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N-Heterocyclic Carbene-Catalyzed Diastereoselective Vinylogous Michael Addition Reaction of γ-Substituted Deconjugated Butenolides

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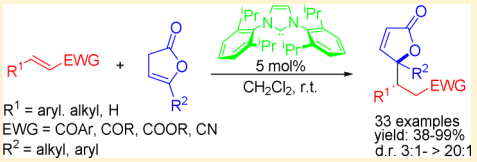
Supporting Information

ABSTRACT: An efficient *N*-heterocyclic carbene (NHC)-catalyzed vinylogous Michael addition of deconjugated butenolides was developed. In the presence of 5 mol % of the NHC catalyst, both γ-alkyl- and aryl-substituted deconjugated butenolides undergo vinylogous Michael addition with various α, β-unsaturated ketones, esters, or nitriles to afford γ,γ-disubstituted butenolides containing adjacent quaternary and tertiary carbon centers in good to excellent yields with excellent diastereoselectivities. In this process, the free carbene is assumed to act as a strong Brønsted base to promote the conjugate addition.



The γ,γ-disubstituted butenolide unit is one of the most ubiquitous structural motifs in a myriad of natural products and pharmaceutically active compounds.[1] In the past decade, continuous efforts have been exerted to develop highly efficient methods for the synthesis of these significant building blocks.[2] On the basis of the transformation of preformed silyloxyfurans, vinylogous Mukaiyama aldol, Mannich, and Michael reactions have been extensively studied, which provide facile access to γ,γ-disubstituted butenolide derivatives.[3] However, with respect to economy and efficiency, the direct stereoselective γ-functionalization of deconjugated butenolide itself is more attractive.[4] Particularly, the application of γ-monosubstituted deconjugated butenolides (e.g., α-angelica lactone) is more interesting, which can lead to γ,γ-disubstituted butenolide with adjacent quaternary and tertiary stereocenters. The first breakthrough was documented by Chen and co-workers.[5] The functionalized γ,γ-disubstituted butenolides were constructed stereoselectively via direct allylic alkylation of deconjugated butenolides with Morita−Baylis−Hillman carbonates. Following this excellent work, several groups developed the direct vinylogous Michael-type addition of γ-substituted deconjugated butenolides with different Michael acceptors.[6] Using a similar strategy, the vinylogous Mannich-type reaction of α-angelica lactone was also reported by Feng and co-workers.[7] Recently, using L-*tert*-leucine-derived amine-thiourea as catalyst, we[8] developed a vinylogous conjugate addition of γ-substituted deconjugated butenolides, which provides optically active γ,γ-butenolide-substituted amides efficiently. Despite remarkable progress made in this research field, the direct functionalization of γ-substituted deconjugated butenolides remains far less examined and some challenges are still unresolved, such as the usage of transition metals, as γ-alkyl- and aryl-substituted butenolides cannot be well-tolerated. Therefore, the development of a more general and efficient protocol for this transformation is still highly desirable.

The past decade has witnessed explosive growth in the field of *N*-heterocyclic carbene (NHC) catalysis.[9] As powerful Lewis base catalysts, NHCs have been utilized broadly in various transformations. Except for the benzoin[10] and Stetter[11] reac-reactions, the NHC-catalyzed homoenolate reaction of enals,[12] redox reaction of functional aldehydes,[13] cycloaddition of ketenes,[14] and other reactions[15] based on the strong nucleophilicity of this organocatalyst have been developed. However, compared to the intensive studies on Lewis basic properties of NHCs, the exploration of Brønsted basic properties of NHCs is still in its infancy. On the basis of this important Brønsted base characteristic, NHC-catalyzed transesterification was independently developed by Nolan and Hedrick,[16] and NHC-mediated amidation of esters was also documented by Movassaghi and our group.[17] Recently, Coquerel and co-workers reported an interesting NHC-promoted carba-Michael addition.[18] Subsequently, NHC-catalyzed oxo-, aza-, and sulpha-Michael additions were also developed by Scheidt, Zhang, Huang, and our group.[19] These works further prompt us to explore the more interesting vinylogous Michael addition. Herein, we report an efficient NHC-catalyzed diastereoselective vinylogous Michael addition of γ-substituted deconjugated butenolides to different Michael acceptors.

We began our study with the commercially available chalcone **1a** and α-angelica lactone **2a**. To our delight, under the catalysis

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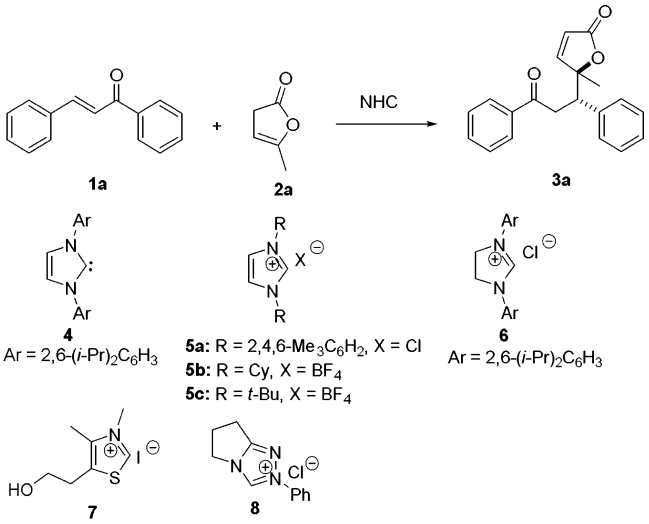
of 10 mol % stable NHC (1,3-bis(2,6-dissopropylphenyl)-imidazole-2-ylidene, IPr),[20] the vinylogous Michael addition smoothly proceeded in THF at room temperature to furnish desired γ,γ-disubstituted butenolide **3a** in 92% yield with good diastereoselectivity (Table 1, entry 1). Encouraged by this result, several other NHCs were subsequently investigated for the addition. NHCs generated in situ from imidazolium and imidazolinium can efficiently promote the reaction with different diastereoselectivities (Table 1, entries 2−5), whereas NHCs derived from triazolium or thiazolium did not catalyze the reaction (Table 1, entries 6 and 7). A brief screening of the reaction media indicated that solvents have an obvious effect on the reaction, and dichloromethane proved to be the best choice with respect to both yields and selectivities (Table 1, entries 8−12). Reduction of catalyst loading to 5 mol % led to improved diastereoselectivities without sacrificing reaction yield (Table 1, entry 13). However, further reduction of the catalyst loading to 1 mol % led to a dramatic decrease of catalytic efficiency (Table 1, entry 14). Other Brønsted bases were also tested for the reaction. As shown in Table 1, only a trace of product **3a** was generated under the catalysis of 5 mol % DBU or Et_3N (Table 1, entries 15 and 16). Further increasing DBU loading to 10 mol % led to the desired product in good yield but only with low diastereoselectivities (Table 1, entry 17).

Table 1. Screening of the Reaction Conditions[a]



entry	NHC	solvent	T (h)	yield (%)[b]	dr[c]
1	**4** (10 mol %)	THF	3 h	92	6:1
2	**5a**, DBU (10 mol %)	THF	3 h	94	4:1
3	**5b**, DBU (10 mol %)	THF	3 h	80	1:1
4	**5c**, DBU (10 mol %)	THF	3 h	95	3:1
5	**6**, DBU (10 mol %)	THF	13 h	90	5:1
6	**7**, DBU (10 mol %)	THF	12 h	trace	
7	**8**, DBU (10 mol %)	THF	12 h	trace	
8	**4** (10 mol %)	toluene	3 h	93	<2:1
9	**4** (10 mol %)	DCM	3 h	93	>20:1
10	**4** (10 mol %)	CH_3CN	3 h	42	5:1
11	**4** (10 mol %)	DMF	3 h	59	12:1
12	**4** (10 mol %)	DMSO	3 h	64	>20:1
13	**4** (5 mol %)	DCM	2 h	92	>20:1
14	**4** (1 mol %)	DCM	7 h	6	
15	DBU (5 mol %)	DCM	24 h	trace	
16	Et_3N (5 mol %)	DCM	24 h	trace	
17	DBU (10 mol %)	DCM	12 h	72	3.7:1

[a]**1a** (1 equiv, 0.5 mmol), **2a** (1.5 equiv, 0.75 mmol), NHC (10 mol %), solvent (2 mL). [b]Isolated total yield of two diastereomers. [c]Determined by ^1H NMR analysis of the crude products.

With the optimal reaction conditions in hand (Table 1, entry 13), the scope of the Michael acceptors was investigated next. A great variety of differently substituted chalcones underwent the vinylogous Michael addition with α-angelica lactone smoothly to produce the corresponding products in high yields with excellent diastereoseletivities (Scheme 1). Meanwhile, the electronic properties and different positions of the substituents have no obvious effect on the reaction yields or selectivities (Scheme 1, **3a−3o**). Both naphthyl enones and heteroaryl anologues performed the direct vinylogous reaction smoothly, producing the corresponding products efficiently with excellent diastereoselectivities (Scheme 1, **3p−3s**). Gratifyingly, alkyl-substituted enones also proved to be suitable reactants for the reaction. In the presence of 20 mol % NHC, alkyl-derived enone **1t** coupled with α-angelica lactone efficiently to produce **3t** in 77% yield, albeit with low diastereoselectivities (Scheme 1, **3t**). Intriguingly, cyclic enone furnished the desired product with excellent *anti/syn*-selectivities (Scheme 1, **3u**). Vinyl ethyl ketone **1v** could also participate in the addition but with low yield owing to the oligomerization of the active terminal enone (Scheme 1, **3v**). Notably, the relatively unreactive acrylates and acrylonitrile performed very well, affording the corresponding disubstituted butenolides in moderate to good yields (Scheme 1, **3w−3y**). To the best of our knowledge, this is the first example of direct vinylogous Michael reaction of deconjugated butenolide with α,β-unsaturated esters and nitrile.

Subsequently, different γ-substituted deconjugated butenolides were explored for the reaction. As shown in Scheme 2, both γ-alkyl- and γ-aryl-substituted deconjugated butenolides underwent the reaction smoothly, producing the desired adducts in excellent diastereoselectivities with moderate to high yields (Scheme 2, **3z−3ag**).

On the basis of the experimental results and pioneering studies,[18,19] a plausible mechanism was proposed as depicted in Scheme 3. The NHC performed as a Brønsted base to attack the α-H of deconjugated butenolide to form complex **I** and, after enolization, to form dienolate intermediate **II**, which might trigger the following conjugate addition to chalcone and lead to the formation of the final product.

A proposed transition state model that accounts for the diastereoselectivity is demonstrated in Figure 1.[21] To minimize the van der Waals repulsion between the phenyl group and the bulky NHC, the nucleophilic addition proceeds via **TS1** preferentially to afford the *anti*-product.

Conversely, NHC might act as a Lewis base to attack chalcone in a 1,4-fashion and initiate the addition. However, the results of a control experiment indicate that in situ generated dienolate **9** cannot react with 1,4-adduct **10** to produce the desired product. Therefore, this possible mechanism can be ruled out (Scheme 4).

In summary, we have developed a novel diastereoselective vinylogous Michael-type addition of deconjugated butenolide that capitalizes on the Brønsted basicities of NHCs; both γ-alkyl- and γ-aryl-substituted deconjugated butenolides are well-tolerated for the reaction. The extremely mild conditions, simple procedure, and broad substrate scope provide an efficient protocol for the synthesis of γ,γ-disubstituted butenolides.

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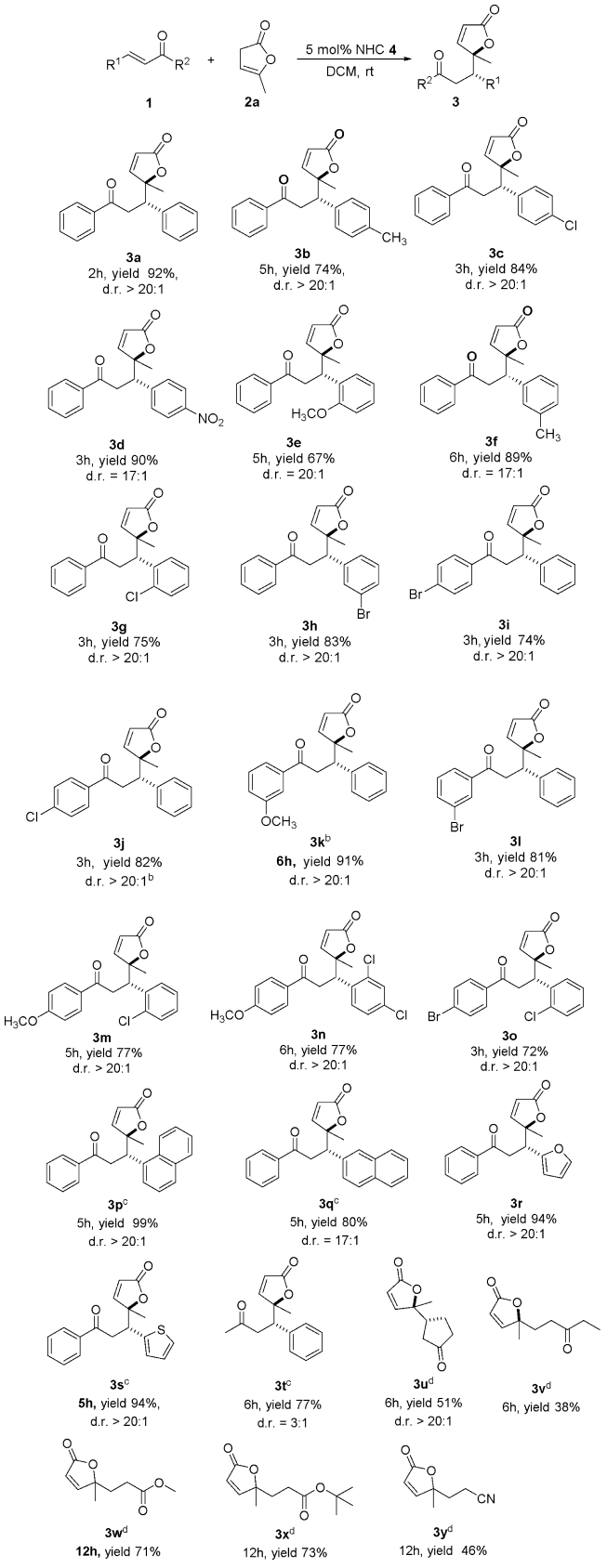
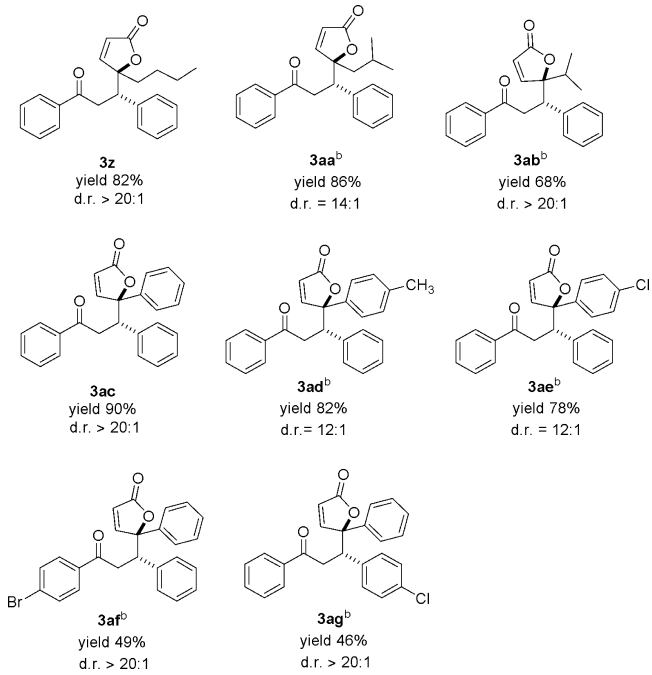
Scheme 1. Evaluation of Michael Acceptors[a]



[a]Reaction conditions: same as in Table 1, entry 13; dr was determined by ^{1}H NMR analysis of the crude reaction mixture; isolated total yield of two diastereomers [b]The relative configuration of the major diastereomer of **3j** was determined by X-ray diffraction analysis. [c]Using 10 mol % NHC **4**. [d]Using 20 mol % NHC **4**.

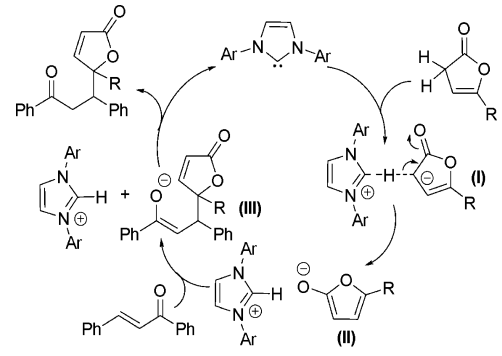
Scheme 1. continued

Scheme 2. Vinylogous Michael Addition of γ-Substituted Deconjugated Butenolides[a]



[a]Reaction conditions: same as in Table 1, entry 13; dr was determined by ^{1}H NMR analysis of the crude reaction mixture; isolated total yield of two diastereomers [b]Using 10 mol % NHC **4**.

Scheme 3. Proposed Mechanism



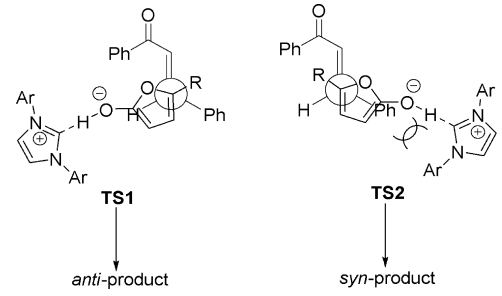


Figure 1. Proposed transition state models.

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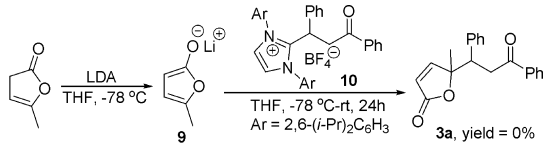
Scheme 4. Control Experiment



EXPERIMENTAL SECTION

All reactions were conducted under a nitrogen atmosphere in oven-dried glassware with a magnetic stirring bar. ^{1}H NMR (400 MHz) and ^{13}C NMR (100 MHz) spectra were recorded using deuterated chloroform as solvent with tetramethylsilane as an internal standard and reported in ppm (δ). α-Angelica lactone and chalcones were obtained from Adamas-beta and used without purification. γ-Substituted deconjugated butenolides[22−24] and compound **10**[25] were synthesized according to literature procedures. Anhydrous THF and toluene were distilled from sodium and benzophenone. CH_2Cl_2 and CH_3CN were distilled from calcium hydride.

General Procedure for NHC-Catalyzed Vinylogous Mukaiyama−Michael Reaction of γ-Substituted Deconjugated Butenolides. IPr **4** (0.015 mmol, 6 mg) was dissolved in anhydrous dichloromethane (1.0 mL); then, chalcone **1a** (0.3 mmol, 62.4 mg) and α-angelica lactone **2a** (0.45 mmol, 41 uL) were added under N_2. Subsequently, the reaction solution was stirred at ambient temperature until full consumption of the starting chalcone as indicated by TLC. The crude mixture was concentrated under vacuum. The crude product was purified by flash silica gel column chromatography to give desired product **3a**.

5-Methyl-5-(3-oxo-1,3-diphenylpropyl)furan-2(5*H*)-one (3a).[6d] Purified with ethyl acetate/petroleum ether (1:3) to give **3a** as a white solid (84.5 mg, 92% yield); mp 93.8−95.4 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.84 (dd, J = 8.2, 1.0 Hz, 2H), 7.55−7.51 (m, 1H), 7.46−7.38 (m, 5H), 7.35−7.25 (m, 3H), 5.98 (d, J = 5.6 Hz, 1H), 3.82 (t, J = 6.3 Hz, 1H), 3.31 (qd, J = 18.0, 6.6 Hz, 2H), 1.32 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 197.7, 172.6, 163.4, 139.4, 136.6, 133.4, 129.4, 128.6, 127.5, 120.4, 90.4, 46.7, 39.4, 22.9; FTIR (film) 3059, 3029, 2904, 1746, 1685, 1595, 1449, 1237, 1105, 956, 816, 748, 702, 685, 535 cm^{-1}; HRMS (MALDI-TOF) m/z calcd for $C_{20}H_{18}O_3$ [M + Na]$^+$ 329.1148, found 329.1153.

***anti*-5-Methyl-5-(3-oxo-3-phenyl-1-(*p*-tolyl)propyl)furan-2(5*H*)-one (3b).** Purified with ethyl acetate/petroleum ether (1:5) to give **3b** as a white solid (71.1 mg, 74% yield); mp 110.2−112.7 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.84 (dd, J = 8.3, 1.2 Hz, 2H), 7.52 (t, J = 6.8 Hz, 1H), 7.43−7.38 (m, 3H), 7.27 (d, J = 8.0 Hz, 2H), 7.12 (d, J = 7.9 Hz, 2H), 5.97 (d, J = 5.6 Hz, 1H), 3.76 (d, J = 6.6 Hz, 1H), 3.31 (qd, J = 17.9, 6.4 Hz, 2H), 2.31 (s, 3H), 1.32 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 197.7, 172.6, 161.5, 137.0, 136.6, 136.3, 133.3, 129.3, 129.2, 128.6, 128.0, 120.3, 90.5, 46.4, 39.4, 22.7, 21.1; FTIR (film) 3074, 2979, 2920, 2360, 2343, 1737, 1694, 1450, 1369, 1231, 1113, 955, 814, 763, 691, 578 cm^{-1}; HRMS (MALDI-TOF) m/z calcd for $C_{21}H_{20}O_3$ [M + Na]$^+$ 343.1305, found 343.1310.

***anti*-5-(1-(4-Chlorophenyl)-3-oxo-3-phenylpropyl)-5-methylfuran-2(5*H*)-one (3c).** Purified with ethyl acetate/petroleum ether (1:3) to give **3c** as a white solid (85.7 mg, 84% yield); mp 153.2−155.5 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.83 (dd, J = 8.3, 1.1 Hz, 2H), 7.54 (d, J = 17.3 Hz, 1H), 7.42 (t, J = 6.7 Hz, 3H), 7.36 (d, J = 8.5 Hz, 2H), 7.29 (d, J = 8.6 Hz, 2H), 6.00 (d, J = 5.6 Hz, 1H), 3.83−3.77 (m, 1H), 3.26 (qd, J = 18.0, 6.3 Hz, 2H), 1.31 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 197.4, 172.4, 170.0, 137.9, 136.4, 133.5, 133.4, 130.8, 128.8, 128.7, 127.9, 120.6, 90.1, 46.1, 39.3, 23.0; FTIR (film) 3422, 3075, 2930, 1741, 1686, 1491, 1459, 1420, 1365, 1232, 1112, 989, 902, 829, 754, 693, 670, 578 cm^{-1}; HRMS (MALDI-TOF) m/z calcd for $C_{20}H_{17}ClO_3$ [M + Na]$^+$ 363.0758, found 363.0762.

***anti*-5-Methyl-5-(1-(4-nitrophenyl)-3-oxo-3-phenylpropyl)-furan-2(5*H*)-one (3d).** Purified with ethyl acetate/petroleum ether (1:3) to give **3d** as a yellow solid (94.8 mg, 90% yield); mp 157.1−159.9 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.23−8.17 (m, 2H), 7.86−7.80 (m, 2H), 7.67−7.61 (m, 2H), 7.59−7.54 (m, 1H), 7.45−7.41 (m, 3H), 6.06 (d, J = 5.6 Hz, 1H), 3.97 (t, J = 6.3 Hz, 1H), 3.29 (qd, J = 18.2, 6.4 Hz, 2H), 1.32 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 196.8, 172.0, 160.4, 147.3, 147.1, 136.1, 133.8, 130.5, 128.8, 127.9, 123.8, 121.1, 89.5, 46.4, 39.2, 23.4; FTIR (film) 3080, 2930, 2855, 2361, 2344, 1753, 1678, 1597, 1518, 1448, 1345, 1217, 951, 824, 691 cm^{-1}; HRMS (MALDI-TOF) m/z calcd for $C_{20}H_{17}NO_5$ [M + Na]$^+$ 374.0999, found 374.0993.

***anti*-5-(1-(2-Methoxyphenyl)-3-oxo-3-phenylpropyl)-5-methylfuran-2(5*H*)-one (3e).** Purified with ethyl acetate/petroleum ether (1:3) to give **3e** as a colorless liquid (67.6 mg, 67% yield); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.92−7.81 (m, 2H), 7.56−7.51 (m, 1H), 7.49−7.38 (m, 4H), 7.28−7.21 (m, 1H), 6.96 (t, J = 7.5 Hz, 1H), 6.89 (d, J = 8.3 Hz, 1H), 5.93 (d, J = 5.6 Hz, 1H), 4.58−4.54 (m, 1H), 3.85 (s, 3H), 3.36−3.24 (m, 2H), 1.33 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 197.9, 172.8, 161.9, 157.2, 136.7, 133.2, 128.6, 128.4, 127.9, 121.0, 119.7, 110.7, 90.8, 55.6, 39.1, 22.1; FTIR (film) 3361, 2922, 2839, 2359, 1667, 1606, 742, 690, 543, 513 cm^{-1}; HRMS (MALDI-TOF) m/z calcd for $C_{21}H_{20}O_4$ [M + Na]$^+$ 359.1254, found 359.1258.

***anti*-5-Methyl-5-(3-oxo-3-phenyl-1-(*m*-tolyl)propyl)furan-2(5*H*)-one (3f).** Purified with ethyl acetate/petroleum ether (1:5) to give **3f** as a colorless liquid (85.5 mg, 89% yield); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.86 (dd, J = 8.4, 1.3 Hz, 2H), 7.56- 7.52 (m, 1H), 7.44−7.39 (m, 3H), 7.27−7.21 (m, 1H), 7.04−6.92 (m, 2H), 6.81 (ddd, J = 8.3, 2.6, 0.9 Hz, 1H), 5.98 (d, J = 5.6 Hz, 1H), 3.81 (s, 4H), 3.32 (qd, J = 18.0, 6.3 Hz, 2H), 1.35 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 197.6, 172.6, 161.4, 159.6, 141.0, 136.6, 133.4, 129.6, 128.6, 128.0, 121.8, 120.3, 115.4, 112.5, 90.3, 55.2, 46.7, 39.3, 22.8; FTIR (film) 3498, 3354, 3086, 2934, 2836, 1770, 1683, 1582, 1489, 1102, 1043, 953, 820, 785, 690, 639, 550, 513, 466 cm^{-1}; HRMS (MALDI-TOF) m/z calcd for $C_{21}H_{20}O_3$ [M + K]$^+$ 359.1044, found 359.1041.

***anti*-5-(1-(2-Chlorophenyl)-3-oxo-3-phenylpropyl)-5-methylfuran-2(5*H*)-one (3g).** Purified with ethyl acetate/petroleum ether (1:5) to give **3g** as a white solid (76.5 mg, 75% yield); mp 189.9−192.5 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.86−7.81 (m, 2H), 7.61 (dd, J = 7.8, 1.7 Hz, 1H), 7.55−7.48 (m, 2H), 7.42−7.38 (m, 3H), 7.27 (td, J = 7.6, 1.4 Hz, 1H), 7.22−7.16 (m, 1H), 5.99 (d, J = 5.6 Hz, 1H), 4.62 (t, J = 6.4 Hz, 1H), 3.30 (qd, J = 18.1, 6.3 Hz, 2H), 1.34 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 197.1, 172.5, 161.4, 137.4, 136.4, 135.0, 133.4, 130.0, 129.6, 128.7, 128.6, 128.0, 127.4, 120.4, 90.3, 41.0, 39.3, 22.5; FTIR (film) 3082, 2990, 2895, 1759, 1678, 1448, 1374, 1296, 1261, 1146, 1103, 952, 824, 754, 694 cm^{-1}; HRMS (MALDI-TOF) m/z calcd for $C_{20}H_{17}ClO_3$ [M + Na]$^+$ 363.0758, found 363.0757.

***anti*-5-(1-(3-Bromophenyl)-3-oxo-3-phenylpropyl)-5-methylfuran-2(5*H*)-one (3h).** Purified with ethyl acetate/petroleum ether (1:5) to give **3h** as a colorless liquid (95.6 mg, 83% yield); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.89−7.81 (m, 2H), 7.60−7.53 (m, 2H), 7.46−7.35 (m, 5H), 7.21 (t, J = 7.8 Hz, 1H), 6.01 (d, J = 5.6 Hz, 1H), 3.81 (t, J = 6.3 Hz, 1H), 3.27 (qd, J = 18.1, 6.2 Hz, 2H), 1.34 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 197.2, 172.4, 161.0, 141.9, 136.4, 133.5, 132.3, 130.7, 130.2, 128.7, 128.2, 128.0, 122.7, 120.6, 90.0, 46.3, 39.3, 23.1; FTIR (film) 3062, 2981, 2932, 2360, 2342, 1755, 1683, 1595, 1567, 1475, 1448, 1103, 953, 820, 755, 691 cm^{-1}; HRMS (MALDI-TOF) m/z calcd for $C_{20}H_{17}BrO_3$ [M + Na]$^+$ 407.0253, found 407.0252.

***anti*-5-(3-(4-Bromophenyl)-3-oxo-1-phenylpropyl)-5-methylfuran-2(5*H*)-one (3i).** Purified with ethyl acetate/petroleum ether (1:5) to give **3i** as a white solid (85.3 mg, 74% yield); mp 149.9−151.2 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.75−7.70 (m, 2H), 7.60−7.55 (m, 2H), 7.44−7.38 (m, 3H), 7.37−7.31 (m, 2H), 7.29 (dt, J = 4.6, 2.1 Hz, 1H), 6.01 (d, J = 5.6 Hz, 1H), 3.83−3.76 (m, 1H), 3.29 (qd, J = 17.9, 6.9 Hz, 2H), 1.34 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 196.7, 172.5, 161.3, 139.1, 135.3, 132.0, 129.5, 129.4, 128.6, 128.6, 127.6, 120.5, 90.3, 46.8, 39.3, 22.8; FTIR (film) 3104, 3078, 3031, 2893, 1746, 1682, 1586, 1492, 1232, 1099, 1068, 922, 824, 735, 701, 644, 537, 459 cm^{-1}; HRMS (MALDI-TOF) m/z calcd for $C_{20}H_{17}BrO_3$ [M + Na]$^+$ 407.0253, found 407.0249.

***anti*-5-(3-(4-Chlorophenyl)-3-oxo-1-phenylpropyl)-5-methylfuran-2(5*H*)-one (3j).** Purified with ethyl acetate/petroleum ether (1:4) to give **3j** as a white solid (83.7 mg, 82% yield); mp 121.1−123.5

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°C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.81−7.79 (m, 2H), 7.39−7.43 (m, 5H), 7.37−7.32 (m, 2H), 7.30−7.27 (m, 1H), 6.01 (d, J = 5.6 Hz, 1H), 3.82−3.76 (m, 1H), 3.30 (qd, J = 17.9, 6.4 Hz, 2H), 1.34 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 196.5, 172.5, 161.3, 139.9, 139.2, 134.9, 129.4, 129.4, 129.0, 128.6, 127.6, 120.4, 90.3, 46.8, 39.3, 22.8; FTIR (film) 2994, 2360, 2343, 1750, 1672, 1585, 1284, 1099, 846, 707, 528 cm^{-1}; HRMS (MALDI-TOF) m/z calcd for $C_{20}H_{17}ClO_3$ [M + Na]$^+$ 363.0758, found 363.0756.

***anti*-5-(3-(3-Methoxyphenyl)-3-oxo-1-phenylpropyl)-5-methylfuran-2(5*H*)-one (3k).** Purified with ethyl acetate/petroleum ether (1:5) to give **3k** as a colorless liquid (91.8 mg, 91% yield); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.46−7.23 (m, 10H), 7.11−7.04 (m, 1H), 5.99 (d, J = 5.6 Hz, 1H), 3.83−3.78 (m, 4H), 3.32 (qd, J = 17.9, 6.4 Hz, 2H), 1.33 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 197.5, 172.5, 161.3, 159.8, 139.3, 137.9, 129.7, 129.4, 128.5, 127.4, 120.5, 120.4, 119.7, 112.2, 90.35, 55.4, 46.8, 39.4, 22.7; FTIR (film) 3361, 2922, 2839, 2359, 1667, 1606, 742, 690, 543, 513 cm^{-1}; HRMS (MALDI-TOF) m/z calcd for $C_{21}H_{20}O_4$ [M + Na]$^+$ 359.1254, found 359.1261.

***anti*-5-(3-(3-Bromophenyl)-3-oxo-1-phenylpropyl)-5-methylfuran-2(5*H*)-one (3l).** Purified with ethyl acetate/petroleum ether (1:3) to give **3l** as a yellow solid (93.3 mg, 81% yield); mp 79.3−81.2 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.97 (t, J = 1.8 Hz, 1H), 7.80−7.72 (m, 1H), 7.66 (ddd, J = 8.0, 2.0, 1.0 Hz, 1H), 7.45- 7.37 (m, 3H), 7.36−7.26 (m, 4H), 6.02 (d, J = 5.6 Hz, 1H), 3.79 (t, J = 6.3 Hz, 1H), 3.30 (qd, J = 18.0, 7.1 Hz, 2H), 1.34 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 196.3, 172.45, 161.3, 139.1, 138.2, 136.2, 131.0, 130.3, 129.4, 128.6, 127.6, 126.5, 123.0, 120.5, 90.3, 46.8, 39.5, 22.8; FTIR (film) 3062, 2905, 1742, 1697, 1566, 1453, 1413, 1375, 1297, 1235, 1105, 997, 953, 813, 704, 677, 537 cm^{-1}; HRMS (MALDI-TOF) m/z calcd for $C_{20}H_{17}BrO_3$ [M + Na]$^+$ 407.0253, found 407.0251.

***anti*-5-(1-(2-Chlorophenyl)-3-(4-methoxyphenyl)-3-oxopropyl)-5-methylfuran-2(5*H*)-one (3m).** Purified with ethyl acetate/petroleum ether (1:5) to give **3m** as a white solid (85.5 mg, 77% yield); mp 114.5−116.8 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.83 (d, J = 8.9 Hz, 2H), 7.61 (dd, J = 7.8, 1.6 Hz, 1H), 7.49 (d, J = 5.6 Hz, 1H), 7.39 (dd, J = 7.9, 1.3 Hz, 1H), 7.26 (dd, J = 7.6, 6.3 Hz, 1H), 7.20 (dd, J = 7.7, 1.7 Hz, 1H), 6.87 (d, J = 8.9 Hz, 2H), 5.97 (d, J = 5.6 Hz, 1H), 4.62 (t, J = 6.4 Hz, 1H), 3.83 (s, 3H), 3.20 (qd, J = 17.9, 6.3 Hz, 2H), 1.34 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 195.5, 172.6, 163.7, 161.5, 137.5, 135.0, 130.3, 130.1, 129.6, 129.4, 128.5, 127.3, 120.3, 113.8, 90.4, 555, 41.0, 38.9, 22.5; FTIR (film) 3422, 3075, 2930, 1741, 1686, 1491, 1459, 1420, 1365, 1232, 1112, 989, 902, 829, 754, 693, 670, 578 cm^{-1}; HRMS (MALDI-TOF) m/z calcd for $C_{21}H_{19}ClO_4$ [M + Na]$^+$ 393.0868, found 393.0864.

***anti*-5-(1-(2,4-Dichlorophenyl)-3-(4-methoxyphenyl)-3-oxopropyl)-5-methylfuran-2(5*H*)-one (3n).** Purified with ethyl acetate/petroleum ether (1:5) to give **3n** as a white solid (93.3 mg, 77% yield); mp 121.1−123.5 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.83 (d, J = 9.0 Hz, 2H), 7.57 (d, J = 8.5 Hz, 1H), 7.49 (d, J = 5.6 Hz, 1H), 7.44 (d, J = 2.2 Hz, 1H), 7.27 (dd, J = 8.7, 2.4 Hz, 1H), 6.90 (d, J = 9.0 Hz, 2H), 6.00 (d, J = 5.6 Hz, 1H), 4.57 (t, J = 6.4 Hz, 1H), 3.86 (s, 3H), 3.18 (qd, J = 17.9, 6.4 Hz, 2H), 1.34 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 195.2, 172.4, 163.8, 161.1, 136.2, 135.7, 133.6, 130.9, 130.3, 129.3, 129.3, 127.7, 120.5, 113.9, 90.1, 55.5, 40.7, 38.8, 22.6; FTIR (film) 3091, 2936, 2838, 1757, 1664, 1599, 1474, 1376, 1252, 1214, 1172, 1103, 1032, 945, 812 cm^{-1}; HRMS (MALDI-TOF) m/z calcd for $C_{21}H_{18}Cl_2O_4$ [M + Na]$^+$ 427.0479, found 427.0474.

***anti*-5-(3-(4-Bromophenyl)-1-(2-chlorophenyl)-3-oxopropyl)-5-methylfuran-2(5*H*)-one(3o).** Purified with ethyl acetate/petroleum ether (1:5) to give **3o** as a white solid (90.3 mg, 72% yield); mp 189.6−192.5 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.71 (d, J = 8.5 Hz, 2H), 7.63−7.53 (m, 3H), 7.49 (d, J = 5.6 Hz, 1H), 7.41 (dd, J = 7.9, 1.2 Hz, 1H), 7.30−7.21 (m, 1H), 7.23−7.21 (m, 1H), 6.01 (d, J = 5.6 Hz, 1H), 4.60 (t, J = 6.4 Hz, 1H), 3.23 (d, J = 6.4 Hz, 2H), 1.35 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 196.2, 172.4, 161.3, 137.2, 135.0, 135.0, 132.0, 129.9, 129.7, 129.5, 128.7, 128.7, 127.4, 120.5, 90.2, 41.0, 39.3, 22.4; FTIR (film) 3091, 2983, 1756, 1672, 1586, 1568, 1474, 1396, 1474, 1396, 1298, 1264, 1104, 1071, 967, 947, 822, 764, 744, 541, 477 cm^{-1}; HRMS (MALDI-TOF) m/z calcd for $C_{20}H_{16}BrClO_3$ [M + Na]$^+$ 440.9863, found 440.9866.

***anti*-5-Methyl-5-(1-(naphthalen-1-yl)-3-oxo-3-phenylpropyl)furan-2(5*H*)-one (3p).** Purified with ethyl acetate/petroleum ether (1:5) to give **3p** as a white solid (105.8 mg, 99% yield); mp 56.3−57.8 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.29 (d, J = 8.5 Hz, 1H), 7.91−7.80 (m, 5H), 7.63−7.50 (m, 4H), 7.46−7.41 (m, 3H), 6.00 (d, J = 5.6 Hz, 1H), 4.94 (t, J = 6.1 Hz, 1H), 3.48 (qd, J = 18.3, 6.2 Hz, 2H), 1.35 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 197.8, 172.7, 161.9, 136.4, 136.1, 133.9, 133.4, 132.3, 129.2, 128.7, 128.0, 126.6, 126.5, 125.6, 125.6, 123.1, 120.1, 90.8, 40.4, 39.1, 22.7; FTIR (film) 3056, 2979, 1751, 1683, 1597, 1511, 1284, 1230, 1101, 951, 820, 781, 760, 689 cm^{-1}; HRMS (MALDI-TOF) m/z calcd for $C_{24}H_{20}O_3$ [M + Na]$^+$ 379.1311, found 379.1305.

***anti*-5-Methyl-5-(1-(naphthalen-2-yl)-3-oxo-3-phenylpropyl)furan-2(5*H*)-one (3q).** Purified with ethyl acetate/petroleum ether (1:3) to give **3q** as a white solid (85.5 mg, 80% yield); mp 44.5−47.2 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.89−7.83 (m, 6H), 7.61 (dd, J = 8.6, 1.8 Hz, 1H), 7.56−7.47 (m, 4H), 7.45−7.40 (m, 2H), 6.04 (d, J = 5.6 Hz, 1H), 4.03 (t, J = 6.3 Hz, 1H), 3.43 (qd, J = 18.0, 6.8 Hz, 2H), 1.38 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 197.6, 172.7, 161.4, 137.0, 136.5, 133.4, 133.3, 132.7, 128.7, 128.4, 128.0, 127.9, 127.6, 127.3, 126.2, 126.0, 120.5, 90.5, 46.8, 39.5, 23.0; FTIR (film) 2361, 1752, 1685, 1449, 1101, 817, 752, 688, 431, 425, 416 cm^{-1}; HRMS (MALDI-TOF) m/z calcd for $C_{24}H_{20}O_3$ [M + Na]$^+$ 379.1308, found 379.1305.

***anti*-5-(1-(Furan-2-yl)-3-oxo-3-phenylpropyl)-5-methylfuran-2(5*H*)-one (3r).** Purified with ethyl acetate/petroleum ether (1:4) to give **3r** as a yellow solid (83.5 mg, 94% yield); mp 41.3−43.5 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.94−7.88 (m, 2H), 7.58−7.54 (m, 1H), 7.47−7.43 (m, 3H), 7.34−7.33 (m, 1H), 6.32−6.30 (m, 1H), 6.23 (d, J = 3.2 Hz, 1H), 6.00 (d, J = 5.6 Hz, 1H), 3.90 (dd, J = 8.5, 4.7 Hz, 1H), 3.44 (ddd, J = 22.3, 17.6, 6.6 Hz, 2H), 1.44 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 197.0, 172.1, 160.6, 152.39, 141.9, 136.4, 133.4, 128.7, 128.0, 120.4, 110.5, 108.4, 89.4, 41.3, 37.4, 21.4; FTIR (film) 2924, 1762, 1684, 1597, 1449, 1107, 956, 822, 761, 690, 562 cm^{-1}; HRMS (MALDI-TOF) m/z calcd for $C_{18}H_{16}O_4$ [M]$^+$ 296.1049, found 296.1046.

***anti*-5-Methyl-5-(3-oxo-3-phenyl-1-(thiophen-2-yl)propyl)-furan-2(5*H*)-one (3s).** Purified with ethyl acetate/petroleum ether (1:5) to give **3s** as a colorless oil liquid (88 mg, 94% yield); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.87 (d, J = 7.3 Hz, 2H), 7.56 (t, J = 7.4 Hz, 1H), 7.46−7.42 (m, 3H), 7.21 (d, J = 5.1 Hz, 1H), 7.05 (d, J = 3.4 Hz, 1H), 6.97−6.95 (m, 1H), 6.00 (d, J = 5.6 Hz, 1H), 4.18 (t, J = 6.3 Hz, 1H), 3.35 (qd, J = 17.8, 6.3 Hz, 2H), 1.46 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 197.2, 172.2, 1108, 962, 906, 818, 764, 720, 689, 577, 543, 512 cm^{-1}; HRMS (MALDI-TOF) m/z calcd for $C_{18}H_{16}O_3S$ [M + Na]$^+$ 335.0712, found 335.0713.

***anti*-5-Methyl-5-(3-oxo-1-phenylbutyl)furan-2(5*H*)-one (3t).**[6i] Purified with ethyl acetate/petroleum ether (1:2) to give **3t** as a colorless liquid (56.4 mg, 77% yield); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.37 (d, J = 5.6 Hz, 1H), 7.23 (m, 5H), 5.95 (d, 5.7 Hz, 1H), 3.76−3.51 (m, 1H), 3.00−2.69 (m, 2H), 2.03 (s, 3H), 1.35 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 206.2, 172.5, 161.2, 139.0, 129.3, 128.6, 127.5, 120.3, 90.1, 46.6, 44.3, 30.6, 22.6.

***anti*-5-Methyl-5-(3-oxocyclopentyl)furan-2(5*H*)-one (3u).**[6i] Purified with ethyl acetate/petroleum ether (1:2) to give **3u** as a colorless liquid (27.6 mg, 51% yield); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.40 (d, J = 5.7 Hz, 1H), 6.12 (d, J = 5.7 Hz, 1H), 2.64−2.55 (m, 1H), 2.46−2.33 (m, 2H), 2.26−2.15 (m, 2H), 1.97−1.89 (m, 1H), 1.63−1.55 (m, 1H), 1.53 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 216.1, 171.9, 158.7, 121.6, 88.9, 43.6, 39.6, 38.4, 23.7, 23.1.

5-Methyl-5-(3-oxopentyl)furan-2(5*H*)-one (3v). Purified with ethyl acetate/petroleum ether (1:3) to give **3v** as a colorless liquid (20.8 mg, 38% yield); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.30 (d, J = 5.6 Hz, 1H), 5.96 (d, J = 5.6 Hz, 1H), 2.41−2.29 (m, 4H), 2.09−2.04(m, 2H), 1.45 (s, 3H), 0.99(t, J = 7.4 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 209.9, 172.3, 160.3, 120.4, 88.1, 36.0, 35.0, 35.8, 31.0, 24.3; FTIR (film) 3568, 2928, 2384, 2348, 1753, 1712, 1383, 1113, 949, 566 cm^{-1}; HRMS (MALDI-TOF) m/z calcd for $C_{10}H_{14}O_3$ [M]$^+$ 182.0943, found 182.0943.

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Methyl 3-(2-Methyl-5-oxo-2,5-dihydrofuran-2-yl)-propanoate (3w). Purified with ethyl acetate/petroleum ether (1:3) to give **3w** as a colorless liquid (39.2 mg, 71% yield); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.33 (d, J = 5.6 Hz, 1H), 6.00 (d, J = 5.6 Hz, 1H), 3.63 (s, 3H), 2.36−2.28 (m, 1H), 2.25−2.14 (m, 2H), 2.11−2.03 (m, 1H), 1.47 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 173.0, 172.1, 159.7, 120.9, 87.8, 32.7, 28.1, 24.2; FTIR (film) 1752, 1438, 1172, 1108, 950, 822 cm^{-1}; HRMS (MALDI-TOF) m/z calcd for $C_9H_{12}O_4$ [M + Na]$^+$ 207.0628, found 207.0632.

***tert*-Butyl 3-(2-Methyl-5-oxo-2,5-dihydrofuran-2-yl)-propanoate (3x).** Purified with ethyl acetate/petroleum ether (1:10) to give **3x** as a colorless liquid (49.5 mg, 73% yield); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.33 (d, J = 5.6 Hz, 1H), 5.96 (d, J = 5.6 Hz, 1H), 2.24−2.00 (m, 4H), 1.45 (s, 3H), 1.43(s, 9H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 172.2, 171.8, 159.9, 120.7, 88.0, 80.7, 32.7, 29.5, 28.0, 24.2; FTIR (film) 2980, 2935, 1759, 1728, 1457, 1368, 1155, 1107, 950, 823 cm^{-1}; HRMS (MALDI-TOF) m/z calcd for $C_{12}H_{18}O_4$ [M + Na]$^+$ 249.1097, found 249.1093.

3-(2-Methyl-5-oxo-2,5-dihydrofuran-2-yl)propanenitrile (3y). Purified with ethyl acetate/petroleum ether (1:3) to give **3y** as a colorless liquid (20.9 mg, 46% yield); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.44 (d, J = 5.6 Hz, 1H), 6.12 (d, J = 5.6 Hz, 1H), 2.46−2.36 (m, 1H), 2.31−2.23(m, 2H), 2.15−2.05(m, 1H), 1.53 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 171.5, 158.7, 121.8, 118.9, 86.8, 33.6, 24.0, 12.0; FTIR (film) 2938, 2249, 1754, 1604, 1185, 1110, 951, 900, 823, 521 cm^{-1}; HRMS (MALDI-TOF) m/z calcd for $C_8H_9NO_2$ [M + Na]$^+$ 174.0526, found 174.0526.

***anti*-5-Butyl-5-(1,3-diphenylpropyl)furan-2(5*H*)-one (3z).** Purified with acetone/petroleum ether (1:6) to give **3z** as a white solid (91.3 mg, 82% yield); mp 72.4−75.8 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.85−7.82 (m, 2H), 7.55−7.51 (m, 1H), 7.49−7.36 (m, 5H), 7.34−7.30 (m, 2H), 7.27−7.23 (m, 1H), 6.02 (d, J = 5.6 Hz, 1H), 3.89 (t, J = 6.2 Hz, 1H), 3.23 (qd, J = 18.0, 6.4 Hz, 2H), 1.73−1.54 (m, 2H), 1.20−1.04 (m, 4H), 0.78 (t, J = 6.9 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 197.8, 172.9, 160.1, 139.5, 136.6, 133.4, 129.5, 128.6, 128.5, 127.9, 127.4, 121.4, 93.1, 45.9, 39.6, 35.2, 25.6, 22.6, 13.8; FTIR (film) 2953, 2859, 1746, 1684, 1446, 1234, 1000, 932, 822, 748, 704, 686, 548 cm^{-1}; HRMS (MALDI-TOF) m/z calcd for $C_{23}H_{24}O_3$ [M + Na]$^+$ 371.1618, found 371.1614.

***anti*-5-(1,3-Diphenylpropyl)-5-isobutylfuran-2(5*H*)-one (3aa).** Purified with acetone/petroleum ether (1:6) to give **3aa** as a white solid (95.7 mg, 86% yield); mp 125.6−129.4 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.63 (d, J = 7.1 Hz, 2H), 7.53 (t, J = 8.0 Hz, 1H), 7.42−7.39 (m, 5H), 7.31 (t, J = 7.0 Hz, 2H), 7.26−7.23 (m, 1H), 6.02 (d, J = 5.6 Hz, 1H), 3.85 (t, J = 6.2 Hz, 1H), 3.24 (d, J = 6.2 Hz, 2H), 1.66−1.61 (m, 2H), 1.47−1.38 (m, 1H), 0.78 (d, J = 6.6 Hz, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 197.8, 172.9, 160.2, 139.6, 136.5, 133.4, 129.6, 128.6, 128.5, 127.9, 127.4, 121.2, 93.3, 46.8, 44.1, 39.6, 24.6, 23.7, 23.6; FTIR (film) 2950, 2866, 1744, 1690, 1607, 1595, 1446, 1364, 1252, 932, 815, 746, 684, 552 cm^{-1}; HRMS (MALDI-TOF) m/z calcd for $C_{23}H_{24}O_3$ [M + Na]$^+$ 371.1618, found 371.1611.

***anti*-5-(1,3-Diphenylpropyl)-5-isopropylfuran-2(5*H*)-one (3ab).** Purified with acetone/petroleum ether (1:6) to give **3ab** as a white solid (72.8 mg, 68% yield); mp 143.4−149.5 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.81−7.78 (m, 2H), 7.54−7.50 (m, 3H), 7.41−7.38 (m, 3H), 7.34−7.30 (m, 2H), 7.26−7.22 (m, 1H), 6.10 (d, J = 5.7 Hz, 1H), 4.15 (t, J = 6.1 Hz, 1H), 3.15 (qd, J = 18.1, 6.0 Hz, 2H), 1.98 (heptet, J = 6.8 Hz 1H), 1.08 (d, J = 6.9 Hz, 3H), 0.66 (d, J = 6.8 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 198.1, 172.8, 157.5, 139.8, 136.5, 133.4, 129.6, 128.63, 128.57, 127.9, 127.3, 123.0, 96.2, 43.1, 40.3, 32.5, 18.1, 16.2; FTIR (film) 3113, 3060, 2959, 1744, 1684, 1448, 1366, 1230, 1129, 1011, 942, 822, 748, 707, 682 cm^{-1}; HRMS (MALDI-TOF) m/z calcd for $C_{22}H_{22}O_3$ [M + Na]$^+$ 357.1461, found 357.1465.

***anti*-5-(3-Oxo-1,3-diphenylpropyl)-5-phenylfuran-2(5*H*)-one (3ac).**[6d] Purified with ethyl acetate/petroleum ether (1:5) to give **3ac** as a white solid (99.4 mg, 90% yield); mp 124.8−126.6 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.90 (dd, J = 8.4, 1.3 Hz, 2H), 7.80 (d, J = 5.6 Hz, 1H), 7.59−7.55 (m, 1H), 7.46 (t, J = 7.7 Hz, 2H), 7.28−7.20 (m, 5H), 7.15−7.09 (m, 5H), 5.99 (d, J = 5.6 Hz, 1H), 4.29 (t, J = 6.3 Hz, 1H), 3.43 (qd, J = 18.1, 6.3 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 197.8, 172.2, 159.8, 138.4, 137.8, 136.6, 133.5, 1297, 128.7, 128.4, 127.99, 127.97, 127.1, 125.5, 119.7, 93.3, 48.4, 39.1.

***anti*-5-(3-Oxo-1,3-diphenylpropyl)-5-(*p*-tolyl)furan-2(5*H*)-one (3ad).**[6d] Purified with ethyl acetate/petroleum ether (1:5) to give **3ad** as a white solid (94 mg, 82% yield); mp 204.3−206.7 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.90−7.88 (m, 2H), 7.77 (d, J = 5.6 Hz, 1H), 7.59−7.55 (m, 1H), 7.45 (t, J = 7.6 Hz, 2H), 7.14−7.05 (m, 9H), 5.97 (d, J = 5.6 Hz, 1H), 4.26 (t, J = 6.3 Hz, 1H), 3.42 (qd, J = 18.1, 6.3 Hz, 2H), 2.29 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 197.6, 172.3, 159.9, 138.5, 137.6, 136.6, 134.7, 133.4, 129.7, 129.0, 128.7, 127.97, 127.95, 127.1, 125.4, 119.5, 93.3, 48.4, 39.2, 21.0.

***anti*-5-(4-Chlorophenyl)-5-(3-oxo-1,3-diphenylpropyl)furan-2(5*H*)-one (3ae).**[6d] Purified with ethyl acetate/petroleum ether (1:5) to give **3ae** as a yellow solid (94.1 mg, 78% yield); mp 198.5−201.3 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.91−7.89 (m, 2H), 7.75 (d, J = 5.6 Hz, 1H), 7.58 (t, J = 7.4 Hz, 1H), 7.46 (t, J = 7.7 Hz, 2H), 7.24−7.10 (m, 9H), 6.00 (d, J = 5.6 Hz, 1H), 4.25 (t, J = 6.2 Hz, 1H), 3.41 (qd, J = 18.2, 6.4 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 197.7, 171.9, 159.4, 138.2, 136.5, 136.4, 133.9, 133.6, 129.6, 128.7, 128.6, 128.1, 128.0, 127.3, 126.8, 120.0, 92.7, 48.2, 39.1.

***anti*-5-(3-(4-Bromophenyl)-3-oxo-1-phenylpropyl)-5-phenylfuran-2(5*H*)-one (3af).** Purified with ethyl acetate/petroleum ether (1:5) to give **3af** as a white solid (65.6 mg, 49% yield); mp 185.7−188.2 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.79−7.74 (m, 3H), 7.61−7.58 (m, 2H), 7.28−7.21 (m, 5H), 7.14−7.08 (m, 5H), 6.01 (d, J = 5.6 Hz, 1H), 4.24 (t, J = 6.3 Hz, 1H), 3.38 (d, J = 18.0, 6.3 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 196.8, 172.0, 159.7, 138.2, 137.6, 135.2, 132.0, 129.6, 129.5, 128.7, 128.4, 128.0, 127.2, 125.5, 119.7, 93.1, 48.5, 39.1; FTIR (film) 3091, 2979, 2932, 1757, 1666, 1595, 1448, 1290, 1226, 1108, 962, 906, 818, 764, 720, 689, 577, 543, 512 cm^{-1}; HRMS (MALDI-TOF) m/z calcd for $C_{25}H_{19}BrO_3$ [M + Na]$^+$ 469.0410, found 469.0411.

***anti*-5-(1-(4-Chlorophenyl)-3-oxo-3-phenylpropyl)-5-phenylfuran-2(5*H*)-one (3ag).**[6d] Purified with ethyl acetate/petroleum ether (1:5) to give **3ag** as a white solid (55.5 mg, 46% yield); mp 161.4−164.3 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.89 (d, J = 7.2 Hz, 2H), 7.77 (d, J = 5.6 Hz, 1H), 7.58 (t, J = 7.4 Hz, 1H), 7.46 (t, J = 7.7 Hz, 2H), 7.29−7.23 (m, 5H), 7.08 (q, J = 8.4 Hz, 4H), 6.00 (d, J = 5.6 Hz, 1H), 4.28 (t, J = 6.3 Hz, 1H), 3.38 (qd, J = 17.9, 6.3 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 197.5, 172.0, 159.5, 137.6, 137.1, 136.4, 133.6, 133.0, 130.9, 128.8, 128.6, 128.1, 128.1, 128.0, 125.2, 119.8, 83.0, 47.7, 39.0.

Procedure for Control Experiment. α-Angelica lactone **2a** (0.16 mmol, 15 uL) was dissolved in anhydrous THF (1.0 mL), and the solution was cooled to −78 °C, then LDA (0.15 mmol, 75 uL, 2 M in THF) was added under N_2. Subsequently, the reaction solution was stirred at −78 °C for 20 min; then, compound **10** was added, and the reaction mixture was allowed to warm to room temperature and stirred overnight. TLC indicated that desired product **3a** was not generated. Then, the crude mixture was concentrated under vacuum and purified by flash silica gel column chromatography to recover compound **10** in 83% yield (57 mg).

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.joc.5b01845.

Copies of ^{1}H and ^{13}C NMR spectra for all of the products (PDF)

X-ray data for compound **3j** (CIF)

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Notes

The authors declare no competing financial interest.

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■ REFERENCES

(1) For recent reviews of natural products containing butenolides, see: (a) Bermejo, A.; Figadère, B.; Zafra-Polo, M.; Barrachina, I.; Estornell, E.; Cortes, D. *Nat. Prod. Rep.* **2005**, *22*, 269. (b) Sellars, J. D.; Steel, P. G. *Eur. J. Org. Chem.* **2007**, *2007*, 3815. (c) Prassas, I.; Diamandis, E. P. *Nat. Rev. Drug Discovery* **2008**, *7*, 926. (d) Roethle, P. A.; Trauner, D. *Nat. Prod. Rep.* **2008**, *25*, 298. (e) Kitson, R. R. A.; Millemaggi, A.; Taylor, R. J. K. *Angew. Chem., Int. Ed.* **2009**, *48*, 9426−9451.

(2) For reviews on the synthesis of butenolides, see: (a) Negishi, E.; Kotora, M. *Tetrahedron* **1997**, *53*, 6707. (b) Montagnon, T.; Tofi, M.; Vassilikogiannakis, G. *Acc. Chem. Res.* **2008**, *41*, 1001.

(3) For reviews, see: (a) Martin, S. F. *Acc. Chem. Res.* **2002**, *35*, 895. (b) Pansare, S. V.; Paul, E. K. *Chem. - Eur. J.* **2011**, *17*, 8770. (c) Casiraghi, G.; Battistini, L.; Curti, C.; Rassu, G.; Zanardi, F. *Chem. Rev.* **2011**, *111*, 3076. (d) Casiraghi, G.; Zanardi, F.; Battistini, L.; Rassu, G. *Synlett* **2009**, *2009*, 1525. (e) Christoffers, J. *Synlett* **2001**, *2001*, 723.

(4) For direct vinylogous reactions of γ-butenolides, see: (a) Yamaguchi, A.; Matsunaga, S.; Shibasaki, M. *Org. Lett.* **2008**, *10*, 2319. (b) Hyde, A. M.; Buchwald, S. L. *Org. Lett.* **2009**, *11*, 2663. (c) Trost, B. M.; Hitce, J. *J. Am. Chem. Soc.* **2009**, *131*, 4572. (d) Zhang, Y.; Yu, C.; Ji, Y.; Wang, W. *Chem. - Asian J.* **2010**, *5*, 1303. (e) Wang, J.; Qi, C.; Ge, Z.; Cheng, T.; Li, R. *Chem. Commun.* **2010**, *46*, 2124. (f) Ube, H.; Shimada, N.; Terada, M. *Angew. Chem., Int. Ed.* **2010**, *49*, 1858.

(5) (a) Cui, H.-L.; Huang, J.-R.; Lei, J.; Wang, Z.-F.; Chen, S.; Wu, L.; Chen, Y.-C. *Org. Lett.* **2010**, *12*, 720. (b) Huang, X.; Peng, J.; Dong, L.; Chen, Y.-C. *Chem. Commun.* **2012**, *48*, 2439.

(6) (a) Quintard, A.; Lefranc, A.; Alexakis, A. *Org. Lett.* **2011**, *13*, 1540. (b) Manna, M. S.; Mukherjee, S. *Chem. - Eur. J.* **2012**, *18*, 15277. (c) Manna, M. S.; Kumar, V.; Mukherjee, S. *Chem. Commun.* **2012**, *48*, 5193. (d) Yang, D.; Wang, L.; Zhao, D.; Han, F.; Zhang, B.; Wang, R. *Chem. - Eur. J.* **2013**, *19*, 4691. (e) Das, U.; Chen, Y.-R.; Tsai, Y.-L.; Lin, W. *Chem. - Eur. J.* **2013**, *19*, 7713. (f) Kumar, V.; Ray, B.; Rathi, P.; Mukherjee, S. *Synthesis* **2013**, *45*, 1641. (g) Ji, J.; Lin, L.-L.; Zhou, L.; Zhang, Y.-H.; Liu, Y.-B.; Liu, X.-H.; Feng, X.-M. *Adv. Synth. Catal.* **2013**, *355*, 2764−2768. (h) Kumar, V.; Mukherjee, S. *Chem. Commun.* **2013**, *49*, 11203−11205. (i) Yin, L.; Takada, H.; Lin, S.; Kumagai, N.; Shibasaki, M. *Angew. Chem., Int. Ed.* **2014**, *53*, 5327−5331. (j) Manna, M. S.; Mukherjee, S. *Chem. Sci.* **2014**, *5*, 1627−1633. (k) Li, X.; Lu, M.; Dong, Y.; Wu, W.; Qian, Q.-Q.; Ye, J.-X.; Dixon, D. J. *Nat. Commun.* **2014**, *5*, 4479.

(7) Zhou, L.; Lin, L.-L.; Ji, J.; Xie, M.-S.; Liu, X.-H.; Feng, X.-M. *Org. Lett.* **2011**, *13*, 3056.

(8) Zhang, W.; Tan, D.; Lee, R.; Tong, G.; Chen, W.; Qi, B.; Huang, K.-W.; Tan, C.-H.; Jiang, Z. *Angew. Chem., Int. Ed.* **2012**, *51*, 10069.

(9) For recent reviews of NHC catalysis, see: (a) Enders, D.; Niemeier, O.; Henseler, A. *Chem. Rev.* **2007**, *107*, 5606. (b) Biju, A. T.; Kuhl, N.; Glorius, F. *Acc. Chem. Res.* **2011**, *44*, 1182. (c) Mahatthananchai, J.; Bode, J. W. *Chem. Sci.* **2012**, *3*, 192−197. (d) Grossmann, A.; Enders, D. *Angew. Chem., Int. Ed.* **2012**, *51*, 314. (e) Hopkinson, N.; Richter, C.; Schedler, M.; Glorius, F. *Nature* **2014**, *510*, 485−496. (f) Menon, R. S.; Biju, A. T.; Nair, V. *Chem. Soc. Rev.* **2015**, *44*, 5040. (g) Flanigan, D. M.; Romanov-Michailidis, F.; White, N. A.; Rovis, T. *Chem. Rev.* **2015**, *115*, 9307. (h) Douglas, J.; Churchill, G.; Smith, A. D. *Synthesis* **2012**, *44*, 2295. (i) Ryan, S. J.; Candish, L.; Lupton, D. W. *Chem. Soc. Rev.* **2013**, *42*, 4906. (j) Izquierdo, J.; Hutson, G. E.; Cohen, D. T.; Scheidt, K. A. *Angew. Chem., Int. Ed.* **2012**, *51*, 11686.

(10) For selected examples, see: (a) Enders, D.; Kallfass, U. *Angew. Chem., Int. Ed.* **2002**, *41*, 1743. (b) Hachisu, Y.; Bode, J. W.; Suzuki, K. *J. Am. Chem. Soc.* **2003**, *125*, 8432. (c) Enders, D.; Niemeier, O.; Balensiefer, T. *Angew. Chem., Int. Ed.* **2006**, *45*, 1463. (d) Takikawa, H.; Hachisu, Y.; Bode, J. W.; Suzuki, K. *Angew. Chem., Int. Ed.* **2006**, *45*, 3492. (e) Sun, L.-H.; Liang, Z.-Q.; Jia, W.-Q.; Ye, S. *Angew. Chem., Int. Ed.* **2013**, *52*, 5803−5806. (f) Wu, K.-J.; Li, G.-Q.; Li, Y.; Dai, L.-X.; You, S.-L. *Chem. Commun.* **2011**, *47*, 493−495. (g) Li, G.-Q.; Dai, L.-X.; You, S.-L. *Chem. Commun.* **2007**, 852−854.

(11) For selected examples, see: (a) Stetter, H.; Schreckenberg, M. *Angew. Chem., Int. Ed. Engl.* **1973**, *12*, 81. (b) Kerr, M. S.; Read de Alaniz, J.; Rovis, T. *J. Am. Chem. Soc.* **2002**, *124*, 10298. (c) Kerr, M. S.; Rovis, T. *J. Am. Chem. Soc.* **2004**, *126*, 8876. (d) Read de Alaniz, J.; Rovis, T. *J. Am. Chem. Soc.* **2005**, *127*, 6284. (e) Mattson, A. E.; Zuhl, A. M.; Reynolds, T. E.; Scheidt, K. A. *J. Am. Chem. Soc.* **2006**, *128*, 4932. (f) Liu, Q.; Perreault, S.; Rovis, T. *J. Am. Chem. Soc.* **2008**, *130*, 14066−14067. (g) Enders, D.; Han, J. W.; Henseler, A. *Chem. Commun.* **2008**, 3989−3991. (h) Dirocco, D. A.; Oberg, K. M.; Dalton, D. M.; Rovis, T. *J. Am. Chem. Soc.* **2009**, *131*, 10872. (i) Hirano, K.; Biju, A. T.; Piel, I.; Glorius, F. *J. Am. Chem. Soc.* **2009**, *131*, 14190−14191. (j) DiRocco, D. A.; Rovis, T. *J. Am. Chem. Soc.* **2011**, *133*, 10402.

(12) For selected examples, see: (a) Burstein, C.; Glorius, F. *Angew. Chem., Int. Ed.* **2004**, *43*, 6205. (b) Sohn, S. S.; Rosen, E. L.; Bode, J. W. *J. Am. Chem. Soc.* **2004**, *126*, 14370. (c) Nair, V.; Vellalath, S.; Poonoth, M.; Suresh, E. *J. Am. Chem. Soc.* **2006**, *128*, 8736−8737. (d) Izquierdo, J.; Scheidt, K. A. *J. Am. Chem. Soc.* **2013**, *135*, 10634. (e) Chen, X.; Fang, X.; Chi, Y.-R. *Chem. Sci.* **2013**, *4*, 2613−2618. (f) Bera, S.; Samanta, R. C.; Daniliuc, C. G.; Studer, A. *Angew. Chem., Int. Ed.* **2014**, *53*, 9622−9626. (g) Lv, H.; Jia, W.-Q.; Sun, L.-H.; Ye, S. *Angew. Chem., Int. Ed.* **2013**, *52*, 8607−8610. (h) White, N. A.; Rovis, T. *J. Am. Chem. Soc.* **2014**, *136*, 14674−14677. (i) Guo, C.; Sahoo, B.; Daniliuc, C. G.; Glorius, F. *J. Am. Chem. Soc.* **2014**, *136*, 17402−17405.

(13) For an excellent review, see: (a) Vora, H. U.; Wheeler, P.; Rovis, T. *Adv. Synth. Catal.* **2012**, *354*, 1617. For selected examples, see: (b) Reynolds, N. T.; Alaniz, J. R. D.; Rovis, T. *J. Am. Chem. Soc.* **2004**, *126*, 9518. (c) Chow, K.Y.-K.; Bode, J. W. *J. Am. Chem. Soc.* **2004**, *126*, 8126. (d) Vora, H. U.; Rovis, T. *J. Am. Chem. Soc.* **2007**, *129*, 13796. (e) Bode, J. W.; Sohn, S. S. *J. Am. Chem. Soc.* **2007**, *129*, 13798. (f) Li, G.-Q.; Li, Y.; Dai, L.-X.; You, S.-L. *Org. Lett.* **2007**, *9*, 3519. (g) Mo, J.; Chen, X.; Chi, Y.-R. *J. Am. Chem. Soc.* **2012**, *134*, 8810. (h) Ni, Q.; Zhang, H.; Grossmann, A.; Loh, C. C. J.; Merkens, C.; Enders, D. *Angew. Chem., Int. Ed.* **2013**, *52*, 13562−13566. (i) See ref 12d. (j) Candish, L.; Levens, A.; Lupton, D. W. *Chem. Sci.* **2015**, *6*, 2366−2370.

(14) (a) For an excellent review, see: Chen, X.-Y.; Ye, S. *Synlett* **2013**, *24*, 1614−1622. For selected examples, see: (b) Zhang, Y.-R.; He, L.; Wu, X.; Shao, P.-L.; Ye, S. *Org. Lett.* **2008**, *10*, 277. (c) Duguet, N.; Campbell, C. D.; Slawin, A. M. Z.; Smith, A. D. *Org. Biomol. Chem.* **2008**, *6*, 1108. (d) Huang, X.-L.; He, L.; Shao, P.-L.; Ye, S. *Angew. Chem., Int. Ed.* **2009**, *48*, 192. (e) Jian, T. Y.; He, L.; Tang, C.; Ye, S. *Angew. Chem., Int. Ed.* **2011**, *50*, 9104. (f) Shao, P.-L.; Chen, X.-Y.; Ye, S. *Angew. Chem., Int. Ed.* **2010**, *49*, 8412. (g) Jian, T.-Y.; Chen, X.-Y.; Sun, L.-H.; Y, S. *Org. Biomol. Chem.* **2013**, *11*, 158−163. (h) Douglas, J.; Taylor, J. E.; Churchill, G.; Slawin, A. M. Z.; Smith, A. D. *J. Org. Chem.* **2013**, *78*, 3925. (i) Zhang, H.-M.; Gao, Z.-H.; Ye, S. *Org. Lett.* **2014**, *16*, 3079−3081.

(15) For selected examples, see: (a) He, L.; Guo, H.; Li, Y.-Z.; Du, G.-F.; Dai, B. *Chem. Commun.* **2014**, *50*, 3719. (b) Fu, Z.; Xu, J.; Zhu, T.; Leong, W. W. Y.; Chi, Y. R. *Nat. Chem.* **2013**, *5*, 835. (c) Chauhan, P.; Enders, D. *Angew. Chem., Int. Ed.* **2014**, *53*, 1485. (d) Bugaut, X.; Liu, F.; Glorius, F. *J. Am. Chem. Soc.* **2011**, *133*, 8130−8133. (e) Hovey, M. T.; Check, C. T.; Sipher, A. F.; Scheidt, K. A. *Angew. Chem., Int. Ed.* **2014**, *53*, 9603−9607. (f) Chen, X.; Gao, Z.; Song, C.; Zhang, C.; Wang, Z.; Ye, S. *Angew. Chem., Int. Ed.* **2014**, *53*, 11611. (g) Li, F.; Wu, Z.; Wang, J. *Angew. Chem., Int. Ed.* **2015**, *54*, 656. (h) Dong, X.; Yang, W.; Hu, W.; Sun, J. *Angew. Chem., Int. Ed.* **2015**, *54*, 660. (i) Wu, Z.; Li, F.; Wang, J. *Angew. Chem., Int. Ed.* **2015**, *54*, 1629.

DOI: 10.1021/acs.joc.5b01845
J. Org. Chem. 2015, 80, 12606−12613

(16) (a) Grasa, G. A.; Kissling, R. M.; Nolan, S. P. *Org. Lett.* **2002**, *4*, 3583. (b) Singh, R.; Kissling, R. M.; Letellier, M. A.; Nolan, S. P. *J. Org. Chem.* **2004**, *69*, 209. (c) Grasa, G. A.; Güveli, T.; Singh, R.; Nolan, S. P. *J. Org. Chem.* **2003**, *68*, 2812. (d) Kano, T.; Sasaki, K.; Maruoka, K. *Org. Lett.* **2005**, *7*, 1347. (e) Nyce, G. W.; Lamboy, J. A.; Connor, E. F.; Waymouth, R. M.; Hedrick, J. L. *Org. Lett.* **2002**, *4*, 3587. (f) Zeng, T.-Q.; Song, G.-H.; Li, C.-J. *Chem. Commun.* **2009**, *41*, 6249. (g) Grasa, G. A.; Singh, R.; Nolan, S. P. *Synthesis* **2004**, 971. (h) Du, G.-F.; Guo, H.; Wang, Y.; Li, W.-J.; Shi, W.-J.; Dai, B. *J. Saudi Chem. Soc.* **2015**, *19*, 112−115.

(17) (a) Movassaghi, M.; Schmidt, M. A. *Org. Lett.* **2005**, *7*, 2453. (b) Guo, H.; Wang, Y.; Du, G.-F.; Dai, B.; He, L. *Tetrahedron* **2015**, *71*, 3472.

(18) (a) Boddaert, T.; Coquerel, Y.; Rodriguez, J. *Adv. Synth. Catal.* **2009**, *351*, 1744−1748. (b) Boddaert, T.; Coquerel, Y.; Rodriguez, J. *Chem. - Eur. J.* **2011**, *17*, 2266−2271.

(19) (a) Phillips, M.; Riedrich, M.; Scheidt, K. A. *J. Am. Chem. Soc.* **2010**, *132*, 13179. (b) Kang, Q.; Zhang, Y. *Org. Biomol. Chem.* **2011**, *9*, 6715. (c) Li, Y.-Z.; Wang, Y.; Du, G.-F.; Zhang, H.-Y.; Yang, H.-L.; He, L. *Asian J. Org. Chem.* **2015**, *4*, 327. (d) Chen, J.-A.; Meng, S.-X.; Wang, L.-M.; Tang, H.-M.; Huang, Y. *Chem. Sci.* **2015**, *6*, 4184.

(20) Arduengo, A. J., III; Krafczyk, R.; Schmutzler, R. *Tetrahedron* **1999**, *55*, 14523.

(21) Zhang, Q.; Xiao, X.; Lin, L.; Liu, X.; Feng, X. *Org. Biomol. Chem.* **2011**, *9*, 5748.

(22) Tsolomitis, A.; Sandris, C. *J. Heterocycl. Chem.* **1983**, *20*, 1545.

(23) Muratore, M. E.; Holloway, C. A.; Pilling, A. W.; Storer, R. L.; Trevitt, G.; Dixon, D. J. *J. Am. Chem. Soc.* **2009**, *131*, 10796.

(24) Marshall, J. A.; Wolf, M. A.; Wallace, E. M. *J. Org. Chem.* **1997**, *62*, 367.

(25) Bhunia, A.; Thorat, S.; Gonnade, R. G.; Biju, A. T. *Chem. Commun.* **2015**, *51*, 13690.

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