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Copper-Catalyzed Enantioselective Hetero-Diels–Alder Reaction of Danishefsky's Diene with Glyoxals

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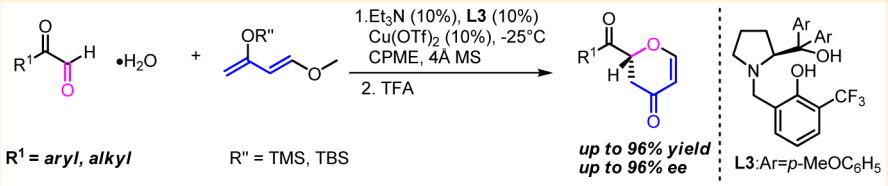
Supporting Information



ABSTRACT: The highly enantioselective hetero-Diels–Alder reaction of Danishefsky's diene with glyoxals was developed by virtue of a readily accessible chiral copper catalyst. This efficient transformation provided a facile and scalable access to a wide range of biologically active dihydropyrones with a high level of enantioselectivities. Moreover, the substrate scope of this reaction could be extended to isatins with this catalytic system. More importantly, the mechanism involved in this reaction was proposed on the basis of the unambiguous structures of intermediates.

The asymmetric hetero-Diels–Alder (HDA) reaction of Danishefsky's diene with aldehydes or α-ketoesters is a very important method to synthesize optically active dihydropyrones,[1] which are one of the most privileged substructures in natural products and medicinal compounds.[2] In this area, various catalytic systems, including Lewis acid catalysts[3] and Brønsted acid catalysts,[4] have been extensively exploited to obtain a diversity of chiral dihydropyrones. The Jørgensen group reported the first highly enantioselective HDA reaction of Danishefsky's diene with ketones catalyzed by a chiral copper(II) complex.[5] After that, the HDA reaction of α-carbonyl esters was further developed by Loh.[6] Recently, a chiral 3,3-dibromo-BINOL-Zn complex was found to be an efficient catalyst in various HDA reactions by Ding et al.[7] Moreover, impressive work on the HDA reaction of substituted Danishefsky's diene with aldehydes had been achieved by Feng's group by using a chiral *N*,*N*-dioxide/In(OTf)$_3$ catalyst.[8] However, to the best of our knowledge, the HDA reaction of Danishefsky's diene with glyoxals has received far less attention. In the previous work of Mikami, a chiral bis-trifluoromethanesulfonylamide was first employed to catalyze this HDA reaction of glyoxals (Scheme 1a).[9] Nevertheless, developing a general method with broader substrate scope remains a great challenge. In this context, we envisioned that our previously used catalyst, which showed high performance in the HDA reaction of β,γ-unsaturated α-ketoesters,[3h] might be applied in this reaction. Indeed, various dihydropyrones were provided with excellent enantioselectivities (up to 96% ee) and high yields (up to 96%) in the presence of this efficient catalyst.

We chose the 2-oxo-2-phenylacetaldehyde hydrate **1a** and Danishefsky's diene **2a** as the model substrates. Inspired by the previous work in our laboratory,[3h,10] we utilized the chiral **L1**–Cu complex to optimize this reaction (Table 1). First, different solvents were screened for this reaction. The results showed that ethers favored this reaction (entries 1–5). Then, different ethers were further optimized, and CPME proved to be the optimal solvent in terms of yield and enantioselectivity (entry 8). Afterward, different reaction temperatures were examined (entries 8–12). When the reaction was performed at −25 °C, a moderate yield and excellent enantioselectivity were obtained. Lowering the temperature to −35 °C resulted in a significant decrease in the reaction yield, although a slightly improved enantiomeric excess was observed (entries 11 and 12). The substitutions of the aromatic ring in the chiral ligand were next explored. It was found that the ligand bearing an electron-enriched aryl ring could give a better performance than the electron-deficient one (entries 13–15). However, a satisfactory result still could not be obtained. Considering the detrimental effect of the crystal water on the stereoselectivity of this reaction, different water scavengers were screened (entries 16–18). To our delight, the enantioselectivity was significantly improved to 95% ee and the yield was remarkably increased to 86% when 4 Å molecular sieves were added to the reaction system (entry 16). As a result, the optimal reaction condition was determined as follows: CPME as the reaction solvent, 4 Å molecular sieves as the additive, and HDA reaction carried out under catalysis with a facile copper complex at −25 °C.

With the optimal conditions in hand, the substrate scope of 2-oxo-2-phenylacetaldehyde hydrate was examined, as shown in Table 2. First, the electronic effect of the substrates was

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Scheme 1. Previous Study and This Work on the Hetero-Diels–Alder Reaction of Danishefsky's Diene with Glyoxals

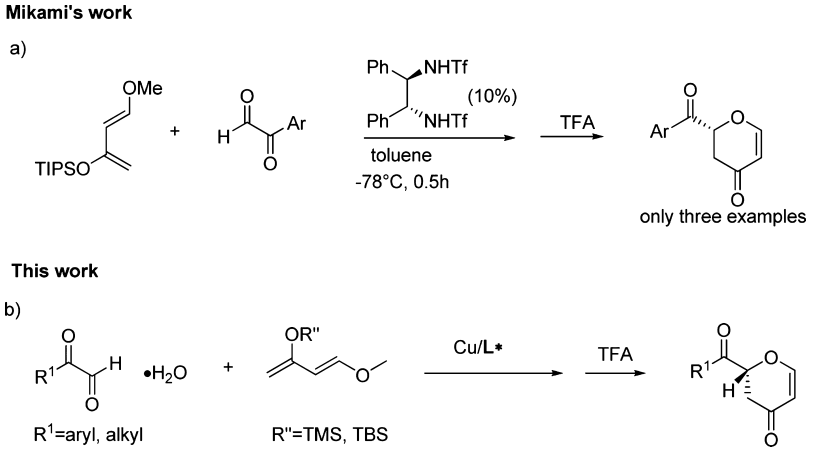
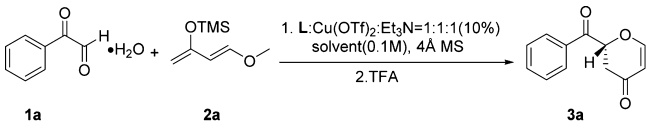
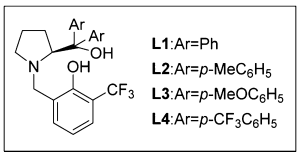


Table 1. Optimization of the Reaction Conditions[a]





entry	ligand	solvent	T (°C)	yield[b] (%)	ee[c] (%)
1	**L1**	EtOAc	−15	79	73
2	**L1**	toluene	−15	64	77
3	**L1**	CH_2Cl_2	−15	89	69
4	**L1**	$CHCl_3$	−15	74	73
5	**L1**	MTBE	−15	69	77
6	**L1**	THF	−15	59	65
7	**L1**	Et_2O	−15	50	75
8	**L1**	CPME	−15	89	78
9	**L1**	CPME	−20	80	78
10	**L1**	CPME	−25	75	79
11	**L1**	CPME	−30	63	80
12	**L1**	CPME	−35	60	81
13	**L2**	CPME	−25	75	80
14	**L4**	CPME	−25	74	75
15	**L3**	CPME	−25	78	81
16[d]	**L3**	CPME	−25	86	95
17[e]	**L3**	CPME	−25	81	91
18[f]	**L3**	CPME	−25	83	91

[a]Unless otherwise noted, all reactions were performed with **1a** (0.1 mmol), **2a** (0.2 mmol), **L** (10 mol %), Et_3N (10 mol %), and $Cu(OTf)_2$ (10 mol %). [b]Isolated yield. [c]Determined by chiral HPLC analysis. [d]Addition of 50 mg of powdered 4 Å molecular sieves. [e]Addition of 50 mg of Na_2SO_4. [f]Addition of 50 mg of $MgSO_4$. Tf = trifluoromethanesulfonyl; MTBE = methyl *tert*-butyl ether; CPME = cyclopentyl methyl ether.

investigated. When the substrates bearing the strong electron-donating groups on the *para*-position of the phenyl ring were employed, the HDA reactions could be carried out smoothly to give the desired products with high yields and excellent enantioselectivities (**3e**, **3g**). Similarly, the electron-withdrawing halogen groups were compatible with the reaction system (**3b**, **3c**, **3d**). The HDA adduct **3f** was obtained with good yield and excellent enantioselectivity when the strong electron-withdrawing trifluoromethyl group was on the *para*-position of the phenyl ring. It was obvious that the substrates with the electron-donating groups could give yields higher than those with the electron-withdrawing groups. Then, the steric effect of the reaction was examined. The results showed that substitutions at different positions on the phenyl group had little influence on the reaction yields and enantioselectivities (**3e**, **3j**, **3k**). In the case of heterocyclic product **3l** (2-thienyldihydropyrone), a satisfactory result could be obtained by simply lowering the reaction temperature to −35 °C. The substrates bearing a 2-naphthyl group and a multisubstituted group could also give the corresponding products with high yields and enantioselectivities (**3m**–**3o**). Notably, when the R^1 group was changed to the aliphatic group, the desired product **3p** was still obtained in moderate yield and excellent enantioselectivity. The absolute configuration of product **3d** was confirmed by X-ray crystal diffraction.[11]

A variety of dihydropyrones were obtained with good yields and enantioselectivities through the catalysis of the copper complex. Next, we wondered whether the catalytic system could promote the asymmetric HDA reaction of isatins. Pleasingly, when isatins were evaluated in this reaction, the desired products **5a** and **5b** could be obtained with high yields and excellent enantioselectivities under this catalytic system (Scheme 2). **5b** was a known compound, and the absolute configuration of **5b** was determined by comparison with corresponding specific rotation data reported in the literature.[8e]

To further demonstrate the robust nature and operational simplicity of this methodology, a gram scale experiment was carried out (Scheme 3). The copper complex of 5% catalytic loading could catalyze the HDA reaction of **1e** and Danishefsky's diene to generate the desired product **3e** with 1.69 g, 78% yield, and 90% ee.

Finally, the reaction mechanism was studied. Generally, two possible reaction pathways, Diels–Alder cycloaddition[12] and stepwise Mukaiyama–aldol condensation,[13] were involved in this transformation. As shown in Scheme 4, in this reaction, 2-oxo-2-phenylacetaldehyde hydrate gradually released the phenylglyoxal **7** when 4 Å molecular sieves was added in the reaction system.[14] With this strategy, the in situ generated phenylglyoxal immediately reacted with Danishefsky's diene in the presence of the chiral copper catalyst.

In order to obtain insight into the reaction mechanism, several control experiments were carried out (Scheme 4). For

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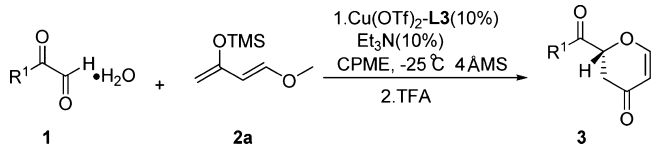
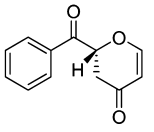
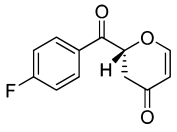
Table 2. Scope of Glyoxals[a–c]



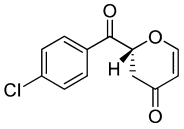
1 2a 3



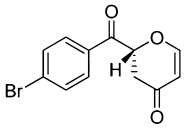
3a 16h, 86% yield, 95% *ee*



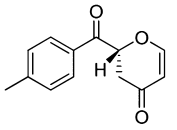
3b 20h, 77% yield, 91% *ee*



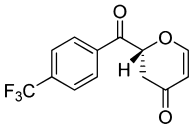
3c 20h, 84% yield, 94% *ee*



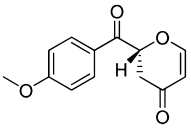
3d 20h, 85% yield, 94% *ee*



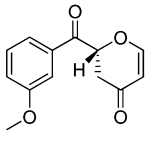
3e 16h, 84% yield, 96% *ee*



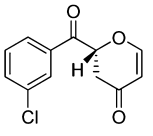
3f 21h, 71% yield, 90% *ee*



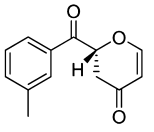
3g 16h, 96% yield, 94% *ee*



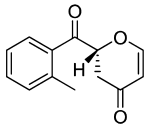
3h 16h, 90% yield, 92% *ee*



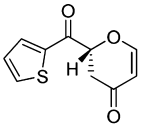
3i 19h, 87% yield, 91% *ee*



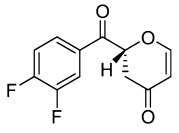
3j 17h, 92% yield, 94% *ee*



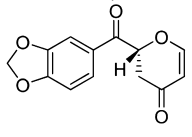
3k 24h , 85% yield, 90% *ee*[d]



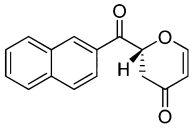
3l 19h, 80% yield, 90% *ee*



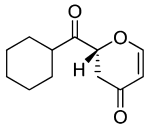
3m 20h, 85% yield, 92% *ee*



3n 19h, 65% yield, 93% *ee*



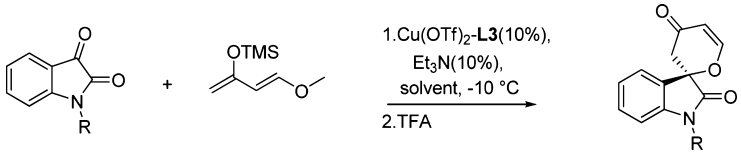
3o 19h, 92% yield, 93% *ee*



3p 24h, 61% yield, 90% *ee*[d]

[a]Unless otherwise noted, the reaction of **1** (0.3 mmol) and **2a** (0.6 mmol) was performed in the presence of **L3** (10 mol %), Et_3N (10 mol %), and $Cu(OTf)_2$ (10 mol %) in CPME (3.0 mL) with 150 mg of powdered 4 Å molecular sieves as additive at −25 °C. [b]Isolated yield. [c]Determined by chiral HPLC analysis. [d]In MTBE (3.0 mL) at −35 °C.

Scheme 2. Scope of Isatins[a–c]



4 2a 5

4a R=CH_3
4b R=Bn

5a 16h, 93% yield, 91% *ee*
5b 16h, 96% yield, 91% *ee*

[a]Unless otherwise noted, the reactions of **4** (0.3 mmol) and **2a** (0.6 mmol) were performed in the presence of **L3** (10 mol %), Et_3N (10 mol %), and $Cu(OTf)_2$ (10 mol %), R = CH_3 in MTBE (3.0 mL) and R = Bn in toluene (3.0 mL) at −10 °C. [b]Isolated yields. [c]Determined by chiral HPLC analysis.

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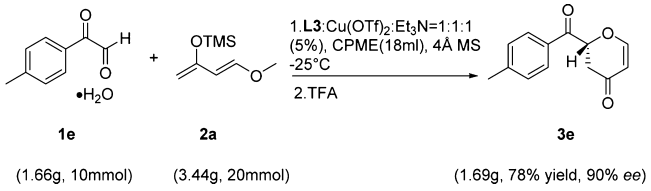
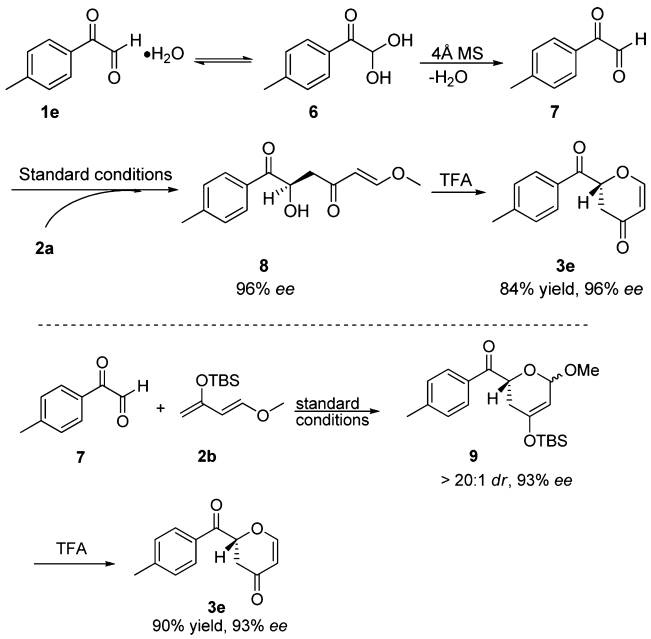
Scheme 3. Asymmetric Hetero-Diels–Alder Reaction on a Gram Scale[a–c]



[a]Reaction of **1e** (10 mmol) and **2a** (20 mmol) was performed in the presence of **L3** (5 mol %), Et_3N (5 mol %), and $Cu(OTf)_2$ (5 mol %) in CPME (18 mL) with 2.5 g of powdered 4 Å molecular sieves as additive at −25 °C. [b]Isolated yield. [c]Determined by chiral HPLC analysis.

Scheme 4. Mechanism Pathway of the Hetero-Diels–Alder Reaction



the HDA reaction of Danishefsky's diene **2a** with **1e**, the intermediate **8** was isolated before treatment with TFA. The NMR spectral experiment of intermediate **8** showed that the Mukaiyama–aldol adduct was produced under the reaction conditions, corresponding to the stepwise pathway. As expected, the ee value of the Mukaiyama–aldol adduct was consistent with that of the final product, which indicated that TFA acidification had no influence on the stereocontrol. However, when the TMS group of Danishefsky's diene was changed to a TBS group, only the cycloaddition adduct **9**, which was confirmed by NMR, was isolated by silica gel chromatography. This cycloaddition intermediate could be easily transferred into the final product by the treatment with TFA. Similarly, the ee value was maintained after TFA acidification. In view of the experimental results above, the different reaction pathways involved in this reaction were greatly dependent on the substrate dienes.

In summary, a copper-catalyzed asymmetric hetero-Diels–Alder reaction of Danishefsky's diene with glyoxals was developed under mild reaction conditions. With this efficient methodology, an unprecedented substrate scope was achieved and a variety of dihydropyranones were provided with excellent enantioselectivities and high yields. Moreover, a detailed reaction mechanism study showed that a substrate-dependent pathway, stepwise Mukaiyama–aldol condensation and concerted cycloaddition, was involved in this reaction.

EXPERIMENTAL SECTION

General Information. ^1H NMR and ^{13}C NMR were recorded on a 400 MHz nuclear magnetic resonance spectrometer (400 MHz for ^1H NMR and 100 MHz for ^{13}C NMR) using TMS as an internal reference. The chemical shifts (δ) and coupling constants (J) were expressed in parts per million and hertz, respectively. UV–vis spectrophotometry was carried out on an infrared spectrometer. HPLC analysis was carried out on a chromatograph with a multiple wavelength detector with commercial chiral columns. Optical rotations were measured on a polarimeter. HRMS (ESI) data were recorded on a Q-TOF Premier. Commercially available compounds were used without further purification. Solvents were purified according to the standard procedures unless otherwise noted. Ligands,[10a,c] various glyoxals,[14a] *N*-methyl isatins,[10d] *N*-benzyl isatins,[15] and Danishefsky's diene[16] were prepared according to literature procedures.

General Procedures for the Hetero-Diels–Alder Reaction. A mixture of ligand (**L3**, 10 mol %), $Cu(OTf)_2$ (10%, 10.8 mg), and Et_3N (10%, 4.17 μL) in corresponding solvent (3.0 mL) was stirred for 1 h in an ambient atmosphere, and corresponding glyoxals (0.3 mmol) and 150 mg of powdered 4 Å molecular sieves as additive were then added. The resulting mixture was cooled to −25 °C. After 30 min, the corresponding diene was added slowly by syringe. After the reactions were finished (monitored by TLC), 5.0 equiv of TFA was added to quench the reaction. The system was quenched by saturated sodium bicarbonate after 2 h and then extracted by ethyl acetate. The organic phase was dried with sodium sulfate and evaporated in vacuo. Purification by column chromatography afforded HDA adducts.

Experimental Data of HDA Adducts. *(R)-2-Benzoyl-2H-pyran-4(3H)-one (**3a**).* The title compound was prepared according to the general working procedure (16 h) and purified by column chromatography (petroleum ether/ethyl acetate = 3:1) to give the product as a light yellow solid: 86% yield; mp = 127–129 °C; $[\alpha]_D^{20}$ −156.7 (c = 0.84, $CHCl_3$, 95% ee); HPLC (Daicel Chiralpak AD-H) hexane/2-propanol = 70:30, flow rate = 0.8 mL/min, T = 23 °C, UV = 254 nm, t_R = 10.56 min (major), t_R = 29.09 min (minor); ^1H NMR (400 MHz, $CDCl_3$) δ 7.96 (d, J = 7.3 Hz, 2H), 7.63 (t, J = 7.4 Hz, 1H), 7.50 (t, J = 7.8 Hz, 2H), 7.40 (d, J = 6.1 Hz, 1H), 5.81 (dd, J = 11.4 Hz, 4.6 Hz, 1H), 5.49 (d, J = 6.04 Hz, 1H), 2.96 (dd, J = 17.1 Hz, 11.5 Hz, 1H), 2.80 (dd, J = 17.0 Hz, 4.5 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 193.1, 190.0, 161.7, 134.3, 133.7, 129.00, 128.99, 107.9, 78.9, 38.0; IR (film, ν/cm^{-1}) 3687, 2923, 2856, 2364, 1959, 1751, 1461, 1263, 1068, 802, 682; HRMS (ESI) m/z calcd for $C_{12}H_{10}O_3$ $[M + Na]^+$ 225.0528, found 225.0523.

*(R)-2-(4-Fluorobenzoyl)-2H-pyran-4(3H)-one (**3b**).* The title compound was prepared according to the general working procedure (20 h) and purified by column chromatography (petroleum ether/ethyl acetate = 3:1) to give the product as a light yellow solid: 77% yield; mp = 146–148 °C; $[\alpha]_D^{20}$ −172.9 (c = 0.84, $CHCl_3$, 91% ee); HPLC (Daicel Chiralpak OD-H) hexane/2-propanol = 70:30, flow rate = 1.0 mL/min, T = 23 °C, UV = 254 nm, t_R = 10.12 min (minor), t_R = 11.75 min (major); ^1H NMR (400 MHz, $CDCl_3$) δ 8.02 (dd, J = 8.6 Hz, 5.4 Hz, 2H), 7.38 (d, J = 6.0 Hz, 1H), 7.18 (t, J = 8.5 Hz, 2H), 5.75 (dd, J = 11.2 Hz, 4.4 Hz, 1H), 5.50 (d, J = 6.0 Hz, 1H), 2.98 (dd, J = 17.0 Hz, 11.3 Hz, 1H), 2.79 (dd, J = 17.0 Hz, 4.4 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 191.6, 190.0, 166.3 ($^1J_{CF}$ = 255.9 Hz, 1C), 161.4, 131.9 ($^3J_{CF}$ = 9.5 Hz, 2C), 130.2 ($^4J_{CF}$ = 2.9 Hz, 1C), 116.2 ($^2J_{CF}$ = 21.9 Hz, 2C), 108.0, 78.8, 37.8; IR (film, ν/cm^{-1}) 3781, 3706, 3461, 2923, 2856, 1689, 1514, 1461, 1375, 1270, 1222, 1031, 859, 743, 601; HRMS (ESI) m/z calcd for $C_{12}H_9FO_3$ $[M + Na]^+$ 243.0433, found 243.0432.

*(R)-2-(4-Chlorobenzoyl)-2H-pyran-4(3H)-one (**3c**).* The title compound was prepared according to the general working procedure (20 h) and purified by column chromatography (petroleum ether/ethyl acetate = 3:1) to give the product as a light yellow solid: 84% yield; mp = 96–98 °C; $[\alpha]_D^{20}$ −149.9 (c = 1.02, $CHCl_3$, 94% ee); HPLC (Daicel

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Chiralpak OD-H) hexane/2-propanol = 70:30, flow rate = 1.0 mL/min, T = 23 °C, UV = 230 nm, t_R = 10.59 min (minor), t_R = 12.28 min (major); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.91 (d, J = 8.5 Hz, 2H), 7.47 (d, J = 8.5 Hz, 2H), 7.37 (d, J = 6.0 Hz, 1H), 5.73 (dd, J = 11.1 Hz, 4.6 Hz, 1H), 5.49 (d, J = 6.0 Hz, 1H), 2.96 (dd, J = 17.0 Hz, 11.2 Hz, 1H), 2.79 (dd, J = 17.0 Hz, 4.5 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 191.0, 188.8, 160.3, 139.8, 131.0, 129.5, 128.3, 107.0, 77.8, 36.7; IR (film, ν/cm^{-1}) 3766, 3704, 3459, 2923, 2856, 2370, 1679, 1592, 1452, 1398, 1085, 802, 609; HRMS (ESI) m/z calcd for $C_{12}H_9ClO_3$ [M + Na]$^+$ 259.0138, found 259.0132.

*(R)-2-(4-Bromobenzoyl)-2H-pyran-4(3H)-one (**3d**).* The title compound was prepared according to the general working procedure (20 h) and purified by column chromatography (petroleum ether/ethyl acetate = 3:1) to give the product as a light yellow solid: 85% yield; mp = 107−109 °C; $[\alpha]_D^{20}$ −129.2 (c = 0.52, $CHCl_3$, 94% ee); HPLC (Daicel Chiralpak AD-H) hexane/2-propanol = 70:30, flow rate = 0.8 mL/min, T = 23 °C, UV = 254 nm, t_R = 11.71 min (major), t_R = 24.21 min (minor); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.84 (d, J = 8.6 Hz, 2H), 7.65 (d, J = 8.5 Hz, 2H), 7.38 (d, J = 6.0 Hz, 1H), 5.73 (dd, J = 11.1 Hz, 4.6 Hz, 1H), 5.50 (d, J = 6.0 Hz, 1H), 2.97 (dd, J = 17.0 Hz, 11.1 Hz, 1H), 2.80 (dd, J = 17.0 Hz, 4.5 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 192.3, 189.9, 161.4, 132.4, 132.3, 130.5, 129.7, 108.1, 78.8, 37.7; IR (film, ν/cm^{-1}) 3714, 2921, 2856, 1677, 1591, 1459, 1398, 1068, 935, 802, 732, 615; HRMS (ESI) m/z calcd for $C_{12}H_{19}BrO_3$ [M + Na]$^+$ 302.9633, found 302.9629.

*(R)-2-(4-Methylbenzoyl)-2H-pyran-4(3H)-one (**3e**).* The title compound was prepared according to the general working procedure (16 h) and purified by column chromatography (petroleum ether/ethyl acetate = 3:1) to give the product as a light yellow solid: 84% yield; mp = 89−91 °C; $[\alpha]_D^{20}$ −123.3 (c = 0.94, $CHCl_3$, 96% ee); HPLC (Daicel Chiralpak AD-H) hexane/2-propanol = 70:30, flow rate = 0.8 mL/min, T = 23 °C, UV = 254 nm, t_R = 11.05 min (major), t_R = 19.61 min (minor); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.85 (d, J = 8.3 Hz, 2H), 7.39 (d, J = 6.0 Hz, 1H), 7.29 (d, J = 8.0 Hz, 2H), 5.78 (dd, J = 11.6 Hz, 4.6 Hz, 1H), 5.48 (dd, J = 6.0 Hz, 0.8 Hz, 1H), 2.95 (dd, J = 17.1 Hz, 11.7 Hz, 1H), 2.78 (ddd, J = 17.0 Hz, 4.5 Hz, 0.9 Hz, 1H), 2.42 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 192.6, 190.2, 161.7, 145.5, 131.2, 129.7, 129.1, 107.8, 78.9, 38.1, 21.8; IR (film, ν/cm^{-1}) 3781, 2923, 2856, 1679, 1596, 1452, 1403, 1277, 1037, 935, 798, 599; HRMS (ESI) m/z calcd for $C_{13}H_{12}O_3$ [M + Na]$^+$ 239.0684, found 239.0684.

*(R)-2-(4-(Trifluoromethyl)benzoyl)-2H-pyran-4(3H)-one (**3f**).* The title compound was prepared according to the general working procedure (21 h) and purified by column chromatography (petroleum ether/ethyl acetate = 3:1) to give the product as a light yellow oil: 71% yield; $[\alpha]_D^{20}$ −109.3 (c = 0.68, $CHCl_3$, 90% ee); HPLC (Daicel Chiralpak OD-H) hexane/2-propanol = 70:30, flow rate = 1.0 mL/min, T = 23 °C, UV = 230 nm, t_R = 9.24 min (minor), t_R = 10.40 min (major); ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.10 (d, J = 8.2 Hz, 2H), 7.79 (d, J = 8.2 Hz, 2H), 7.38 (d, J = 6.1 Hz, 1H), 5.77 (dd, J = 10.8 Hz, 4.6 Hz, 1H), 5.53 (d, J = 6.0 Hz, 1H), 3.01 (dd, J = 17.0 Hz, 10.8 Hz, 1H), 2.85 (dd, J = 17.1 Hz, 4.5 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 191.6, 188.7, 160.2, 135.5, 134.3 (q, $^2J_{CF}$ = 32.8 Hz, 1C), 128.5, 125.0 (q, $^4J_{CF}$ = 3.6 Hz, 2C), 122.3 (q, $^1J_{CF}$ = 271.2 Hz, 1C), 107.2, 77.9, 36.5; IR (film, ν/cm^{-1}) 3704, 3363, 2923, 2856, 2724, 2279, 1936, 1697, 1598, 1457, 1332, 1267, 1135, 1068, 1025, 966, 856, 804, 727, 597; HRMS (ESI) m/z calcd for $C_{13}H_9F_3O_3$ [M + Na]$^+$ 293.0401, found 293.0401.

*(R)-2-(4-Methoxybenzoyl)-2H-pyran-4(3H)-one (**3g**).* The title compound was prepared according to the general working procedure (16 h) and purified by column chromatography (petroleum ether/ethyl acetate = 3:1) to give the product as a light yellow solid: 96% yield; mp = 122−124 °C; $[\alpha]_D^{20}$ −116.9 (c = 1.10, $CHCl_3$, 94% ee); HPLC (Daicel Chiralpak OD-H) hexane/2-propanol = 70:30, flow rate = 1.0 mL/min, T = 23 °C, UV = 254 nm, t_R = 12.99 min (minor), t_R = 14.51 min (major); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.95 (d, J = 9.2 Hz, 2H), 7.39 (d, J = 6.0 Hz, 1H), 6.96 (d, J = 8.8 Hz, 2H), 5.76 (dd, J = 11.8 Hz, 4.4 Hz, 1H), 5.48 (d, J = 6.0 Hz, 1H), 3.88 (s, 3H), 2.96 (dd, J = 17.0 Hz, 11.8 Hz, 1H), 2.76 (dd, J = 17.0 Hz, 4.3 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 191.3, 190.3, 164.4, 161.7, 131.4, 126.6, 114.2, 107.8, 78.8, 55.6, 38.2; IR (film, ν/cm^{-1}) 3781, 2923, 2856, 2724, 1747, 1681, 1598, 1457, 1375, 1261, 1168, 1091, 1027, 804, 599; HRMS (ESI) m/z calcd for $C_{13}H_{12}O_4$ [M + Na]$^+$ 255.0633, found 255.0639.

*(R)-2-(3-Methoxybenzoyl)-2H-pyran-4(3H)-one (**3h**).* The title compound was prepared according to the general working procedure (16 h) and purified by column chromatography (petroleum ether/ethyl acetate = 3:1) to give the product as a light yellow oil: 90% yield; mp = 71−73 °C; $[\alpha]_D^{20}$ −115.3 (c = 0.86, $CHCl_3$, 92% ee); HPLC (Daicel Chiralpak OD-H) hexane/2-propanol = 70:30, flow rate = 1.0 mL/min, T = 23 °C, UV = 240 nm, t_R = 12.03 min (major), t_R = 13.77 min (minor); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.51−7.38 (m, 4H), 7.17−7.15 (m, 1H), 5.79 (dd, J = 11.4 Hz, 4.6 Hz, 1H), 5.48 (d, J = 6.0 Hz, 1H), 3.84 (s, 3H), 2.94 (dd, J = 17.0 Hz, 11.4 Hz, 1H), 2.79 (dd, J = 17.0 Hz, 4.6 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 191.9, 189.0, 160.7, 159.0, 133.9, 128.9, 120.4, 119.7, 112.3, 106.8, 77.9, 54.5, 37.0; IR (film, ν/cm^{-1}) 3704, 3363, 2923, 2856, 2726, 2364, 2067, 1936, 1687, 1594, 1457, 1375, 1265, 1203, 1033, 873, 798; HRMS (ESI) m/z calcd for $C_{13}H_{12}O_4$ [M + Na]$^+$ 255.0633, found 255.0634.

*(R)-2-(3-Chlorobenzoyl)-2H-pyran-4(3H)-one (**3i**).* The title compound was prepared according to the general working procedure (19 h) and purified by column chromatography (petroleum ether/ethyl acetate = 3:1) to give the product as a light yellow oil: 87% yield; mp = 115−117 °C; $[\alpha]_D^{20}$ −118.6 (c = 1.02, $CHCl_3$, 91% ee); HPLC (Daicel Chiralpak AD-H) hexane/2-propanol = 70:30, flow rate = 1.0 mL/min, T = 23 °C, UV = 230 nm, t_R = 8.28 min (major), t_R = 16.44 min (minor); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.93 (s, 1H), 7.84 (d, J = 7.8 Hz, 1H), 7.61−7.59 (m, 1H), 7.45 (t, J = 7.9 Hz, 1H), 7.39 (d, J = 6.0 Hz, 1H), 5.74 (dd, J = 11.0 Hz, 4.6 Hz, 1H), 5.50 (d, J = 6.0 Hz, 1H), 2.96 (dd, J = 17.0 Hz, 11.0 Hz, 1H), 2.81 (dd, J = 17.0 Hz, 4.5 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 192.1, 189.9, 161.5, 135.31, 135.25, 134.2, 130.3, 129.1, 127.2, 108.1, 78.8, 37.7; IR (film, ν/cm^{-1}) 3781, 3704, 2923, 2856, 2726, 1687, 1596, 1459, 1267, 1085, 946, 798, 728, 630; HRMS (ESI) m/z calcd for $C_{12}H_9ClO_3$ [M + Na]$^+$ 259.0138, found 259.0144.

*(R)-2-(3-Methylbenzoyl)-2H-pyran-4(3H)-one (**3j**).* The title compound was prepared according to the general working procedure (17 h) and purified by column chromatography (petroleum ether/ethyl acetate = 3:1) to give the product as a light yellow oil: 92% yield; $[\alpha]_D^{20}$ −124.4 (c = 0.98, $CHCl_3$, 94% ee); HPLC (Daicel Chiralpak AD-H) hexane/2-propanol = 70:30, flow rate = 1.0 mL/min, T = 23 °C, UV = 230 nm, t_R = 8.04 min (major), t_R = 17.75 min (minor); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.74 (d, J = 8.4 Hz, 2H), 7.45−7.37 (m, 3H), 5.81 (dd, J = 11.6 Hz, 4.6 Hz, 1H), 5.50 (d, J = 6.0 Hz, 1H), 2.95 (dd, J = 17.0 Hz, 11.6 Hz, 1H), 2.79 (dd, J = 17.0 Hz, 4.4 Hz, 1H), 2.42(s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 193.3, 190.0, 161.7, 138.9, 135.1, 133.8, 129.4, 128.8, 126.1, 107.8, 78.9, 38.1, 21.3; IR (film, ν/cm^{-1}) 3704, 3627, 3459, 3359, 3187, 2923, 2856, 2732, 2630, 2443, 2258, 2069, 1903, 1685, 1594, 1457, 1376, 1160, 1033, 952, 875, 796, 736; HRMS (ESI) m/z calcd for $C_{13}H_{12}O_3$ [M + Na]$^+$ 239.0684, found 239.0687.

*(R)-2-(2-Methylbenzoyl)-2H-pyran-4(3H)-one (**3k**).* The title compound was prepared according to the general working procedure (24 h) and purified by column chromatography (petroleum ether/ethyl acetate = 3:1) to give the product as a light yellow oil: 85% yield; mp = 95−97 °C; $[\alpha]_D^{20}$ −155.1 (c = 0.82, $CHCl_3$, 90% ee); HPLC (Daicel Chiralpak AD-H) hexane/2-propanol = 70:30, flow rate = 1.0 mL/min, T = 23 °C, UV = 230 nm, t_R = 8.65 min (major), t_R = 19.02 min (minor); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.56 (d, J = 7.9 Hz, 1H), 7.45−7.40 (m, 1H), 7.35 (d, J = 6.1 Hz, 1H), 7.30 (s, 1H), 7.28 (s, 1H), 5.67 (dd, J = 10.5 Hz, 5.0 Hz, 1H), 5.46 (dd, J = 6.1 Hz, 0.4 Hz, 1H), 2.89 (dd, J = 17.0 Hz, 10.4 Hz, 1H), 2.78 (ddd, J = 17.0 Hz, 5.0 Hz, 0.6 Hz, 1H), 2.45(s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 197.4, 189.9, 161.7, 139.3, 134.3, 132.3, 132.2, 128.5, 125.7, 108.0, 80.1, 37.7, 20.9; IR (film, ν/cm^{-1}) 3781, 3704, 3459, 2923, 2856, 1679, 1594, 1454, 1403, 1272, 1066, 804, 736, 607; HRMS (ESI) m/z calcd for $C_{13}H_{12}O_3$ [M + Na]$^+$ 239.0684, found 239.0682.

*(R)-2-(Thiophene-2-carbonyl)-2H-pyran-4(3H)-one (**3l**).* The title compound was prepared according to the general working procedure (19 h) and purified by column chromatography (petroleum ether/

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ethyl acetate = 3:1) to give the product as a light yellow solid: 80% yield; mp = 81−82 °C; $[\alpha]_D^{20}$ −136.4 (*c* = 0.74, $CHCl_3$, 90% ee); HPLC (Daicel Chiralpak AD-H) hexane/2-propanol = 70:30, flow rate = 1.0 mL/min, *T* = 23 °C, UV = 240 nm, t_R = 9.70 min (major), t_R = 22.76 min (minor); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.91 (d, *J* = 3.6 Hz, 1H), 7.76 (d, *J* = 4.8 Hz, 1H), 7.42 (d, *J* = 6.0 Hz, 1H), 7.18 (t, *J* = 4.4 Hz, 1H), 5.55 (dd, *J* = 11.8 Hz, 4.4 Hz, 1H), 5.50 (d, *J* = 6.0 Hz, 1H), 2.99 (dd, *J* = 17.0 Hz, 11.8 Hz, 1H), 2.80 (dd, *J* = 17.0 Hz, 4.4 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 189.9, 186.2, 161.4, 140.0, 135.8, 134.2, 128.6, 108.1, 80.1, 38.3; IR (film, ν/cm^{-1}) 2923, 2856, 2726, 2364, 1751, 1675, 1594, 1459, 1375, 1265, 1218, 908, 802, 727; HRMS (ESI) *m*/*z* calcd for $C_{10}H_8SO_3$ $[M + Na]^+$ 231.0092, found 231.0094.

(R)-2-(3,4-Difluorobenzoyl)-2H-pyran-4(3H)-one (**3m**). The title compound was prepared according to the general working procedure (20 h) and purified by column chromatography (petroleum ether/ethyl acetate = 2:1) to give the product as a light yellow oil: 85% yield; $[\alpha]_D^{20}$ −140.4 (*c* = 1.06, $CHCl_3$, 92% ee); HPLC (Daicel Chiralpak AD-H) hexane/2-propanol = 70:30, flow rate = 1.0 mL/min, *T* = 23 °C, UV = 230 nm, t_R = 7.77 min (major), t_R = 21.33 min (minor); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.87−7.77 (m, 2H), 7.37 (d, *J* = 6.0 Hz, 1H), 7.30 (dd, *J* = 17.1 Hz, 8.7 Hz, 1H), 5.70 (dd, *J* = 10.9 Hz, 4.6 Hz, 1H), 5.50 (d, *J* = 6.0 Hz, 1H), 2.98 (dd, *J* = 17.1 Hz, 11.0 Hz, 1H), 2.80 (dd, *J* = 17.0 Hz, 4.5 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 190.8, 189.8, 161.2, 154.3 (dd, $^1J_{CF}$ = 258.0 Hz, $^2J_{CF}$ = 13.2 Hz, 1C), 150.6 (dd, $^1J_{CF}$ = 250.5 Hz, $^2J_{CF}$ = 12.8 Hz, 1C), 130.8 (dd, $^3J_{CF}$ = 4.4 Hz, $^4J_{CF}$ = 3.7 Hz, 1C), 126.4 (dd, $^3J_{CF}$ = 8.0 Hz, $^4J_{CF}$ = 3.6 Hz, 1C), 118.7 (dd, $^3J_{CF}$ = 18.2 Hz, $^4J_{CF}$ = 2.1 Hz, 1C), 118.0 (d, *J* = 17.7 Hz, 1C), 108.2, 78.8, 37.6; IR (film, ν/cm^{-1}) 3781, 3706, 3461, 3072, 2923, 2856, 1683, 1598, 1513, 1459, 1270, 1033, 894, 802, 607; HRMS (ESI) *m*/*z* calcd for $C_{12}H_8F_2O_3$ $[M + Na]^+$ 261.0339, found 261.0346.

(R)-2-(Benzo[d][1,3]dioxole-5-carbonyl)-2H-pyran-4(3H)-one (**3n**). The title compound was prepared according to the general working procedure (19 h) and purified by column chromatography (petroleum ether/ethyl acetate = 2:1) to give the product as a light yellow solid: 65% yield; mp = 123−125 °C $[\alpha]_D^{20}$ −125.5 (*c* = 0.58, $CHCl_3$, 93% ee); HPLC (Daicel Chiralpak AD-H) hexane/2-propanol = 70:30, flow rate = 1.0 mL/min, *T* = 23 °C, UV = 254 nm, t_R = 13.26 min (major), t_R = 25.28 min (minor); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.59 (dd, *J* = 8.2 Hz, 1.6 Hz, 1H), 7.45 (d, *J* = 1.6 Hz, 1H), 7.41 (d, *J* = 6.0 Hz, 1H), 6.90 (d, *J* = 8.2 Hz, 1H), 6.09 (s, 2H), 5.72 (dd, *J* = 11.8 Hz, 4.4 Hz, 1H), 5.51 (d, *J* = 6.0 Hz, 1H), 2.98 (dd, *J* = 17.0 Hz, 11.8 Hz, 1H), 2.77 (dd, *J* = 17.1 Hz, 4.4 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 190.9, 190.2, 161.6, 152.8, 148.5, 128.4, 125.7, 108.6, 108.2, 107.9, 102.2, 78.7, 38.2; IR (film, ν/cm^{-1}) 3781, 3714, 3461, 2923, 2856, 1679, 1594, 1452, 1398, 1259, 1072, 802, 613; HRMS (ESI) *m*/*z* calcd for $C_{13}H_{10}O_5$ $[M + Na]^+$ 269.0426, found 269.0429.

(R)-2-(2-Naphthoyl)-2H-pyran-4(3H)-one (**3o**). The title compound was prepared according to the general working procedure (19 h) and purified by column chromatography (petroleum ether/ethyl acetate = 3:1) to give the product as a light yellow oil: 92% yield; $[\alpha]_D^{20}$ −69.3 (*c* = 1.00, $CHCl_3$, 93% ee); HPLC (Daicel Chiralpak OD-H) hexane/2-propanol = 70:30, flow rate = 1.0 mL/min, *T* = 23 °C, UV = 240 nm, t_R = 14.65 min (major), t_R = 24.44 min (minor); ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.50 (s, 1H), 8.02−7.89 (m, 4H), 7.67−7.57 (m, 2H), 7.44 (d, *J* = 6.0 Hz, 1H), 5.97 (dd, *J* = 11.6 Hz, 4.5 Hz, 1H), 5.54 (d, *J* = 6.0 Hz, 1H), 3.04 (dd, *J* = 17.0 Hz, 11.6 Hz, 1H), 2.87 (dd, *J* = 17.0 Hz, 4.3 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 193.0, 190.2, 161.7, 136.0, 132.4, 131.1, 131.0, 129.8, 129.3, 129.0, 127.9, 127.2, 124.1, 108.0, 79.0, 38.2; IR (film, ν/cm^{-1}) 3781, 3461, 3060, 2923, 2856, 2726, 2364, 1955, 1681, 1594, 1459, 1376, 1265, 1182, 1093, 1027, 809, 873, 584; HRMS (ESI) *m*/*z* calcd for $C_{16}H_{12}O_3$ $[M + Na]^+$ 275.0684, found 275.0685.

(R)-2-(Cyclohexanecarbonyl)-2H-pyran-4(3H)-one (**3p**). The title compound was prepared according to the general working procedure (24 h) and purified by column chromatography (petroleum ether/ethyl acetate = 3:1) to give the product as a light yellow oil: 61% yield; $[\alpha]_D^{20}$ −41.9 (*c* = 0.44, $CHCl_3$, 90% ee); HPLC (Daicel Chiralpak AD-H) hexane/2-propanol = 70:30, flow rate = 1.0 mL/min, *T* = 23 °C, UV = 254 nm, t_R = 5.75 min (major), t_R = 8.96 min (minor); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.40 (d, *J* = 6.0 Hz, 1H), 5.47 (d, *J* = 6.0 Hz, 1H), 4.95 (dd, *J* = 11.0 Hz, 5.9 Hz, 1H), 2.85−2.78 (m, 1H), 2.75−2.71 (m, 2H), 1.88−1.67 (m, 5H), 1.41−1.20 (m, 5H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 208.1, 190.2, 161.7, 108.1, 80.9, 46.3, 37.6, 28.4, 28.0, 25.6, 25.57, 25.4; IR (film, ν/cm^{-1}) 3781, 3714, 2923, 2856, 2387, 1452, 1375, 1068, 800, 721, 609; HRMS (ESI) *m*/*z* calcd for $C_{12}H_{16}O_3$ $[M + Na]^+$ 231.0997, found 231.1000.

(R)-1-Methylspiro[indoline-3,2′-pyran]-2,4′(3′H)-dione (**5a**). The title compound was prepared according to the general working procedure (16 h) and purified by column chromatography (petroleum ether/ethyl acetate = 3:1) to give the product as a white solid: 93% yield; mp = 106−108 °C; $[\alpha]_D^{20}$ +363.9 (*c* = 1.08, $CHCl_3$, 91% ee); HPLC (Daicel Chiralpak AD-H) hexane/2-propanol = 70:30, flow rate = 1.0 mL/min, *T* = 23 °C, UV = 240 nm, t_R = 9.09 min (major), t_R = 11.95 min (minor); ^{1}H NMR (400 MHz, $CDCl_3$) δ7.47 (ddd, *J* = 7.5 Hz, 1.2 Hz, 0.5 Hz, 1H), 7.41−7.37 (m, 2H), 7.07−7.03 (m, 1H), 6.87 (d, *J* = 7.9 Hz, 1H), 5.60 (dd, *J* = 6.2 Hz, 0.8 Hz, 1H), 3.21 (s, 3H), 3.18 (d, *J* = 16.6 Hz, 1H), 2.64 (dd, *J* = 16.6 Hz, 0.8 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 189.3, 171.9, 161.4, 143.0, 131.3, 127.5, 124.3, 123.6, 109.1, 107.0, 81.4, 41.3, 26.5; IR (film, ν/cm^{-1}) 3781, 2923, 2856, 1727, 1679, 1604, 1461, 1375, 1093, 1029, 904, 800, 607; HRMS (ESI) *m*/*z* calcd for $C_{13}H_{11}NO_3$ $[M + Na]^+$ 252.0637, found 252.0639.

(R)-1-Benzylspiro[indoline-3,2′-pyran]-2,4′(3′H)-dione (**5b**). The title compound was prepared according to the general working procedure (16 h) and purified by column chromatography (petroleum ether/ethyl acetate = 3:1) to give the product as a white solid: 96% yield; mp = 106−108 °C $[\alpha]_D^{20}$ +186.3 (−191.7, reported) (*c* = 0.30, CH_2Cl_2, 91% ee); HPLC (Daicel Chiralpak ID) hexane/2-propanol = 70:30, flow rate = 1.0 mL/min, *T* = 23 °C, UV = 254 nm, t_R = 24.36 min (minor), t_R = 34.95 min (major) [HPLC (Daicel Chiralpak ID) hexane/2-propanol = 70:30, flow rate = 1.0 mL/min, UV = 254 nm, t_{r1} = 21.15 min (major), t_{r2} = 29.10 min (minor), reported]; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.50−7.48 (m, 1H), 7.42 (d, *J* = 6.2 Hz, 1H), 7.35−7.31 (m, 2H), 7.29−7.24 (m, 4H), 7.04−7.00 (m, 1H), 6.76 (d, *J* = 7.9 Hz, 1H), 5.64 (dd, *J* = 6.2 Hz, 0.7 Hz, 1H), 4.93 (d, *J* = 15.6 Hz, 1H), 4.85(1H, *J* = 15.6 Hz, 1H), 3.25 (d, *J* = 16.6 Hz, 1H), 2.73 (dd, *J* = 16.6 Hz, 0.7 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 189.2, 172.2, 161.4, 142.1, 134.8, 131.2, 129.0, 128.0, 127.5, 127.2, 124.4, 123.6, 110.1, 107.0, 81.4, 44.0, 41.4; IR (film, ν/cm^{-1}) 3459, 2923, 2856, 2724, 1733, 1702, 1669, 1459, 1375, 1265, 1155, 802, 730, 613; HRMS (ESI) *m*/*z* calcd for $C_{19}H_{15}NO_3$ $[M + Na]^+$ 328.0950, found 328.0944.

(R)-2-Hydroxy-6-methoxy-1-p-tolylhex-5-ene-1,4-dione (**8**). The title compound was prepared according to the general working procedure and purified by column chromatography (dichloromethane/ethyl acetate = 8:1) to give the product as a colorless oil: $[\alpha]_D^{20}$ +5.7 (*c* = 0.33, $CHCl_3$, 96% ee); HPLC (Daicel Chiralpak AD-H) hexane/2-propanol = 70:30, flow rate = 1.0 mL/min, *T* = 23 °C, UV = 230 nm, t_R = 10.93 min (minor), t_R = 12.01 min (major); ^{1}H NMR (400 MHz, CD_3COCD_3) δ 7.92 (d, *J* = 8.2 Hz, 2H), 7.68 (d, *J* = 12.7 Hz, 1H), 7.35 (d, *J* = 8.0 Hz, 2H), 5.69 (d, *J* = 12.8 Hz, 1H), 5.45 (dd, *J* = 7.2 Hz, 4.4 Hz, 1H), 3.76 (s, 3H), 2.98 (dd, *J* = 16.4 Hz, 4.4 Hz, 1H), 2.87 (dd, *J* = 16.3 Hz, 7.2 Hz, 1H), 2.41 (s, 3H); [^{1}H NMR (400 MHz, $(CD_3)_2SO$) δ 7.87 (d, *J* = 8.2 Hz, 2H), 7.71 (d, *J* = 12.7 Hz, 1H), 7.33 (d, *J* = 8.0 Hz, 2H), 5.65 (d, *J* = 12.8 Hz, 1H), 5.52 (d, *J* = 7.2 Hz, 1H), 5.29 (dd, *J* = 12.8 Hz, 6.7 Hz, 1H), 3.70 (s, 3H), 2.93 (dd, *J* = 16.3 Hz, 5.7 Hz, 1H), 2.81 (dd, *J* = 16.3 Hz, 6.9 Hz, 1H), 2.38 (s, 3H)]; ^{13}C NMR (100 MHz, CD_3COCD_3) δ 200.4, 196.6, 164.3, 145.0, 133.2, 130.2, 129.7, 107.1, 70.7, 58.3, 45.8, 21.6; IR (film, ν/cm^{-1}) 3687, 3459, 2923, 2856, 2726, 2281, 1745, 1679, 1594, 1459, 1176, 1089, 808, 728, 599, 522; HRMS (ESI) *m*/*z* calcd for $C_{14}H_{16}O_4$ $[M + Na]^+$ 271.0946, found 271.0945.

(R)-4-(tert-Butyldimethylsilyloxy)-6-methoxy-3,6-dihydro-2H-pyran-2-yl)(p-tolyl)methanone (**9**). The title compound was prepared according to the general working procedure and purified by column chromatography (dichloromethane/ethyl acetate = 10:1) to give the product as a colorless oil: $[\alpha]_D^{20}$ −7.5 (*c* = 0.78, $CHCl_3$, 93% ee); HPLC (Daicel Chiralpak AD-H) hexane/2-propanol = 70:30, flow rate

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= 0.7 mL/min, T = 23 °C, UV = 230 nm, t_R = 5.61 min (major), t_R = 6.01 min (minor); ^{1}H NMR (400 MHz, CD_3COCD_3) δ 7.95 (d, J = 8.2 Hz, 2H), 7.38−7.36 (m, 2H), 5.30 (ddd, J = 11.2 Hz, 3.7 Hz, 0.6 Hz, 1H), 5.07−5.06 (m, 1H), 4.95 (dd, J = 3.2 Hz, 2.0 Hz, 1H), 3.45 (s, 3H), 2.63−2.55 (m, 1H), 2.42 (s, 3H), 2.10−2.04 (m, 1H), 0.95 (s, 9H), 0.23 (s, 3H), 0.22 (s, 3H); ^{13}C NMR (100 MHz, CD_3COCD_3) δ 195.3, 152.2, 144.0, 133.1, 129.1, 102.5, 98.2, 68.1, 55.3, 30.7, 25.1, 20.8, 17.7, −5.1, −5.4; IR (film, ν/cm^{-1}) 3775, 3704, 3459, 3189, 2925, 2856, 2726, 1743, 1672, 1606, 1459, 1373, 1263, 1211, 1126, 1056, 950, 898, 829; HRMS (ESI) m/z calcd for $C_{20}H_{30}O_4Si$ [M + Na]$^+$ 385.1811, found 385.1814.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.joc.5b02780.

^{1}H and ^{13}C NMR spectra for all products and HPLC profiles (PDF)

Crystallographic data for compound **3d** (CIF)

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Notes

The authors declare no competing financial interest.

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