the reaction mixture was allowed to warm to room temperature and then methanol (0.2 mL) and DBU (61 mg, 0.4 mmol) were added in the described sequence. After an additionally 30 min of stirring, the crude reaction mixture was diluted with saturated aqueous NH_4Cl, extracted with EtOAc (3 × 5 mL), dried over $MgSO_4$, and concentrated in vacuo. The residue was purified by column chromatography on silica gel (200−300 mesh, eluted with methylene chloride) to afford the desired optically active 3-substituted carboxylate **10**.

(*R*)-Methyl 3-(1,4-dihydro-2-hydroxy-1,4-dioxonaphthalen-3-yl)butanoate (10a): yellow solid, 54 mg, 99% yield, mp 98−99 °C, $[\alpha]^{20}_D$ −7.0 (*c* 1.0, $CHCl_3$), 98% ee; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 1.32 (d, *J* = 7.2 Hz, 3H), 2.73 (dd, *J* = 6.8 and 16.0 Hz, 1 H), 2.97 (dd, *J* = 8.4 and 16.0 Hz, 1 H), 3.61 (s, 3 H), 3.71−3.80 (m, 1 H), 7.51 (br s, 1 H), 7.67 (t, *J* = 7.6 Hz, 1 H), 7.75 (t, *J* = 7.6 Hz, 1 H), 8.06 (d, *J* = 7.6 Hz, 1 H), 8.12 (d, *J* = 7.6 Hz, 1 H); ^{13}C NMR ($CDCl_3$, 100.6 MHz) δ 18.2, 26.7, 38.2, 51.5, 126.0, 127.0, 129.2, 132.9, 133.0, 135.0, 152.8, 173.0, 181.6, 184.1; HRMS (ESI) *m*/*z* calcd for $C_{15}H_{14}O_5$ $[M + Na]^+$ 297.0733, found 297.0724; HPLC analysis (Chiralpak OJ-H column, hexane:2-propanol = 75:25, flow rate = 1.0 mL/min, wavelength = 220 nm) R_t = 13.96 (major) and 20.12 min (minor).

(*R*)-Ethyl 3-(1,4-dihydro-2-hydroxy-1,4-dioxonaphthalen-3-yl)butanoate (10b): yellow solid, 47 mg, 82% yield, mp 90−91 °C, $[\alpha]^{20}_D$ −4.0 (*c* 1.0, $CHCl_3$), 97% ee; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 1.17 (t, *J* = 7.2 Hz, 3 H), 1.32 (d, *J* = 7.2 Hz, 3H), 2.71 (dd, *J* = 6.8 and 16.0 Hz, 1 H), 2.96 (dd, *J* = 8.8 and 16.0 Hz, 1 H), 3.71−3.81 (m, 1 H), 4.05 (dq, *J* = 2.8 and 7.2 Hz, 2 H), 7.48 (br s, 1 H), 7.67 (dt, *J* = 1.2 and 7.6 Hz, 1 H), 7.76 (dt, *J* = 1.2 and 7.6 Hz, 1 H), 8.06 (dd, *J* = 1.2 and 7.6 Hz, 1 H), 8.12 (dd, *J* = 0.8 and 7.6 Hz, 1 H); ^{13}C NMR ($CDCl_3$, 100.6 MHz) δ 14.1, 18.2, 26.7, 38.5, 60.2, 126.0, 126.2, 127.0, 129.2, 132.8, 133.0, 135.0, 152.8, 172.5, 181.6, 184.1; HRMS (ESI) *m*/*z* calcd for $C_{16}H_{16}O_5$ $[M - H]^-$ 287.0925, found 287.0925; HPLC analysis (Chiralpak OJ-H column, hexane:2-propanol = 75:25, flow rate = 1.0 mL/min, wavelength = 220 nm) R_t = 9.51 (major) and 14.20 min (minor).

(*R*)-Methyl 3-(1,4-dihydro-2-hydroxy-1,4-dioxonaphthalen-3-yl)pentanoate (10c): yellow oil, 47 mg, 81% yield and 49 mg, 85% yield (from (*E*)-diethyl pent-2-enoylphosphonate), $[\alpha]^{20}_D$ +4.0 (*c* 1.0, $CHCl_3$), 96% ee and 98 ee (from (*E*)-diethyl pent-2-enoylphosphonate); ^{1}H NMR ($CDCl_3$, 400 MHz) δ 0.88 (t, *J* = 7.2 Hz, 3 H), 1.68−1.76 (m, 1 H), 1.80−1.89 (m, 1 H), 2.74 (dd, *J* = 6.0 and 15.6 Hz, 1 H), 2.99 (dd, *J* = 9.2 and 16.0 Hz, 1 H), 3.59 (s, 2 H), 3.54−3.61 (m, 1 H), 7.51 (br s, 1 H), 7.67 (t, *J* = 7.6 Hz, 1 H), 7.75 (t, *J* = 7.6 Hz, 1 H), 8.07 (d, *J* = 7.6 Hz, 1 H), 8.12 (d, *J* = 7.6 Hz, 1 H); ^{13}C NMR ($CDCl_3$, 100.6 MHz) δ 12.2, 25.7, 33.8, 36.9, 51.5, 124.8, 126.0, 127.0, 129.3, 132.8, 133.0, 135.0, 153.3, 173.2, 181.4, 184.3; HRMS (ESI) *m*/*z* calcd for $C_{16}H_{16}O_5$ $[M - H]^-$ 287.0925, found 287.0926; HPLC analysis (Chiralpak AS-H column, hexane:

dx.doi.org/10.1021/jo2002825 |*J. Org. Chem.* 2011, 76, 4119–4124

2-propanol = 75:25, flow rate = 1.0 mL/min, wavelength = 220 nm) R_t = 10.95 (minor) and 14.48 min (major).

(*R*)-methyl 3-(1,4-dihydro-2-hydroxy-1,4-dioxonaphthalen-3-yl)hexanoate (10d): yellow oil, 58 mg, 96% yield, $[\alpha]^{20}_D$ −4.6 (*c* 1.0, $CHCl_3$), 97% ee; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 0.88 (d, *J* = 7.2 Hz, 3 H), 1.21−1.34 (m, 2 H), 1.56−1.67 (m, 1 H), 1.78−1.91 (m, 1 H), 2.72 (dd, *J* = 6.0 and 15.9 Hz, 1 H), 2.97 (dd, *J* = 9.3 and 15.9 Hz, 1 H), 3.59 (s, 3 H), 3.64−3.72 (m, 1 H), 7.50 (br s, 1 H), 7.67 (dt, *J* = 1.2 and 7.5 Hz, 1 H), 7.75 (dt, *J* = 1.5 and 7.5 Hz, 1 H), 8.06 (dd, *J* = 1.2 and 7.5 Hz, 1 H), 8.12 (dd, *J* = 0.9 and 7.5 Hz, 1 H); ^{13}C NMR ($CDCl_3$, 75.0 MHz) δ 14.0, 20.9, 31.9, 34.9, 37.2, 51.5, 125.0, 126.0, 127.0, 129.2, 132.8, 133.0, 135.0, 153.2, 173.1, 181.4, 184.3; HRMS (ESI) *m*/*z* calcd for $C_{17}H_{18}O_5$ $[M - H]^-$ 301.1081, found 301.1082; HPLC analysis (Chiralpak OJ-H column, hexane:2-propanol = 75:25, flow rate = 1.0 mL/min, wavelength = 220 nm) R_t = 7.81 (major) and 24.18 min (minor).

(*S*)-Methyl 3-(1,4-dihydro-2-hydroxy-1,4-dioxonaphthalen-3-yl)-4-methylpentanoate (10e): yellow oil, 54 mg, 90% yield, $[\alpha]^{20}_D$ −1.2 (*c* 1.0, $CHCl_3$); ^{1}H NMR ($CDCl_3$, 400 MHz) δ 0.84 (d, *J* = 6.8 Hz, 3 H), 1.03 (d, *J* = 6.8 Hz, 3 H), 2.13−2.22 (m, 1 H), 2.79 (dd, *J* = 4.8 and 16.0 Hz, 1 H), 3.01 (dd, *J* = 10.8 and 16.0 Hz, 1 H), 3.30−3.36 (m, 1 H), 3.55 (s, 3 H), 7.51 (br s, 1 H), 7.67 (t, *J* = 7.6 Hz, 1 H), 7.75 (t, *J* = 7.6 Hz, 1 H), 8.06 (d, *J* = 7.6 Hz, 1 H), 8.12 (d, *J* = 7.6 Hz, 1 H); ^{13}C NMR ($CDCl_3$, 100.6 MHz) 21.1, 21.3, 30.3, 35.2, 39.3, 51.5, 125.2, 126.0, 127.1, 129.3, 132.8, 132.9, 135.0, 153.2, 181.3, 184.4; HRMS (ESI) *m*/*z* calcd for $C_{17}H_{18}O_5$ $[M - H]^-$ 301.1081, found 301.1082; HPLC analysis (Chiralpak OJ-H column, hexane:2-propanol = 75:25, flow rate = 1.0 mL/min, wavelength = 220 nm) R_t = 8.45 (major) and 13.89 min (minor).

(*R*)-Methyl 3-(1,4-dihydro-2-hydroxy-1,4-dioxonaphthalen-3-yl)heptanoate (10f): yellow solid, 32 mg, 50% yield, mp 60−61 °C, $[\alpha]^{20}_D$ −0.6 (*c* 1.0, $CHCl_3$), 94% ee; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 0.84 (t, *J* = 6.0 Hz, 3 H), 1.18−1.29 (m, 4 H), 1.64 (br s, 1 H), 1.84 (br s, 1 H), 2.73 (dd, *J* = 5.6 and 15.6 Hz, 1 H), 2.96 (dd, *J* = 10.0 and 15.6 Hz, 1 H), 3.59 (s, 3 H), 3.63−3.64 (m, 1 H), 7.50 (br s, 1 H), 7.67 (t, *J* = 7.2 Hz, 1 H), 7.76 (t, *J* = 7.2 Hz, 1 H), 8.07 (d, *J* = 7.6 Hz, 1 H), 8.12 (d, *J* = 7.6 Hz, 1 H); ^{13}C NMR ($CDCl_3$, 100.6 MHz) δ 13.9, 22.6, 29.9, 32.1, 32.4, 37.2, 51.5, 125.1, 126.0, 127.1, 129.3, 132.8, 132.9, 133.0, 135.0, 153.2, 173.1, 181.4, 184.3; HRMS (ESI) *m*/*z* calcd for $C_{18}H_{20}O_5$ $[M + Na]^+$ 339.1203, found 339.1199; HPLC analysis (Chiralpak OJ-H column, hexane:2-propanol = 85:15, flow rate = 1.0 mL/min, wavelength = 220 nm) R_t = 9.77 (major) and 13.77 min (minor).

(*R*)-Methyl 3-(1,4-dihydro-2-hydroxy-1,4-dioxonaphthalen-3-yl)-5-methylhexanoate (10g): yellow oil, 56 mg, 88% yield, $[\alpha]^{20}_D$ −5.0 (*c* 1.0, $CHCl_3$), 97% ee; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 0.80 (br s, 3 H), 0.85 (br s, 3 H), 1.35 (br s, 2 H), 1.79−1.83 (m, 1 H), 2.62 (d, *J* = 15.6 Hz, 1 H), 2.88 (dd, *J* = 10.0 and 15.2 Hz, 1 H), 3.52 (s, 3 H), 3.67−3.69 (m, 1 H), 7.46 (br s, 1 H), 7.61 (t, *J* = 6.8 Hz, 1 H), 7.69 (t, *J* = 6.4 Hz, 1 H), 7.99 (d, *J* = 6.8 Hz, 1 H), 8.05 (d, *J* = 7.2 Hz, 1 H); ^{13}C NMR ($CDCl_3$, 100.6 MHz) δ 22.1, 23.3, 26.3, 30.2, 37.5, 41.8, 51.5, 125.1, 126.0, 127.0, 129.2, 132.8, 133.0, 135.0, 153.3, 173.0, 181.4, 184.2; HRMS (ESI) *m*/*z* calcd for $C_{18}H_{20}O_5$ $[M - H]^-$ 315.1238, found 315.1236; HPLC analysis (Chiralpak OJ-H column, hexane:2-propanol = 85:15, flow rate = 1.0 mL/min, wavelength = 220 nm) R_t = 8.57 (major) and 11.12 min (minor).

(3*S*)-Methyl 3-(1,4-dihydro-2-hydroxy-1,4-dioxonaphthalen-3-yl)-4-methylhexanoate (10h): yellow oil, 37 mg, 58% yield, $[\alpha]^{20}_D$ −10.4 (*c* 1.0, $CHCl_3$), 72/28 dr, 99% ee for major diastereomer and 96% ee for minor diastereomer; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 0.83 (t, *J* = 8.1 Hz, 3 H), 0.99 (d, *J* = 6.6 Hz, 3 H), 1.05−1.20 (m, 1 H), 1.32−1.38 (m, 1 H), 1.95−2.03 (m, 1 H), 2.77 (dd, *J* = 6.4 and 15.6 Hz, 1 H), 3.03 (dd, *J* = 10.8 and 15.6 Hz, 1 H), 3.39−3.48 (m, 1 H), 3.55 (s, 3 H), 7.51 (br s, 1 H), 7.67 (t, *J* = 7.2 Hz, 1 H), 7.75 (t, *J* = 7.2 Hz, 1 H), 8.06 (d, *J* = 7.5 Hz, 1 H), 8.12 (d, *J* = 7.5 Hz, 1 H); ^{13}C NMR ($CDCl_3$, 75.0 MHz) δ 10.9 (minor isomer), 11.2 (major isomer), 16.8 (major isomer), 17.1 (minor isomer), 26.9 (minor isomer), 27.5 (major isomer), 34.8 (major isomer), 35.0 (minor isomer), 36.6, 37.4 (minor isomer), 37.9 (major isomer), 51.4, 125.3, 126.0, 127.1, 129.3, 132.8, 133.0, 134.9, 153.2, 173.5, 181.3, 184.3; HRMS (ESI) *m*/*z* calcd for $C_{18}H_{20}O_5$ $[M - H]^-$ 315.1238, found 315.1236; HPLC analysis (Chiralpak AD-H column, hexane:2-propanol = 85:15, flow rate = 1.0 mL/min, wavelength = 220 nm) R_t = 9.40 (minor, major isomer), 10.15 (major, major isomer), 11.20 (major, minor isomer), and 12.34 min (minor, minor isomer).

(*S*)-Methyl 3-(1,4-dihydro-2-hydroxy-1,4-dioxonaphthalen-3-yl)-3-phenylpropanoate (10i): yellow oil, 67 mg, 99% yield, $[\alpha]^{20}_D$ −15 (*c* 1.0, $CHCl_3$), >99% ee; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 3.21 (dd, *J* = 6.4 and 16.4 Hz, 1 H), 3.55 (dd, *J* = 9.6 and 16.8 Hz, 1 H), 3.62 (s, 3 H), 5.00 (dd, *J* = 6.4 and 9.6 Hz, 1 H), 7.19 (t, *J* = 7.2 Hz, 1 H), 7.28 (t, *J* = 7.6 Hz, 2 H), 7.47 (d, *J* = 7.6 Hz, 1 H), 7.63 (s, 1 H), 7.73 (t, *J* = 7.2 Hz, 1 H), 8.03 (d, *J* = 7.2 Hz, 1 H), 8.11 (d, *J* = 7.6 Hz, 1 H); ^{13}C NMR ($CDCl_3$, 100.6 MHz) δ 36.3, 36.9, 51.7, 124.3, 126.0, 127.1, 128.1, 128.5, 129.1, 132.8, 132.9, 135.1, 141.2, 152.7, 172.7, 181.6, 184.0; HRMS (ESI) *m*/*z* calcd for $C_{20}H_{16}O_5$ $[M - H]^-$ 335.0925, found 335.0929; HPLC analysis (Chiralpak OJ-H column, hexane:2-propanol = 75:25, flow rate = 1.0 mL/min, wavelength = 220 nm) R_t = 42.17 min (major).

(*R*)-Methyl 3-(1,4-dihydro-2-hydroxy-6-methoxy-1,4-dioxonaphthalen-3-yl)butanoate (10j): yellow oil, 58 mg, 95% yield, $[\alpha]^{20}_D$ −8.0 (*c* 1.0, $CHCl_3$), 99% ee; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.31 (d, *J* = 7.2 Hz, 3 H), 2.72 (dd, *J* = 6.9 and 15.9 Hz, 1 H), 2.95 (dd, *J* = 8.4 and 16.0 Hz, 1 H), 3.61 (s, 3 H), 3.67−3.77 (m, 1 H), 3.95 (s, 3 H), 7.11 (dd, *J* = 2.4 and 8.4 Hz, 1 H), 7.58 (d, *J* = 2.7 Hz, 1 H), 7.60 (br s, 1 H), 8.00 (d, *J* = 8.4 Hz, 1 H); ^{13}C NMR ($CDCl_3$, 75.0 MHz) 18.2, 26.7, 38.3, 51.5, 56.0, 111.0, 119.2, 122.4, 125.3, 128.7, 135.6, 153.1, 165.4, 180.2, 184.0; HRMS (ESI) *m*/*z* calcd for $C_{16}H_{16}O_6$ $[M - H]^+$ 303.0874, found 303.0873; HPLC analysis (Chiralpak AD-H column, hexane:2-propanol = 90:10, flow rate = 1.0 mL/min, wavelength = 220 nm) R_t = 38.29 (minor) and 50.42 min (major), 99% ee.

(*R*)-Methyl 3-(1,4-dihydro-2-hydroxy-6-methoxy-1,4-dioxonaphthalen-3-yl)hexanoate (10k): yellow oil, 41 mg, 62% yield, $[\alpha]^{20}_D$ −3.8 (*c* 1.0, $CHCl_3$), 96% ee; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 0.88 (t, *J* = 7.2 Hz, 3 H), 1.25−1.32 (m, 2 H), 1.59−1.63 (m, 1 H), 1.79−1.88 (m, 1 H), 2.71 (dd, *J* = 6.0 and 15.6 Hz, 1 H), 2.95 (dd, *J* = 9.2 and 15.6 Hz, 1 H), 3.59 (s, 3 H), 3.62−3.68 (m, 1 H), 3.95 (s, 3 H), 7.11 (dd, *J* = 2.4 and 8.4 Hz, 1 H), 7.58 (d, *J* = 2.8 Hz, 1 H), 7.60 (br s, 1 H), 8.00 (d, *J* = 8.4 Hz, 1 H); ^{13}C NMR ($CDCl_3$, 100.6 MHz) δ 14.0, 20.9, 31.9, 34.8, 37.2, 51.5, 56.0, 110.9, 119.2, 122.5, 124.1, 128.7, 135.5, 153.5, 165.3, 173.2, 180.0, 184.2; HRMS (ESI) *m*/*z* calcd for $C_{18}H_{20}O_6$ $[M + Na]^+$ 355.1152, found 355.1155; HPLC analysis (Chiralpak AD-H column, hexane:2-propanol = 85:15, flow rate = 1.0 mL/min, wavelength = 220 nm) R_t = 33.40 (minor) and 45.05 min (major).

(*S*)-Methyl 3-(3-hydroxy-7-methoxy-1,4-dioxo-1,4-dihydronaphthalen-2-yl)-4-methylpentanoate (10*l*): yellow solid, 39 mg, 59% yield, mp 63−64 °C, $[\alpha]^{20}_D$ −1.8 (*c* 1.0, $CHCl_3$), 99% ee; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 0.84 (d, *J* = 6.8 Hz, 3 H), 1.03 (d, *J* = 6.8 Hz, 3 H), 2.12−2.21 (m, 1 H), 2.78 (dd, *J* = 4.0 and 16.0 Hz, 1 H), 3.01 (dd, *J* = 10.8 and 16.0 Hz, 1 H), 3.28−3.34 (m, 1 H), 3.55 (s, 3 H), 3.95 (s, 3 H), 7.12 (dd, *J* = 2.4 and 8.4 Hz, 1 H), 7.59 (br s, 2 H), 8.01 (d, *J* = 8.8 Hz, 1 H); ^{13}C NMR ($CDCl_3$, 100.6 MHz) 21.1, 21.3, 30.3, 35.2, 39.3, 51.5, 56.0, 111.0, 119.3, 122.5, 124.3, 128.7, 135.5, 153.5, 165.3, 173.5, 180.0, 184.3; HRMS (ESI) *m*/*z* calcd for $C_{18}H_{20}O_6$ $[M + Na]^+$ 355.1152, found 355.1152; HPLC analysis (Chiralpak AD-H column, hexane:2-propanol = 75:25, flow rate = 1.0 mL/min, wavelength = 220 nm) R_t = 32.38 (major) and 37.18 min (minor).

(*R*)-Methyl 3-(1,4-dihydro-2-hydroxy-6-methoxy-1,4-dioxonaphthalen-3-yl)heptanoate (10m): yellow oil, 45 mg, 65% yield, $[\alpha]^{20}_D$ −2.2 (*c* 1.0, $CHCl_3$), 94% ee; ^{1}H NMR ($CDCl_3$, 400 MHz) δ

dx.doi.org/10.1021/jo2002825 |*J. Org. Chem.* 2011, 76, 4119–4124

0.84 (d, J = 6.8 Hz, 3 H), 1.25−1.33 (m, 4 H), 1.60−1.66 (m, 1 H), 1.80−1.86 (m, 1 H), 2.71 (dd, J = 6.0 and 15.6 Hz, 1 H), 2.95 (dd, J = 9.6 and 15.6 Hz, 1 H), 3.61 (s, 3 H), 3.62−3.65 (m, 1 H), 3.95 (s, 3 H), 7.12 (dd, J = 2.4 and 8.4 Hz, 1 H), 7.58 (s, 1 H), 7.59 (br s, 1 H), 8.01 (d, J = 8.4 Hz, 1 H); ^{13}C NMR ($CDCl_3$, 100.6 MHz) δ 14.0, 22.6, 29.9, 32.1, 32.4, 37.2, 51.5, 56.0, 110.9, 119.3, 122.4, 124.1, 128.7, 135.5, 153.5, 165.3, 173.2, 180.0, 184.2; HRMS (ESI) m/z calcd for $C_{19}H_{22}O_6$ $[M + Na]^+$ 369.1309, found 369.1304; HPLC analysis (Chiralpak AD-H column, hexane:2-propanol = 75:25, flow rate = 1.0 mL/min, wavelength = 220 nm) R_t = 32.38 (major) and 37.18 min (minor).

(*R*)-Methyl 3-(3-hydroxy-7-methoxy-1,4-dioxo-1,4-dihydronaphthalen-2-yl)-5-methylhexanoate (10n): yellow oil, 64 mg, 92% yield, $[\alpha]^{20}_D$ −4.0 (c 1.0, $CHCl_3$), 99% ee; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 0.87 (d, J = 6.3 Hz, 3 H), 0.91 (d, J = 6.0 Hz, 3 H), 1.35−1.46 (m, 2 H), 1.80−1.92 (m, 1 H), 2.67 (dd, J = 6.3 and 15.9 Hz, 1 H), 2.92 (dd, J = 9.3 and 15.9 Hz, 1 H), 3.59 (s, 3 H), 3.67−3.77 (m, 1 H), 3.94 (s, 3 H), 7.11(dd, J = 2.7 and 8.7 Hz, 1 H), 7.58 (d, J = 2.4 Hz, 1 H), 7.63 (br s, 1 H), 7.99 (d, J = 8.4 Hz, 1 H); ^{13}C NMR ($CDCl_3$, 100.6 MHz) δ 22.1, 23.3, 26.3, 30.2, 37.5, 41.8, 51.5, 56.0, 110.9, 119.2, 122.5, 124.2, 128.7, 135.6, 153.6, 165.3, 173.1, 180.0, 184.2; HRMS (ESI) m/z calcd for $C_{19}H_{22}O_6$ $[M + Na]^+$ 369.1309, found 369.1307; HPLC analysis (Chiralpak AD-H column, hexane:2-propanol = 75:25, flow rate = 1.0 mL/min, wavelength = 220 nm) R_t = 18.4 (minor) and 26.54 min (major), 99% ee.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information. Copies of NMR spectra, HPLC analysis, as well as complete data for the reported crystal structure. This material is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: z.h.zhou@nankai.edu.cn and youmingwang@eyou.com.

■ ACKNOWLEDGMENT

We are grateful to the National Natural Science Foundation of China (Nos. 20772058 and 20972070), the National Basic research Program of China (973 program 2010CB833300), and the Key laboratory of Elemento-Organic Chemistry for generous financial support for our programs.

■ REFERENCES

(1) For review, see: Perlmutter, P. *Conjugate addition reactions in organic synthesis*; Pergamon: Oxford, UK, 1992.

(2) For selected reviews on organocatalytic asymmetric conjugate additions, see: (a) Vicario, J. L.; Badia, D.; Carrillo, L. *Synthesis* **2007**, 2065. (b) Tsogoeva, S. B. *Eur. J. Org. Chem.* **2007**, 1701. (c) Almasi, D.; Alonso, D. A.; Najera, C. *Tetrahedron: Asymmetry* **2007**, *18*, 299. (d) Sulzer-Mossé, S.; Alexakis, A. *Chem. Commun.* **2007**, 3123. (e) Enders, D.; Wang, C.; Liebich, J. X. *Chem.—Eur. J.* **2009**, *15*, 11058 and references cited therein.

(3) Sibi, M. P.; Itoh, K. *J. Am. Chem. Soc.* **2007**, *129*, 8064.

(4) Vakulya, B.; Varga, S.; Soós, T. *J. Org. Chem.* **2008**, *73*, 3475.

(5) Baschieri, A.; Bernardi, L.; Ricci, A.; Suresh, S.; Adamo, M. A. *Angew. Chem., Int. Ed.* **2009**, *48*, 9342.

(6) (a) Hoashi, Y.; Okino, T.; Takemoto, Y. *Angew. Chem., Int. Ed.* **2005**, *44*, 4032. (b) Inokuma, T.; Hoashi, Y.; Takemoto, Y. *J. Am. Chem. Soc.* **2006**, *128*, 9413. (c) Elsner, P.; Jiang, H.; Nielsen, J. B.; Pasi, F.; Jøgensen, K. A. *Chem. Commun.* **2008**, 5827.

(7) (a) For pioneering work on the use of these Michael acceptors in asymmetric catalysis, see: (a) Telan, L. A.; Poon, C.-D.; Evans, S. A. *J. Org. Chem.* **1996**, *61*, 7455. (b) Evans, D. A.; Johnson, J. S. *J. Am. Chem. Soc.* **1998**, *120*, 4895. (c) Evans, D. A.; Johnson, J. S.; Burgey, C. S.; Campos, K. R. *Tetrahedron Lett.* **1999**, *40*, 2879. (d) Evans, D. A.; Johnson, J. S.; Olhava, E. J. *J. Am. Chem. Soc.* **2000**, *122*, 1635. (e) Evans, D. A.; Scheidt, K. A.; Fandrick, K. R.; Lam, H. W.; Wu, J. *J. Am. Chem. Soc.* **2003**, *125*, 10780. (f) Samanta, S.; Zhao, C.-G. *J. Am. Chem. Soc.* **2006**, *128*, 7442. (g) Takenaka, N.; Abell, J. P.; Yamamoto, H. *J. Am. Chem. Soc.* **2007**, *129*, 742. (h) Samanta, S.; Krause, J.; Mandai, T.; Zhao, C.-G. *Org. Lett.* **2007**, *9*, 2745.

(8) (a) Jiang, H.; Paixão, M. W.; Monge, D.; Jørgensen, K. A. *J. Am. Chem. Soc.* **2010**, *132*, 2775. (b) Bachu, P.; Akiyama, T. *Chem. Commun.* **2010**, 4112.

(9) For works on the use of 2-hydroxy-1,4-naphthoquinones as Michael donors, see: (a) Rueping, M.; Sugiono, E.; Merino, E. *Angew. Chem., Int. Ed.* **2008**, *47*, 3046. (b) Zhou, W.-M.; Liu, H.; Du, D.-M. *Org. Lett.* **2008**, *10*, 2817. (c) Wang, Y.-F.; Zhang, W.; Luo, S.-P.; Zhang, G.-C.; Xia, A.-B.; Xu, X.-S.; Xu, D.-Q. *Eur. J. Org. Chem.* **2010**, 4981.

(10) Ravelo, A.; Estévez-Braun, A.; Chávez-Orellana, H.; Pérez-Sacau, E.; Mesa-Silverio, D. *Curr. Top. Med. Chem.* **2004**, *4*, 241.

(11) Sekine, M.; Kume, A.; Hata, T. *Tetrahedron Lett.* **1981**, *37*, 3617.

(12) Okino, T.; Nakamura, A.; Furukawa, T.; Takemoto, Y. *Org. Lett.* **2004**, *6*, 625.

(13) Vakulya, B.; Varga, S.; Csampai, A.; Soós, T. *Org. Lett.* **2005**, *7*, 1967.

(14) (a) Wang, C. G.; Zhou, Z. H.; Tang, C. C. *Org. Lett.* **2008**, *10*, 1707. (b) Gao, P.; Wang, C. G.; Wu, Y.; Zhou, Z. H.; Tang, C. C. *Eur. J. Org. Chem.* **2008**, 4563.