JOC The Journal of Organic Chemistry

Article

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The Reaction of 2-Aroylvinylcinnamaldehydes with Aromatic Aldehydes by Dual Catalysis with a Chiral N-Heterocyclic Carbene and a Lewis Acid: Enantioselective Construction of Tetrahydroindeno[1,2-*c*]furan-1-ones

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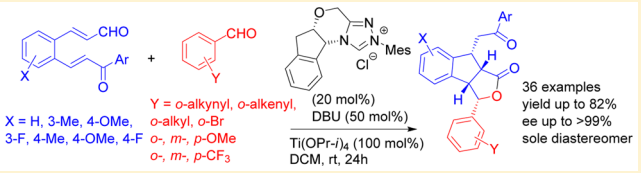
Supporting Information

ABSTRACT: The cooperative chiral N-heterocyclic carbene and Lewis acid catalyzed reactions between 2-aroylvinylcinnamaldehydes and various aromatic aldehydes produced multifunctional tetrahydroindeno[1,2-*c*]furan-1-ones with excellent enantioselectivity. This work developed a versatile and efficient method for highly enantioselective construction of chiral tetrahydroindeno[1,2-*c*]furan-1-one, which are not easily prepared by other synthetic methods.



INTRODUCTION

Indane-fused-butyrolactones are present in many biologically active natural and synthetic compounds.[1] Tetrahydroindeno[1,2-*c*]furan-1-one, tetrahydroindeno[1,2-*c*]furan-3-one, tetrahydroindeno[1,2-*b*]furan-2-one, and tetrahydroindeno[2,1-*b*]furan-2-one are four analogous structures in the family of indane-fused-butyrolactones. In contrast to a plethora of investigations in the synthesis and bioactivity of tetrahydroindeno[1,2-*b*]furan-2-ones and tetrahydroindeno[2,1-*b*]furan-2-ones,[1a−d,2] the studies on the tetrahydroindeno[1,2-*c*]furan-1-ones are very limited. In literature, the most frequently studied reaction that forms a tetrahydroindeno[1,2-*c*]furan-1-one ring is the Baeyer−Villiger oxidation of tetrahydrocyclobuta[*a*]-inden-1-one.[3] The asymmetric synthesis of tetrahydroindeno[1,2-*c*]furan-1-ones has also been achieved by Baeyer−Villiger oxidation in the presence of various chiral catalysts.[3c−f] However, these reactions have the disadvantage of producing a mixture of tetrahydroindeno[1,2-*c*]furan-1-one and tetrahydroindeno[2,1-*b*]furan-2-one with low selectivity. Other known methods for construction of tetrahydroindeno[1,2-*c*]furan-1-ones include Michael addition of *ortho*-lithiated aryloxiranes to α,β-unsaturated malonates,[4] photoirradiated cyclization of 3-benzylfuran-2-ones,[5] and cascade cyclization of 2-(2-styrylbenzyl)malonates with iodine electrophiles.[6] All the aforementioned methods for the synthesis of tetrahydroindeno[1,2-*c*]furan-1-ones either used uncommon substrates such as lithiated aryloxiranes or inconvenient reaction conditions such as very low temperature or photoirradiation or led to the formation of two isomeric products with low regioselectivity. Therefore, the development of versatile, convenient, and efficient methods, especially enantioselective reactions, for the construction of tetrahydroindeno[1,2-*c*]furan-1-one ring is highly desirable and of importance.

In 2004, Glorius[7a] and Bode[8] independently reported the N-heterocyclic carbene (NHC)-catalyzed reactions of α,β-unsaturated aldehydes with aromatic aldehydes and electron-deficient ketones, which produced γ-butyrolactones (dihydrofuran-2-ones) via a formal [3 + 2] annulation between the homoenolate intermediates and the carbonyls of substrates. While using NHC as a sole catalyst, the [3 + 2] annulation of enals with aldehydes and ketones generally gives lower chemical yields and/or steroselectivity.[7,8] In recent years, a few studies on the NHC/Lewis acid or Brønsted acid cooperative mediated reactions between α,β-unsaturated aldehydes (including enals and ynals) and carbonyl compounds have been reported to produce dihydrofuran-2-ones or furan-2-one derivatives.[9] The cooperative catalysis involving NHCs/Lewis or Brønsted acids has been demonstrated to enhance the reactivity of substrates[9c] and even to incorporate previously inactive reaction partners,[9a] and to improve enantioselectivity or diastereoselectivity.[9b,d,e]

2-Aroylvinylcinnamaldehydes are a kind of aromatic *o*-vinyl enals. Under the catalysis of a triazole carbene alone or a combination of a triazole carbene and an oxidant, the 2-aroylvinylcinnamaldehydes reacted with 2-aroylvinylchalcones (the aromatic *o*-bisenones), β-diketones, or α,β-unsaturated imines to produce various 9-substituted indeno[2,1-*c*]pyran-1-ones or indenocyclopentan-1-one derivatives via different types of cascade Michael addition and lactonization reactions.[10] While in the absence of a reaction partner, the 2-aroylvinylcinnamaldehydes underwent intramolecular Michael addition and lactonization to afford indeno[2,1-*c*]pyran-1-ones under the catalysis of a chiral triazole carbene.[11] Very recently, we have discovered that the addition of $Ti(OPr\text{-}i)_4$ as a cocatalyst

Received: June 6, 2016
Published: August 22, 2016

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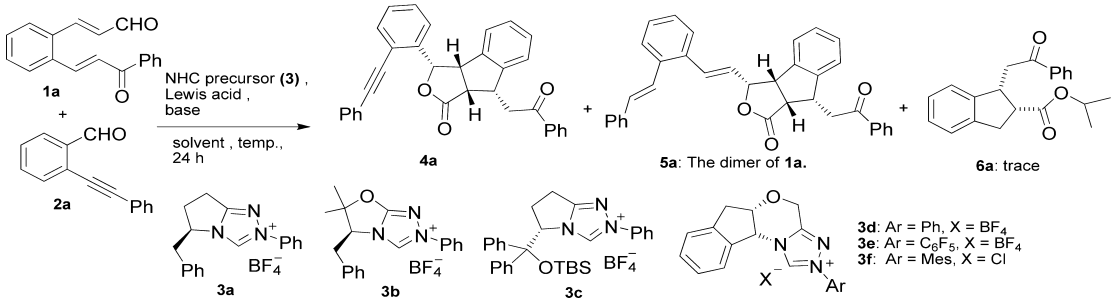
DOI: 10.1021/acs.joc.6b01362
J. Org. Chem. 2016, 81, 8276−8286

Table 1. Optimization of Reaction Conditions



									yield (%)[e]	
entry	1a:2a	3 (mol %)	Lewis acid (mol %)	base (mol %)	sol.	temp	yield of 4a (%)[c]	ee of 4a (%)[d]	5a	6a
1[a]	1:1	3f (20)	–	DBU (20)	DCM	rt	–	–	mess	
2[a]	1:1	3a (20)	Ti(OPr-*i*)$_4$ (100)	DBU (20)	DCM	rt	3	−83	20	–[f]
3[a]	1:1	3b (20)	Ti(OPr-*i*)$_4$ (100)	DBU (20)	DCM	rt	5	−93	22	–[f]
4[a]	1:1	3c (20)	Ti(OPr-*i*)$_4$ (100)	DBU (20)	DCM	rt	9	95	31	–[f]
5[a]	1:1	3d (20)	Ti(OPr-*i*)$_4$ (100)	DBU (20)	DCM	rt	3	92	31	–[f]
6[a]	1:1	3e (20)	Ti(OPr-*i*)$_4$ (100)	DBU (20)	DCM	rt	11	67	22	–[f]
7[a]	1:1	3f (20)	Ti(OPr-*i*)$_4$ (100)	DBU (20)	DCM	rt	31	>99	55	–[f]
8[b]	1:1	3f (20)	Ti(OPr-*i*)$_4$ (100)	DBU (20)	DCM	rt	59	>99	13	3
9[b]	1.5:1	3f (20)	Ti(OPr-*i*)$_4$ (100)	DBU (20)	DCM	rt	70	99	15	4
10[b]	2:1	3f (20)	Ti(OPr-*i*)$_4$ (100)	DBU (20)	DCM	rt	69	99	32	6
11[b]	1:1.5	3f (20)	Ti(OPr-*i*)$_4$ (100)	DBU (20)	DCM	rt	53	>99	12	–[f]
12[b]	1:1.5	3f (20)	Ti(OCH$_3$)$_4$ (100)	DBU (20)	DCM	rt	24	86	trace	–
13[b]	1:1.5	3f (20)	Mg(OBu-*t*)$_2$ (100)	DBU (20)	DCM	rt	13	96	trace	–
14[b]	1:1.5	3f (20)	Mg(OTf)$_2$ (100)	DBU (20)	DCM	rt	24	97	trace	–
15[b]	1:1.5	3f (20)	Sc(OTf)$_3$ (100)	DBU (20)	DCM	rt	18	98	trace	–
16[b]	1:1.5	3f (20)	LiCl (100)	DBU (20)	DCM	rt	20	90	trace	–
17[b]	1.5:1	3f (20)	Ti(OPr-*i*)$_4$ (100)	DIPEA (20)	DCM	rt	35	99	53	–[f]
18[b]	1.5:1	3f (20)	Ti(OPr-*i*)$_4$ (100)	Cs_2CO_3 (20)	DCM	rt	22	99	60	–[f]
19[b]	1.5:1	3f (10)	Ti(OPr-*i*)$_4$ (100)	NaH (20)	DCM	rt	29	99	50	–[f]
20[b]	1.5:1	3f (20)	Ti(OPr-*i*)$_4$ (100)	*t*-BuOK (20)	DCM	rt	32	99	44	–[f]
21[b]	**1.5:1**	**3f (20)**	**Ti(OPr-*i*)$_4$ (100)**	**DBU (50)**	**DCM**	**rt**	**76**	**>99**	**19**	**5**
22[b]	1.5:1	3f (20)	Ti(OPr-*i*)$_4$ (100)	DBU (50)	THF	rt	29	99	27	–[f]
23[b]	1.5:1	3f (20)	Ti(OPr-*i*)$_4$ (100)	DBU (50)	dioxane	rt	48	98	17	–[f]
24[b]	1.5:1	3f (20)	Ti(OPr-*i*)$_4$ (100)	DBU (50)	benzene	rt	53	99	38	–[f]
25[b]	1.5:1	3f (20)	Ti(OPr-*i*)$_4$ (100)	DBU (50)	CH_3CN	rt	73	99	18	–[f]
26[b]	1.5:1	3f (20)	Ti(OPr-*i*)$_4$ (100)	DBU (50)	DCM	0 °C	45	99	58	–[f]
27[b]	1.5:1	3f (20)	Ti(OPr-*i*)$_4$ (100)	DBU (50)	DCM	reflux	67	99	20	–[f]

[a]Method A: Under a nitrogen atmosphere, substrate **1a** (0.5 mmol), **2a** (0.5 mmol), and NHC precursor **3** (0.1 mmol) were dissolved in dry dichloromethane (10 mL). To the resulting mixture, Ti(OPr-*i*)$_4$ (0.5 mmol) and DBU (0.1 mmol) were added respectively using a microsyringe. The reaction mixture was then stirred at room temperature for 24 h. [b]Method B: Under a nitrogen atmosphere, NHC precursor **3f** (0.1 mmol) and a base (0.25 mmol) were mixed in dry dichloromethane (5 mL) in a flask, while the aldehyde **1a** (0.5−1 mmol), **2a** (0.5−1 mmol), and Ti(OPr-*i*)$_4$ (0.5 mmol) were dissolved in dry dichloromethane (5 mL) in a dropping funnel. The solution of reactants **1a**, **2a**, and Ti(OPr-*i*)$_4$ in DCM was added dropwise to the mixture of catalyst **3f** and a base in DCM over 1 h. Then the reaction mixture was stirred at room temperature for 24 h. [c]Isolated yield that was calculated based on the loading of nonexcess substrate **2a**. [d]Determined by HPLC analysis on an AD-H column. [e]Isolated yield that was calculated based on the loading of **1a**. [f]A trace amount of **6a** was detected without isolation.

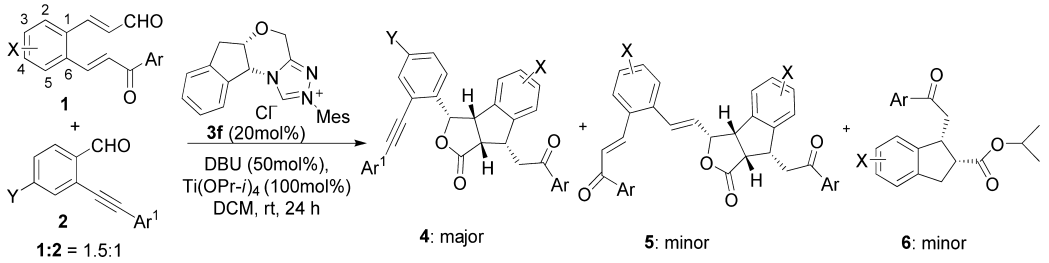
switches the reaction pathway of otherwise the same chiral triazole carbene catalyzed reaction of 2-aroylvinylcinnamaldehydes from the intramolecular cyclization to the intermolecular dimerization, leading to the formation of tetrahydroindeno[1,2-*c*]furan-1-one derivatives in good yields with excellent enantioselectivity.[12] We envisioned that the cooperative NHC/Lewis acid catalyzed reaction between 2-aroylvinylcinnamaldehydes and aldehydes probably could also be developed into a versatile strategy for the construction of tetrahydroindeno[1,2-*c*]furan-1-ones in an enantioselective fashion. Herein, we report a systematic study on the NHC/Lewis acid catalyzed reaction of 2-aroylvinylcinnamaldehydes with various aromatic aldehydes.

RESULTS AND DISCUSSION

We commenced our study by investigating the reaction between 2-aroylvinylcinnamaldehydes **1** and *o*-alkynyl benzaldehydes **2**. 2-Benzoylvinylcinnamaldehyde **1a** and 2-(phenylethynyl)benzaldehyde **2a** were employed as the model substrates to optimize the reaction conditions. We first examined the reaction between 2-benzoylvinylcinnamaldehyde **1a** and 2-(phenylethynyl)benzaldehyde **2a** catalyzed by a chiral triazole carbene alone, which was generated from the tetracyclic triazolium salt **3f** and DBU in dichloromethane at room temperature. It was found that, while most of the 2-(phenylethynyl)benzaldehyde **2a** was unconsumed, all of the 2-benzoylvinylcinnamaldehyde **1a** was converted into messy

DOI: 10.1021/acs.joc.6b01362
J. Org. Chem. 2016, 81, 8276−8286

Table 2. Chiral Triazole Carbene/Ti(OPr-*i*)$_4$-Catalyzed Reaction of 2-Aroylvinylcinnamaldehydes 1 with *o*-Alkynyl Benzaldehydes 2



entry	1	X	Ar	2	Y	Ar^1	yield of 4 (%)[c]	ee of 4 (%)[d]	yield (%)[e] 5	yield (%)[e] 6[f]
1[a]	**1a**	H	Ph	**2a**	H	Ph	**4a**: 76	>99	**5a**: 19	**6a**: 5
2[b]	**1a**	H	Ph	**2a**	H	Ph	**4a**: 54[g]	>99	**5a**: 20	**6a**: 14
3[a]	**1a**	H	Ph	**2b**	F	Ph	**4b**: 72	98	**5a**: 30	**6a**: 11
4[a]	**1a**	H	Ph	**2c**	Me	Ph	**4c**: 63	>99	**5a**: 29	**6a**: 10
5[a]	**1a**	H	Ph	**2d**	OMe	Ph	**4d**: 57	96	**5a**: 29	**6a**: 7
6[a]	**1a**	H	Ph	**2e**	H	*p*-FC$_6$H$_4$	**4e**: 74	>99	**5a**:20	**6a**: 8
7[a]	**1a**	H	Ph	**2f**	H	*p*-MeC$_6$H$_4$	**4f**: 78	99	**5a**: 17	**6a**: 8
8[a]	**1a**	H	Ph	**2g**	H	*p*-MeOC$_6$H$_4$	**4g**: 80	98	**5a**: 22	**6a**: 6
9[a]	**1a**	H	Ph	**2h**	H	H	**4h**: 75	>99	**5a**: 17	**6a**: 11
10[a]	**1b**	4-F	Ph	**2a**	H	Ph	**4i**: 63	>99	**5b**: 20	trace
11[a]	**1c**	4-Me	Ph	**2a**	H	Ph	**4j**: 60	>99	**5c**: 26	trace
12[a]	**1d**	4-OMe	Ph	**2a**	H	Ph	**4k**: 42	>99	**5d**: 39	**6d**: 7
13[a]	**1e**	3-F	Ph	**2a**	H	Ph	**4l**: 82	>99	**5e**: 14	**6e**: 11
14[a]	**1f**	3-Me	Ph	**2a**	H	Ph	**4m**: 79/73[h]	99	**5f**: 21/19[h]	**6f**: 8/–
15[a]	**1g**	3-OMe	Ph	**2a**	H	Ph	**4n**: 81/74[h]	>99	**5g**: 16/25[h]	**6g**: 5/–
16[a]	**1h**	H	4-BrC$_6$H$_4$	**2a**	H	Ph	**4o**:64	>99	**5h**:13	**6h**: 8
17[a]	**1i**	H	4-MeC$_6$H$_4$	**2a**	H	Ph	**4p**: 68	>99	**5i**: 29	**6i**: 8
18[b]	**1i**	H	4-MeC$_6$H$_4$	**2a**	H	Ph	**4p**: 58[g]	>99	**5i**: 24	**6i**: 15
19[a]	**1j**	H	4-MeOC$_6$H$_4$	**2a**	H	Ph	**4q**: 51	99	**5j**: 13	trace

[a]Method B: Under a nitrogen atmosphere, NHC precursor **3f** (0.1 mmol) and DBU (0.25 mmol) were mixed in dry dichloromethane (5 mL) in a flask, while the enals **1** (0.75 mmol), aldehydes **2** (0.5 mmol), and Ti(OPr-*i*)$_4$ (0.5 mmol) were dissolved in dry dichloromethane (5 mL) in a dropping funnel. The solution of reactants **1**, **2**, and Ti(OPr-*i*)$_4$ in DCM was added dropwise to the mixture of catalyst **3f** and DBU in DCM over 1 h. Then the reaction mixture was stirred at room temperature for 24 h. [b]Method C: Under a nitrogen atmosphere, the NHC precursor **3f** (0.1 mmol), *o*-alkynyl benzaldehydes 2 (0.5 mmol), and Ti(OPr-*i*)$_4$ (0.25 mmol) were mixed in dry dichloromethane (5 mL) in a flask, and DBU (0.25 mmol) was added using a microsyringe. The 2-aroylvinylcinnamaldehydes **1** (0.75 mmol) and Ti(OPr-*i*)$_4$ (0.25 mmol) were dissolved in dry dichloromethane (5 mL). The solution of enals **1** and Ti(OPr-*i*)$_4$ in DCM was added dropwise to the flask using a syringe pump over 2 h. The resulting reaction mixture was stirred at room temperature for 24 h. [c]The isolated yields of major products **4** were calculated based on the loading of *o*-alkynyl benzaldehydes **2**. [d]Determined by HPLC analysis on an AD-H or OD-H column. The details of HPLC separation conditions for each product **4** have been listed in the Supporting Information. [e]The isolated yields of byproducts **5** and **6** were calculated based on the loading of 2-aroylvinylcinnamaldehydes **1**. [f]Except for **6a** and **6h** that were characterized by IR, ^{1}H NMR, ^{13}C NMR, and HRMS, other **6** compounds were not fully characterized. [g]Under the conditions of method C, the *α*-diketone **7a** derived from aldehyde **2a** was also isolated in 18–20% yields. [h]The reaction time was 12 h.

products under these conditions. The reaction of **1a** with **2a** was then studied by using the cooperative catalysis of chiral N-heterocyclic carbenes and Lewis acids. Initially, the substrates **1a** and **2a** (0.5 mmol, **1a**:**2a** = 1:1) and NHC precursors **3** (20 mol %) were dissolved in dry dichloromethane (10 mL) in a flask, followed by the addition of DBU (20 mol %) and Ti(OPr-*i*)$_4$ (100 mol %) using a microsyringe. The resulting reaction mixture was stirred at ambient temperature for 24 h (Method A). It was found that the reactions catalyzed by the combination of Ti(OPr-*i*)$_4$ and bicyclic triazolium salts **3a**–**3c** or *N*-phenyl- and *N*-perfluorophenyl substituted tetracyclic triazolium salts **3d** and **3e** produced only 20%–31% yields of **5a**, a dimer of 2-benzoylvinylcinnamaldehyde **1a**, along with a trace amount of product **4a** (3%–11%) that was derived from the interaction of **1a** with **2a** (Table 1, entries 1–5). However, the reaction of **1a** with **2a** catalyzed by the *N*-mesityltriazolium substituted tetracyclic triazolium salt **3f** and Ti(OPr-*i*)$_4$ produced the targeted product **4a** and dimer **5a** in 31% and 55% yields, respectively (Table 1, entry 6). It was noted that the dimerization reaction of 2-benzoylvinylcinnamaldehyde **1a** proceeded much fast than the reaction between **1a** and **2a**. On the other hand, we also found that the aldehyde **2a** undergo slow benzoin reaction to produce a *α*-hydroxylketone (36%) or an *α*-diketone (the bis(*o*-phenylethynyl)benzil, 63%), the latter being the aerobic oxidation product of the former one, under the catalysis of NHC **3f** alone or **3f** and Ti(OPr-*i*)$_4$ in the absence of enal **1a**. (The formations of *α*-diketones from the NHC-catalyzed reactions of aldehydes have been documented in literature.[13]) We thought that the slow addition of **1a** into the catalysts could probably inhibit the formation of dimer **5a**. Thus, we repeated the reaction of **1a** with **2a** catalyzed by triazolium salt **3f** and Ti(OPr-*i*)$_4$ with the changes of reaction conditions as follows: The NHC precursor **3f** (20 mol %) and DBU (20 mol %) were mixed in dry dichloromethane (5 mL)

DOI: 10.1021/acs.joc.6b01362
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in a flask, while aldehydes **1a**, **2a** (0.5 mmol, **1a:2a** = 1:1), and Ti(OPr-*i*)$_4$ (100 mol %) were dissolved in dry dichloromethane (5 mL) in a dropping funnel. The solution of **1a**, **2a**, and Ti(OPr-*i*)$_4$ in DCM was added dropwise to the mixture of catalyst **3f** and base in DCM over 1 h. The resulting reaction mixture was stirred at room temperature for 24 h (Method B). Delightfully, the expected product **4a** was isolated in 59% yield with excellent enantioselectivity, along with the formation of a 13% yield of dimer **5a** (Table 1, entry 7). The reaction conditions were then further optimized by carrying out the reaction as described in method B. It was found that the utilization of 1.5 equiv of enal **1a** increased the yield of **4a** to 70% with 99% ee (Table 1, entry 8). However, further increasing the loading of **1a** to 2 equiv has a negligible effect on the yield of **4a**, but leading to the formation of more dimer **5a** (Table 1, entry 9). On the other hand, the use of excess aldehyde **2a** (**1a:2a** = 1:1.5) was not beneficial to the formation of **4a** because much of **2a** was not converted (Table 1, entry 10). The variation of Lewis acids indicated that Ti(OMe)$_4$, Mg(OBu-*t*)$_2$, Mg(OTf)$_2$, Sc(OTf)$_3$, and LiCl were not efficient promoters for this reaction, as very low yields of product **4a** were isolated from the reactions under the catalysis of the combination of **3f** with each of these Lewis acids (Table 1, entries 11−15). The replacement of DBU with DIPEA, Cs_2CO_3, NaH, or *t*-BuOK all led to diminished yields of the product **4a** (Table 1, entries 16−19). Increasing the loading of DBU to 50 mol % slightly improved the yield of **4a** to 76% (>99% ee) (Table 1, entry 20). The employment of other solvents such as THF, 1,4-dioxane, benzene, and acetonitrile all decreased the yields of the product **4a** (Table 1, entries 21−24). In dichloromethane, either lowering the reaction temperature to 0 °C or raising it to the boiling point of solvent did not have a beneficial effect (Table 1, entries 25 and 26). It was worth noting that, under the catalysis of chiral triazolium salt **3f** and Ti(OPr-*i*)$_4$, the reaction of **1a** with **2a** has excellent enantioselectivity under all examined reaction conditions (98% → 99% ee). In addition to the product **4a** and dimer **5a**, only a trace amount of byproduct **6a**, ca. 3%−6%, that was derived from one molecule of **1a** and isopropanol was also isolated in some cases.

Under the optimized reaction conditions and mixing the substrates and catalysts as described in method B, the substrates scope was surveyed by varying a number of 2-aroylvinylcinnamaldehydes **1** and *o*-alkynyl benzaldehydes **2** attached by different substituents. First, a variety of *o*-alkynyl benzaldehydes **2** were employed to react with 2-benzoylvinylcinnamaldehyde **1a**. It was found that 2-(phenylethynyl)benzaldehyde **2a** and 4-fluoro-2-(phenylethynyl)benzaldehyde **2b** reacted with **1a** to produce the corresponding 3-(2-alkynyl)phenylindeno[1,2-*c*]furan-1-ones **4a** and **4b** in 72%−76% yields with 98% → 99% ee, while the 4-methyl- and 4-methoxy-2-(phenylethynyl)-benzaldehydes **2c** and **2d** provided the slightly lower yields of products **4c** and **4d** (57%−63% yields, 96% → 99% ee), probably due to the electron-donating *p*-substituents that reduce the reactivity of aldehydes **2** (Table 2, entries 1, 3−5). On the other hand, the arylethynyl groups of benzaldehydes **2** have a negligible effect, as the reactions of 2-((*p*-fluorophenyl)-ethynyl)- (**2e**), 2-((*p*-methylphenyl)ethynyl)- (**2f**), 2-((*p*-methoxyphenyl)ethynyl)- (**2g**) and 2-ethynylbenzaldehyde **2h** with enal **1a** all provided the corresponding products **4** in good yields with excellent enantioselectivity (74%−80% yields, 98% → 99% ee) (Table 2, entries 6−9). The reactions between different 2-aroylvinylcinnamaldehydes **1** and 2-(phenylethynyl)benzaldehyde **2a** were next examined. When reacted with aldehyde **2a**, the 4-fluoro- and 4-methyl-2-benzoylvinylcinnamaldehydes **1b** and **1c** produced moderated yields of products **4i** and **4j** (60%−63%) with >99% ee, while the 4-methoxy-2-benzoylvinylcinnamaldehyde **1d** gave a lower yield of **4k** (42%, > 99% ee), probably also due to the deactivation effect of the strong electron-donating *p*-methoxy to the enal aldehyde of **1d** (Table 2, entries 10−12). However, all reactions of 3-fluoro-, 3-methyl- and 3-methoxy-2-benzoylvinylcinnamaldehydes **1e−1g** with **2a** formed the corresponding products **4** in good yields with excellent enantioselectivity (79%−82% yields, 99% → 99% ee) (Table 2, entries 13−15). Reducing the reaction time from 24 to 12 h in the reactions of **1f** and **1g** with **2a** slightly decreased the yields of products **4m** and **4n** (Table 2, entries 14 and 15). These results indicated that the substituents attached to the *para*-position of the enal group of **1** strongly influenced the outcomes of the reaction, while the *meta*-substituents of the enals **1** have a negligible effect. Finally, the effect of the aroyl groups of substrates **1** was examined. It was clear that the substituent attached to the benzoyl groups of **1** slightly decreased the efficiency of the reaction between **1** and **2**, as the reaction of 2-(*p*-bromobenzoylvinyl)-, 2-(*p*-methylbenzoylvinyl)-, and 2-(*p*-methoxybenzoylvinyl)cinnamaldehyde **1h−1j** with 2-(phenylethynyl)-benzaldehyde **2a** afforded the corresponding **4o−4q** in 51%−68% yields with 99% ee (Table 2, entries 16, 17, 19). Significantly, although products **4** have four stereogenic centers, no other diastereomers of **4** were found in all reactions. It should be mentioned that, in addition to the target products **4**, the byproducts **5** and **6** both derived from cinnamaldehydes **1** were also isolated in 13%−39% and 5%−11% yields, respectively. In some reactions, a small amount of unconsumed 2-alkynylbenzaldehydes **2** and the α-diketones **7** derived from the benzoin reaction of aldehydes **2**, and other messy minor products derived from enals **1**, were also detected without isolation.

Since there was still an appreciable amount of dimers **5** in some reactions of enals **1** with aldehydes **2**, to further minimize the side reactions of enals **1**, we altered the reaction conditions by changing the manner of mixing substrates with catalysts. Thus, the reactions of **1a** and **1i** with **2a** were repeated under the conditions as follows (Method C): Under a nitrogen atmosphere, the NHC precursor **3f** (0.1 mmol), *o*-alkynyl benzaldehydes **2** (0.5 mmol), and Ti(OPr-*i*)$_4$ (0.25 mmol) were mixed in dry dichloromethane (5 mL) in a flask, and DBU (0.25 mmol) was added using a microsyringe. The 2-aroylvinylcinnamaldehydes **1** (0.75 mmol) and Ti(OPr-*i*)$_4$ (0.25 mmol) were dissolved in dry dichloromethane (5 mL). The solution of enals **1** and Ti(OPr-*i*)$_4$ in DCM were added dropwise to the flask over 2 h using a syringe pump. The resulting reaction mixture was stirred at room temperature for 24 h. Disappointingly, under these conditions, the reactions provided lower yields of major products **4**, similar yields of dimers **5**, and higher yields of byproducts **6** compared to the reactions conducted using method B (Table 2, entries 1, 2, 17, 18). In addition, the α-diketone **7a** (bis(*o*-phenylethynyl)-benzil) that was derived from the benzoin reaction of **2a** followed by an aerobic oxidation was also isolated in 18−20% yields at this time.

The reaction between 2-aroylvinylcinnamaldehydes **1** and *o*-alkenyl benzaldehydes **8** was then studied. A number reactions of enals **1** with alkenyl substituted aldehydes **8** both attached by different groups were surveyed under the optimized conditions.

DOI: 10.1021/acs.joc.6b01362
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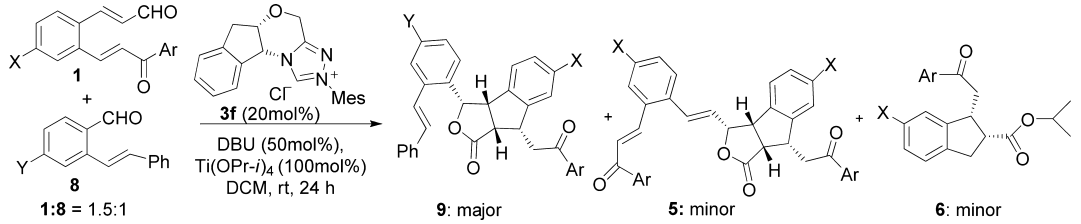
Table 3. Chiral Triazole Carbene/Ti(OPr-*i*)$_4$-Catalyzed Reaction of 2-Aroylvinylcinnamaldehydes 1 with *o*-Alkenyl Benzaldehydes 8



entry	1	X	Ar	8	Y	yield of 9 (%)[a]	ee of 9 (%)[b]	yield (%)[c] 5	6
1	**1a**	H	Ph	**8a**	H	**9a**: 69	>99	**5a**: 26	**6a**: 14
2	**1a**	H	Ph	**8b**	F	**9b**: 82	>99	**5a**: 22	**6a**: 13
3	**1a**	H	Ph	**8c**	Me	**9c**: 40	>99	**5a**: 29	**6a**: 13
4	**1a**	H	Ph	**8d**	OMe	**9d**: 46	99	**5a**: 32	**6a**: 7
5	**1b**	F	Ph	**8a**	H	**9e**: 56	99	**5b**: 21	**6b**: 4
6	**1c**	Me	Ph	**8a**	H	**9f**: 53	99	**5c**: 33	**6c**: 7
7	**1d**	OMe	Ph	**8a**	H	**9g**: 39	99	**5d**: 27	**6d**: 5
8	**1h**	H	4-BrC_6H_4	**8a**	H	**9h**: 54	97	**5h**: 24	**6h**: 6
9	**1i**	H	4-MeC_6H_4	**8a**	H	**9i**: 49	>99	**5i**: 21	**6i**: 12
10	**1j**	H	4-MeOC_6H_4	**8a**	H	**9j**: 47	>99	**5j**: 24	**6j**: 8

[a]The isolated yields of major products **9** were calculated based on the loading of *o*-alkenyl benzaldehydes **8**. [b]Determined by HPLC analysis on a AD-H or OD-H column. The details of HPLC separation conditions for each product **9** have been listed in the Supporting Information. [c]The isolated yields of byproducts **5** and **6** were calculated based on the loadings of 2-aroylvinylcinnamaldehydes **1**.

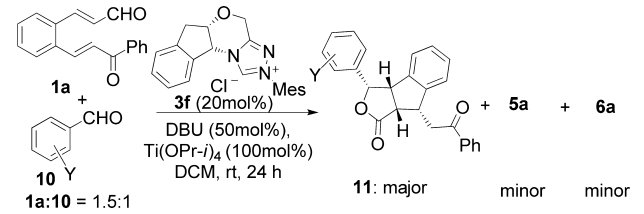
In the aforementioned reactions of 2-aroylvinylcinnamaldehydes **1** and *o*-alkynyl benzaldehydes **2**, we have found that the *m*-substituents of the enal group of **1** or the substituents attached to the ethynyl group of **2** had negligible effects to the reaction. Therefore, in this portion of work, we only varied the substituents that were attached to the *para*-position of enals **1** or benzaldehydes **8**, and to the aroyl groups of **1**. It was found that the *o*-alkenyl benzaldehydes **8** were generally less reactive than *o*-alkynyl benzaldehydes **2** in the reactions with 2-aroylvinylcinnamaldehydes **1**. As summarized in Table 3, (*E*)-2-styrylbenzaldehyde **8a** and 4-fluoro-2-styrylbenzaldehyde **8b** reacted efficiently with 2-benzoylvinylcinnamaldehyde **1a** to produce the corresponding 3-(2-alkenyl)phenyl substituted indeno[1,2-*c*]furan-1-ones **9a** and **9b** in 69% and 82% yields, respectively, both with >99% ee (Table 3, entries 1 and 2). However, the reactions of 4-methyl-2-styrylbenzaldehyde **8c** and 4-methoxy-2-styrylbenzaldehyde **8d** with enal **1a** only provided 40%−46% yields of products **9c** and **9d** (99 → 99% ee) (Table 3, entries 3 and 4). On the other hand, when the reactions of 4-fluoro- (**1b**) and 4-methyl-2-benzoylvinylcinnamaldehydes **1c** with 2-styrylbenzaldehyde **8a** produced moderated yields of products **9e** and **9f** (53%−56%, 99% ee), the 4-methoxy-2-benzoylvinylcinnamaldehydes **1d** gave only a 39% yield of **9g** (99% ee) in the reaction with **8a** under the same conditions (Table 3, entries 5−7). The outcomes suggested that the *para*-substituted electron-donating groups inactived both cinnamaldehydes **1** and styrylbenzaldehydes **8** in this NHC/Lewis acid catalyzed reaction. Variation of the aroyl groups of substrates **1** showed that the 2-(*p*-bromobenzoylvinyl)-, 2-(*p*-methylbenzoylvinyl)-, and 2-(*p*-methoxybenzoylvinyl) substituted cinnamaldehydes **1h**−**1j** have similar reactivity toward 2-styrylbenzaldehyde **8a** to produce the corresponding **9h**−**9j** in 47%−54% yields with 97% → 99% ee (Table 3, entries 8−10). In the reactions of cinnamaldehydes **1** with styrylbenzaldehydes **8**, the byproducts **5** and **6** were also isolated in 21%−33% and 4%−14% yields, respectively.

Finally, a number of aromatic aldehydes **10** bearing different substituents were employed to react with 2-benzoylvinylcinnamaldehydes **1a** under the optimized conditions for the reaction of enals **1** with *o*-alkynyl benzaldehydes **2**. Benzaldehyde **10a** and *o*-ethylbenzaldehyde **10b** were much less reactive than both 2-(phenylethynyl)benzaldehyde **2a** and 2-styrylbenzaldehyde **8a** in the reactions with **1a**. After reacting for 24 h at ambient temperature, the reaction of **10a** or **10b** with **1a** afforded the indeno[1,2-*c*]furan-1-one **11a** or **11b**, which has a similar polarity to that of enal **1a** in TLC analysis, in 52% or 49% yield with excellent enantioselectivity (Table 4, entries 1 and 2). When the strong electron-donating methoxy substituted benzaldehydes **10c**−**10e** were used as the reaction partners of **1a**, wherever the methoxy group attached to the *ortho*-, *meta*-, or *para*-position, the reaction produced the corresponding 3-(methoxyphenyl)indeno[1,2-*c*]furan-1-one **11c**−**11e** in lower yields (37%−49% yields, 97% → 99% ee) (Table 4, entries 3−5). In contrast, the reaction of **1a** with the electron-deficient *o*-bromobenzaldehyde **10f** gave a much higher yield of target product **11f** (72% yield, >99% ee) under the same conditions (Table 4, entry 6). However, while the benzaldehyde was substituted by a strong electron-withdrawing trifluoromethyl group, no further improvement was observed. As indicated in Table 4, the reactions of *o*-, *m*-, and *p*-trifluoromethylbenzaldehydes **10g**−**10i** with **1a** all produced the corresponding **11g**−**11i** in moderated yields (45%−57% yields, 94%−99% ee) (Table 4, entries 6−9). Besides the major products **11**, the minor products **5a** and **6a** were also isolated in 18%−38% and 5%−10% yields, respectively, from these reactions.

The most plausible catalytic cycle for the reaction of 2-aroylvinylcinnamaldehydes with aldehydes is depicted in Figure 1. The addition of the NHC catalyst to enals **1** forms initially homoenolate intermediates **12**. The homoenolates **12** undergo

DOI: 10.1021/acs.joc.6b01362
J. Org. Chem. 2016, 81, 8276−8286

Table 4. Chiral Triazole Carbene/Ti(OPr-*i*)$_4$-Catalyzed Reaction of 2-Benzoylvinylcinnamaldehyde 1a with Other Aromatic Aldehydes 10



entry	10	Y	yield of 11 (%)[a]	ee of 11 (%)[b]	yield (%)[c] 5	6
1	10a	H	11a: 52	>99	5a: 28	6a: 10
2	10b	*o*-Et	11b: 49	99	5a: 18	6a: 4
3	10c	*o*-OMe	11c: 44	>99	5a: 30	6a: 5
4	10d	*m*-OMe	11d: 49	97	5a: 28	6a: 6
5	10e	*p*-OMe	11e: 37	99	5a: 38	6a: 5
6	10f	*o*-Br	11f: 72	>99	5a: 20	6a: 10
7	10g	*o*-CF_3	11g: 57	99	5a: 24	6a: 8
8	10h	*m*-CF_3	11h: 45	94	5a: 27	6a: 6
9	10i	*p*-CF_3	11i: 53	99	5a: 25	6a: 7

[a]The isolated yields of major products **11** were calculated based on the loadings of aldehydes **10**. [b]Determined by HPLC analysis on a AD-H or OD-H column. The details of HPLC separation conditions for each product **11** have been listed in the Supporting Information. [c]The yields of **5a** and **6a** were calculated based on the loading of 2-benzoylvinylcinnamaldehyde **1a**.

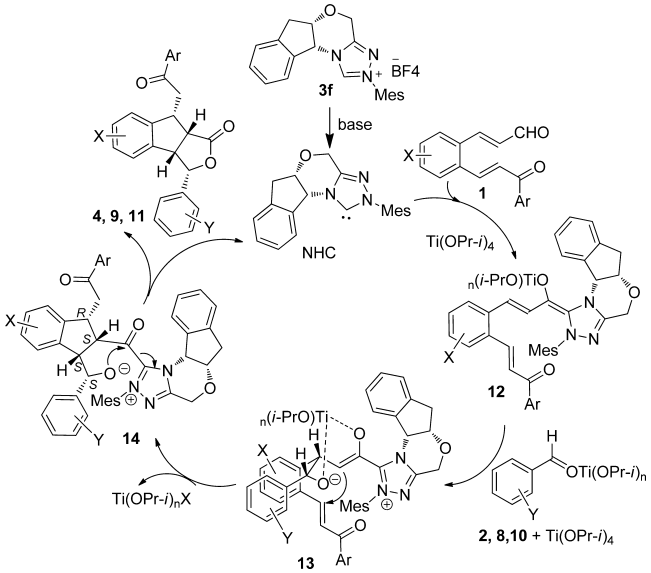


Figure 1. Plausible mechanism for the formation of (3*S*,3*aS*,8*R*,8*aS*)-8-(aroylmethyl)-3-arylindeno[1,2-*c*]furan-1-ones **4**, **9**, and **11** from the reactions of 2-aroylvinylcinnamaldehydes with aromatic aldehydes.

an intermolecular nucleophilic addition to the carbonyl groups of aldehydes **2**, **8**, or **10** that are activated by Ti(OPr-*i*)$_4$. To avoid the steric hindrance of the indane ring, the NHC-substituted homoenolates **12** attack preferentially the Si-face of aldehyde, leading to the formation of *S*-configured alcohol anions **13**. An intramolecular Michael addition of enolates to the enone species of **13**, which also occurs preferentially to the Si-face of C=C bond, yields the (1*R*,2*S*,3*S*)-trisubstituted indane intermediates **14**. Finally, the lactonization reaction of **14** produces the major products (3*S*,3*aS*,8*R*,8*aS*)-8-(aroylmethyl)-3-arylindeno[1,2-*c*]furan-1-ones **4**, **9**, or **11** (see Supporting Information for the single crystal structure of (3*S*,3*aS*,8*R*,8*aS*)-8-(4-bromobenzoyl)methyl-3-((2-styryl)phenyl)indeno[1,2-*c*]-furan-1-one **9h**). The minor products **5** are the dimers derived from the addition of homoenolates **12** to the aldehyde group of enals **1**.[12] The byproducts **6** are most likely resulted from the NHC-catalyzed intramolecular cyclization of 2-aroylvinylcinnamaldehydes **1** to form the indeno[2,1-*c*]pyran-1-one intermediates, followed by the ring opening of pyranone with isopropanol released from Ti(OPr-*i*)$_4$ (see the similar reactions in Scheidt's[11] and You's[14] reports.).

CONCLUSION

We have systematically studied the NHC/Lewis acid cocatalyzed reaction between 2-aroylvinylcinnamaldehydes and different aromatic aldehydes. It was found that, under the cooperative catalysis of a chiral triazole carbene and Ti(OPr-*i*)$_4$, the 2-aroylvinylcinnamaldehydes are able to react with either electron-rich or electron-deficient aromatic aldehydes to produce various 8-(aroylmethyl)-3-arylindeno[1,2-*c*]furan-1-ones in moderate to good yields with excellent enantio- and diastereoselectivity. To the best of our knowledge, the catalytic enantioselective methods for the efficient construction of tetrahydroindeno[1,2-*c*]furan-1-ones are very rare. The current work provides a versatile, simple, and efficient synthetic route to highly enantiomerically pure chiral multifunctional tetrahydroindeno[1,2-*c*]furan-1-ones, which are not easily prepared by other synthetic methods.

EXPERIMENTAL SECTION

General Procedure for the Enantioselective Synthesis of (3*S*,3*aS*,8*R*,8*aS*)-8-(Aroylmethyl)-3-arylindeno[1,2-*c*]furan-1-ones 4, 9, and 11. Under a nitrogen atmosphere, the NHC precursor **3f** (37 mg, 0.1 mmol) and DBU (37.5 μL, 0.25 mmol) were mixed in dry dichloromethane (5 mL) in a flask and stirred for 15 min at room temperature. In a dropping funnel, the 2-aroylvinylcinnamaldehydes **1** (0.75 mmol) and aromatic aldehydes **2**, **8**, or **10** (0.5 mmol) and Ti(OPr-*i*)$_4$ (0.5 mmol) were dissolved in dry dichloromethane (5 mL). The solution of substrate enals **1**, aldehydes **2**, **8**, or **10**, and Ti(OPr-*i*)$_4$ in DCM were added dropwise to the mixture of catalyst **3f** and DBU in DCM over 1 h. The resulting reaction mixture was stirred at room temperature for 24 h. After removal of the solvent, the residue was chromatographed on a silica gel column eluting with a mixture of petroleum ether and ethyl acetate (PE/EA from 20:1 to 5:1) to give the target products (3*S*,3*aS*,8*R*,8*aS*)-8-(aroylmethyl)-3-arylindeno[1,2-*c*]furan-1-ones **4**, **9**, and **11**. In addition, the dimers **5** (13%−39%) and a trace amount of byproducts **6** were also isolated.

(Note: The preparation and characterization of dimers **5** have been reported in our primary communication.[12])

(3*S*,3*aS*,8*R*,8*aS*)-8-(Benzoylmethyl)-3-(2-(phenylethynyl)-phenyl)-3,3a,8,8a-tetrahydroindeno[1,2-*c*]furan-1-one 4a. White solid, 176 mg, 76%, ee 99%, $[\alpha]^{20}_D$ = −159.9 (CH_2Cl_2, *c* = 0.50), mp 142−143 °C (recrystallization from AcOEt/hexane); IR *ν* (cm^{-1}) 2215 (w), 1774, 1735, 1694; ^{1}H NMR (400 MHz, $CDCl_3$) *δ* (ppm) 8.10 (d, *J* = 8.5 Hz, 2H), 7.67 (dd, *J* = 7.6, 0.7 Hz, 1H), 7.60 (tt, *J* = 7.4, 2.0 Hz, 1H), 7.54−7.56 (m, 2H), 7.51 (t, *J* = 7.2 Hz, 2H), 7.37−7.44 (m, 4H), 7.28 (td, *J* = 7.8, 1.0 Hz, 1H), 7.14−7.19 (m, 3H), 6.85 (td, *J* = 7.9, 2.4 Hz, 1H), 6.30 (d, *J* = 6.2 Hz, 1H), 5.82 (d, *J* = 7.7 Hz, 1H), 4.73 (t, *J* = 6.8 Hz, 1H), 4.14−4.20 (m, 1H), 4.01−4.09 (m, 2H), 3.55 (dd, *J* = 18.0, 4.5 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) *δ* (ppm) 199.3, 176.4, 145.2, 138.0, 137.6, 137.2, 133.0, 132.0, 131.5, 128.9, 128.63, 128.59, 128.5, 128.2, 128.1, 128.0, 126.8, 126.3, 122.8, 122.6, 120.4, 95.2, 86.3, 80.3, 48.7, 47.2, 40.3, 38.3; HRMS (TOF-ESI): $[M + H]^+$ calcd for $C_{33}H_{25}O_3$: 469.1804; found: 469.1798.

DOI: 10.1021/acs.joc.6b01362
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(3*S*,3*aS*,8*R*,8*aS*)-8-(Benzoylmethyl)-3-(4-fluoro-2-(phenylethynyl)phenyl)-3,3a,8,8a-tetrahydroindeno[1,2-*c*]furan-1-one 4b. White solid, 169 mg, 72%, ee 98%, $[\alpha]^{20}_{D}$ = −165.2 (CH_2Cl_2, *c* = 0.48), mp 146−147 °C (recrystallization from AcOEt/hexane); IR *ν* (cm^{-1}) 2205 (w), 1778, 1686; ^{1}H NMR (400 MHz, $CDCl_3$) *δ* (ppm) 8.10 (d, *J* = 7.3 Hz, 2H), 7.54−7.61 (m, 3H), 7.50 (t, *J* = 7.8 Hz, 2H), 7.41−7.44 (m, 3H), 7.37 (dd, *J* = 8.9, 2.6 Hz, 1H), 7.19 (t, *J* = 7.6 Hz, 1H), 7.16 (d, *J* = 7.7 Hz, 1H), 7.11 (dd, *J* = 8.7, 5.7 Hz, 1H), 6.98 (td, *J* = 8.4, 2.6 Hz, 1H), 6.90 (t, *J* = 7.6 Hz, 1H), 6.26 (d, *J* = 6.2 Hz, 1H), 5.89 (d, *J* = 7.7 Hz, 1H), 4.68 (t, *J* = 6.8 Hz, 1H), 4.15−4.20 (m, 1H), 4.01−4.09 (m, 2H), 3.55 (dd, *J* = 18.0, 4.6 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) *δ* (ppm) 199.3, 176.3, 162.0 (d, J_{C-F} = 246 Hz), 145.2, 137.4, 137.1, 134.1 (d, J_{C-F} = 3 Hz), 133.1, 131.6, 129.3,128.7, 128.6, 128.3 (d, J_{C-F} = 9 Hz), 128.2, 128.1, 126.9, 126.7, 123.0, 122.2, 122.1, 118.6 (d, J_{C-F} = 23 Hz), 115.8 (d, J_{C-F} = 21 Hz),96.2, 85.2 79.9, 48.8, 47.1, 40.4, 38.2; HRMS (TOF-ESI): $[M + H]^+$ calcd for $C_{33}H_{24}FO_3$: 487.1709; found: 487.1701.

(3*S*,3*aS*,8*R*,8*aS*)-8-(Benzoylmethyl)-3-(4-methyl-2-(phenylethynyl)phenyl)-3,3a,8,8a-tetrahydroindeno[1,2-*c*]-furan-1-one 4c. White solid, 152 mg, 63%, ee >99%, $[\alpha]^{20}_{D}$ = −172.2 (CH_2Cl_2, *c* = 0.50), mp 97−98 °C (recrystallization from AcOEt/hexane); IR *ν* (cm^{-1}) 1773, 1734, 1691; ^{1}H NMR (400 MHz, $CDCl_3$) *δ* (ppm) 8.10 (d, *J* = 7.3 Hz, 2H), 7.59 (t, *J* = 7.3 Hz, 1H), 7.52−7.55 (m, 3H), 7.48−7.50 (m, 2H), 7.39−7.42 (m, 3H), 7.17 (t, *J* = 7.6 Hz, 1H), 7.14 (d, *J* = 6.9 Hz, 1H), 7.08 (d, *J* = 8.0 Hz, 1H), 7.03 (d, *J* = 8.0 Hz, 1H), 6.87 (td, *J* = 7.9, 1.5 Hz, 1H),6.27 (d, *J* = 6.2 Hz, 1H), 5.89 (d, *J* = 7.8 Hz, 1H), 4.69 (t, *J* = 6.8 Hz, 1H), 4.14−4.20 (m, 1H), 4.06 (dd, *J* = 18.0, 10.8 Hz, 1H),4.00 (t, *J* = 7.9 Hz, 1H), 3.54 (dd, *J* = 17.9, 4.6 Hz, 1H), 2.41 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) *δ* (ppm) 199.4, 176.5, 145.2, 137.9, 137.7, 137.2, 135.0, 133.0, 132.5, 131.5, 129.4, 128.8, 128.62, 128.59, 128.2, 127.9, 126.9, 126.8, 126.3, 122.8, 122.7, 120.2, 94.8, 86.6, 80.4, 48.8, 47.2, 40.3, 38.3, 21.1; HRMS (TOF-ESI): $[M + H]^+$ calcd for $C_{34}H_{27}O_3$: 483.1960; found: 483.1953.

(3*S*,3*aS*,8*R*,8*aS*)-8-(Benzoylmethyl)-3-(4-methoxy-2-(phenylethynyl)phenyl)-3,3a,8,8a-tetrahydroindeno[1,2-*c*]-furan-1-one 4d. White solid, 143 mg, 57%, ee 96%, $[\alpha]^{20}_{D}$ = −188.1 (CH_2Cl_2, *c* = 0.50), mp 81−82 °C (recrystallization from AcOEt/hexane); IR *ν* (cm^{-1}) 1773, 1686; ^{1}H NMR (400 MHz, $CDCl_3$) *δ* (ppm) 8.09 (d, *J* = 7.6 Hz, 2H), 7.59 (t, *J* = 7.2 Hz, 1H), 7.54−7.55 (m, 2H), 7.50 (t, *J* = 7.4 Hz, 2H), 7.40−7.44 (m, 3H), 7.13−7.19 (m, 3H), 7.03 (d, *J* = 8.6 Hz, 1H), 6.89 (t, *J* = 7.0 Hz, 1H), 6.81 (d, *J* = 8.7 Hz, 1H), 6.26 (d, *J* = 6.0 Hz, 1H), 5.91 (d, *J* = 7.7 Hz, 1H), 4.65 (t, *J* = 6.6 Hz, 1H), 4.14−4.17 (m, 1H), 4.05 (dd, *J* = 17.9, 10.3 Hz, 1H), 4.00 (t, *J* = 7.8 Hz, 1H), 3.88 (s, 3H), 3.54 (dd, *J* = 18.0, 3.7 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) *δ* (ppm) 199.4, 176.5, 159.1, 145.2, 137.7, 137.2, 133.0, 131.6, 130.2, 129.0, 128.64, 128.59, 128.2, 128.0, 127.7, 127.0, 126.8, 122.8, 122.5, 121.3, 116.6, 114.8, 94.9, 86.3, 80.2, 55.5, 49.0, 47.2, 40.4, 38.3; HRMS (TOF-ESI): $[M + H]^+$ calcd for $C_{34}H_{27}O_4$: 499.1903; found: 499.1904.

(3*S*,3*aS*,8*R*,8*aS*)-8-(Benzoylmethyl)-3-(2-((4-fluorophenyl)-ethynyl)phenyl)-3,3a,8,8a-tetrahydroindeno[1,2-*c*]furan-1-one 4e. White solid, 181 mg, 74%, ee >99%, $[\alpha]^{20}_{D}$ = −165.4 (CH_2Cl_2, *c* = 0.50), mp 94−95 °C (recrystallization fromAcOEt/hexane); IR *ν* (cm^{-1}) 1773, 1686, 1686; ^{1}H NMR (400 MHz, $CDCl_3$) *δ* (ppm)8.09 (d, *J* = 7.6 Hz, 2H), 7.65 (d, *J* = 7.6 Hz, 1H), 7.60 (t, *J* = 7.3 Hz, 1H), 7.49−7.55 (m, 4H), 7.39 (t, *J* = 7.6 Hz, 1H), 7.28 (t, *J* = 7.7 Hz, 1H), 7.15−7.19 (m, 3H), 7.10 (t, *J* = 8.5 Hz, 2H), 6.85 (t, *J* = 6.4 Hz, 1H), 6.28 (d, *J* = 6.2 Hz, 1H), 5.81 (d, *J* = 7.7 Hz, 1H), 4.69 (t, *J* = 6.7 Hz, 1H), 4.15−4.20 (m, 1H), 4.05 (dd, *J* = 17.9, 10.1 Hz, 1H), 4.02 (t, *J* = 7.9 Hz, 1H), 3.55 (dd, *J* = 18.0, 4.4 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) *δ* (ppm) 199.3, 176.4, 162.8 (d, J_{C-F} = 249 Hz), 145.2, 138.0, 137.5, 137.1, 133.5, 133.4, 133.0, 132.0, 128.6, 128.2,128.1, 128.0, 126.8, 126.7, 126.4, 122.8,120.2, 118.7 (d, J_{C-F} = 3 Hz), 116.0 (d, J_{C-F} = 22 Hz), 94.1, 86.1, 80.2, 48.7, 47.2, 40.4, 38.2; HRMS (TOF-ESI): $[M + H]^+$ calcd for $C_{33}H_{24}FO_3$: 487.1709; found: 487.1706.

(3*S*,3*aS*,8*R*,8*aS*)-8-(Benzoylmethyl)-3-(2-(4-methylphenyl-ethynyl)phenyl)-3,3a,8,8a-tetrahydroindeno[1,2-*c*]furan-1-one 4f. White solid, 188 mg, 78%, ee 99%, $[\alpha]^{20}_{D}$ = −155.6 (CH_2Cl_2, *c* = 0.50), mp 92−93 °C (recrystallization from AcOEt/hexane); IR *ν* (cm^{-1}) 2212 (w), 1772, 1685; ^{1}H NMR (400 MHz, $CDCl_3$) *δ* (ppm) 8.10 (d, *J* = 8.5 Hz, 2H), 7.65 (d, *J* = 7.6 Hz, 1H), 7.59 (tt, *J* = 7.3, 2.0 Hz, 1H), 7.51 (t, *J* = 7.8 Hz, 2H),7.44 (d, *J* = 8.1 Hz, 2H), 7.38 (td, *J* = 7.5, 1.1 Hz, 1H), 7.26 (td, *J* = 8.3, 1.1 Hz, 1H), 7.21 (d, *J* = 7.9 Hz, 2H), 7.14−7.18 (m, 3H), 6.84 (td, *J* = 7.9, 2.4 Hz, 1H), 6.30 (d, *J* = 6.2 Hz, 1H), 5.83 (d, *J* = 7.8 Hz, 1H), 4.72 (t, *J* = 6.8 Hz, 1H), 4.15−4.20 (m, 1H), 4.06 (dd, *J* = 18.0, 10.0 Hz, 1H), 4.01 (t, *J* = 8.0 Hz, 1H), 3.55 (dd, *J* = 18.0, 4.6 Hz, 1H), 2.40 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) *δ* (ppm) 199.4, 176.5, 145.2, 139.2, 138.0, 137.7, 137.2, 133.1, 131.9, 131.4, 129.4, 128.6, 128.3, 128.2, 128.1, 128.0, 126.8, 126.3, 122.8, 120.6, 119.6, 95.5, 85.8, 80.3, 48.7, 47.2, 40.4, 38.3, 21.6;HRMS (TOF-ESI): $[M + H]^+$ calcd for $C_{34}H_{27}O_3$: 483.1960; found: 483.1958.

(3*S*,3*aS*,8*R*,8*aS*)-8-(Benzoylmethyl)-3-(2-((4-methoxy-phenyl)ethynyl)phenyl)-3,3a,8,8a-tetrahydroindeno[1,2-*c*]-furan-1-one 4g. White solid, 198 mg, 80%, ee 98%, $[\alpha]^{20}_{D}$ = −165.5 (CH_2Cl_2, *c* = 0.50), mp 63−64 °C (without recrystallization); IR *ν* (cm^{-1}) 2203 (w), 1773, 1692; ^{1}H NMR (400 MHz, $CDCl_3$) *δ* (ppm) 8.10 (d, *J* = 7.6 Hz, 2H), 7.64 (d, *J* = 7.6 Hz, 1H), 7.59 (t, *J* = 7.2 Hz, 1H), 7.48−7.52 (m, 4H), 7.37 (t, *J* = 7.4 Hz, 1H), 7.25 (t, *J* = 7.6 Hz, 1H), 7.14−7.18 (m, 3H), 6.93 (d, *J* = 8.3 Hz, 2H), 6.85 (t, *J* = 5.7 Hz, 1H), 6.29 (d, *J* = 6.0 Hz, 1H), 5.83 (d, *J* = 7.7 Hz, 1H), 4.72 (t, *J* = 6.6 Hz, 1H),4.15−4.17 (m, 1H), 4.06 (dd, *J* = 18.0, 10.1 Hz, 1H), 4.02 (t, *J* = 7.8 Hz, 1H), 3.85 (s, 3H), 3.55 (dd, *J* = 17.9, 4.1 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) *δ* (ppm) 199.4, 176.5, 160.1, 145.2, 137.8, 137.7, 137.2, 133.0, 131.8, 128.6, 128.19, 128.15, 128.1, 128.0, 126.81, 126.78, 126.3, 122.8, 120.8, 114.7, 114.3, 95.4, 85.2, 80.3, 55.4, 48.7, 47.2, 40.4, 38.3; HRMS (TOF-ESI): $[M + H]^+$ calcd for $C_{34}H_{27}O_4$: 499.1909; found: 499.1902.

(3*S*,3*aS*,8*R*,8*aS*)-8-(Benzoylmethyl)-3-(2-ethynylphenyl)-3,3a,8,8a-tetrahydroindeno[1,2-*c*]furan-1-one 4h. White solid, 147 mg, 75%, ee >99%, $[\alpha]^{20}_{D}$ = −217.0 (CH_2Cl_2, *c* = 0.50), mp 165−166 °C (recrystallization from AcOEt/hexane); IR *ν* (cm^{-1}) 3229, 2102, 1767, 1680; ^{1}H NMR (400 MHz, $CDCl_3$) *δ* (ppm) 8.10 (d, *J* = 8.5 Hz, 2H), 7.64 (dd, *J* = 7.6, 1.0 Hz, 1H), 7.60 (tt, *J* = 7.4, 2.0 Hz, 1H), 7.51 (t, *J* = 7.5 Hz, 2H), 7.36 (td, *J* = 7.5, 1.1 Hz, 1H), 7.28 (td, *J* = 7.7, 1.1 Hz, 1H), 7.15−7.18 (m, 2H), 7.12 (d, *J* = 7.8 Hz, 1H), 6.81−6.85 (m, 1H), 6.23 (d, *J* = 6.2 Hz, 1H), 5.73 (d, *J* = 7.7 Hz, 1H), 4.68 (t, *J* = 6.8 Hz, 1H), 4.14−4.20 (m, 1H), 4.05 (dd, *J* = 18.0, 10.0 Hz, 1H), 4.00 (t, *J* = 8 Hz, 1H), 3.55 (dd, *J* = 18.0, 4.7 Hz, 1H), 3.46 (s, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) *δ* (ppm) 199.3, 176.5, 145.2, 138.7, 137.5, 137.1, 133.1, 132.7, 129.0, 128.6, 128.2, 128.1, 128.0, 126.8, 126.7, 126.4, 122.8, 119.2, 83.2, 80.9, 80.0, 48.5, 47.1, 40.3, 38.3; HRMS (TOF-ESI): $[M + H]^+$ calcd for $C_{27}H_{21}O_3$: 393.1491; found: 393.1486.

(3*S*,3*aS*,8*R*,8*aS*)-8-(Benzoylmethyl)-6-fluoro-3-(2-(phenyl-ethynyl)phenyl)-3,3a,8,8a-tetrahydroindeno[1,2-*c*]furan-1-one 4i. White solid, 153 mg, 63%, ee >99%, $[\alpha]^{20}_{D}$ = −148.1 (CH_2Cl_2, *c* = 0.45), mp 87−88 °C (recrystallization from AcOEt/hexane); IR *ν* (cm^{-1}) 1773, 1686; ^{1}H NMR (400 MHz, $CDCl_3$) *δ* (ppm) 8.09 (d, *J* = 7.6 Hz, 2H), 7.67 (d, *J* = 7.6 Hz, 1H), 7.60 (t, *J* = 7.3 Hz, 1H), 7.55−7.58 (m, 2H), 7.51 (t, *J* = 7.5 Hz, 2H), 7.37−7.41 (m, 4H), 7.28 (t, *J* = 7.7 Hz, 1H), 7.16 (d, *J* = 7.8 Hz, 1H), 6.84 (d, *J* = 8.6 Hz, 1H), 6.55 (t, *J* = 8.5 Hz, 1H), 6.28 (d, *J* = 6.1 Hz, 1H), 5.74 (dd, *J* = 8.2, 5.4 Hz, 1H), 4.67 (t, *J* = 6.6 Hz, 1H), 4.13−4.18 (m, 1H), 4.02−4.10 (m, 2H), 3.48 (dd, *J* = 17.7, 4.1 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) *δ* (ppm) 198.9, 176.1, 163.0 (d, J_{C-F} = 245 Hz), 147.6 (d, J_{C-F} = 8 Hz), 137.8, 137.0, 133.2, 133.0 (d, J_{C-F} = 2 Hz), 132.0, 131.5, 129.0, 128.64 (d, J_{C-F} = 1 Hz), 128.57, 128.23, 128.19, 128.0, 127.9, 126.3, 122.5, 120.4, 114.0 (d, J_{C-F} = 22 Hz), 110.0 (d, J_{C-F} = 22 Hz), 95.3, 86.2, 80.2, 48.1, 47.7, 40.3, 38.1; HRMS (TOF-ESI): $[M + H]^+$ calcd for $C_{33}H_{24}FO_3$: 487.1709; found: 487.1706.

(3*S*,3*aS*,8*R*,8*aS*)-8-(Benzoylmethyl)-6-methyl-3-(2-(phenylethynyl)phenyl)-3,3a,8,8a-tetrahydroindeno[1,2-*c*]-furan-1-one 4j. White solid, 144 mg, 60%, ee >99%, $[\alpha]^{20}_{D}$ = −236.1 (CH_2Cl_2, *c* = 0.50), mp 175−176 °C (recrystallization from AcOEt/hexane); IR *ν* (cm^{-1}) 1765, 1690; ^{1}H NMR (400 MHz, $CDCl_3$) *δ* (ppm) 8.11 (d, *J* = 7.6 Hz, 2H), 7.67 (d, *J* = 7.6 Hz, 1H), 7.60 (t, *J* = 7.3 Hz, 1H), 7.55−7.58 (m, 2H), 7.51 (t, *J* = 7.6 Hz, 2H), 7.37−7.40 (m, 4H), 7.28 (t, *J* = 7.7 Hz, 1H), 7.18 (d, *J* = 7.8 Hz, 1H), 6.96 (s, 1H), 6.67 (d, *J* = 7.8 Hz, 1H), 6.28 (d, *J* = 6.1 Hz, 1H), 5.70 (d, *J* = 7.9

DOI: 10.1021/acs.joc.6b01362
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Hz, 1H), 4.69 (t, J = 6.6 Hz, 1H), 4.11−4.17 (m, 1H), 3.99−4.09 (m, 2H), 3.54 (dd, J = 17.6, 3.8 Hz, 1H), 2.26 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 199.4, 176.5, 145.3, 138.1, 137.9, 137.2, 134.6, 133.0, 131.9, 131.5, 128.9, 128.61, 128.57, 128.5, 128.2, 128.0, 127.7, 126.4, 126.3, 123.4, 122.6, 120.4, 95.2, 86.4, 80.3, 48.4, 47.4, 40.2, 38.3, 21.3; HRMS (TOF-ESI): $[M + H]^+$ calcd for $C_{34}H_{27}O_3$: 483.1960; found: 483.1957.

(3*S*,3*aS*,8*R*,8*aS*)-8-(Benzoylmethyl)-6-methoxy-3-(2-(phenylethynyl)phenyl)-3,3a,8,8a-tetrahydroindeno[1,2-*c*]furan-1-one 4k. White solid, 105 mg, 42%, ee >99%, $[\alpha]^{20}_D$ = −240.2 (CH_2Cl_2, c = 0.50), mp 152−153 °C (recrystallization from AcOEt/hexane); IR ν (cm^{-1}) 1765, 1690; ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.10 (d, J = 7.6 Hz, 2H), 7.66 (d, J = 7.6 Hz, 1H), 7.59 (t, J = 7.3 Hz, 1H), 7.55−7.58 (m, 2H),7.50 (t, J = 7.5 Hz, 2H), 7.36−7.43 (m, 4H), 7.28 (t, J = 7.6 Hz, 1H), 7.17 (d, J = 7.8 Hz, 1H), 6.67 (s, 1H), 6.40 (d, J = 8.4 Hz, 1H), 6.26 (d, J = 6.0 Hz, 1H), 5.70 (d, J = 8.5 Hz, 1H), 4.66 (t, J = 6.6 Hz, 1H), 4.10−4.16 (m, 1H), 4.00−4.10 (m, 2H), 3.71 (s, 3H), 3.50 (dd, J = 17.4, 3.5 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 199.3, 176.5, 159.9, 146.8, 138.2, 137.2, 133.0, 131.9, 131.5, 129.5, 128.9, 128.61, 128.59, 128.5, 128.2, 128.0, 127.4, 126.3, 122.6, 120.3, 112.8, 108.2, 95.2, 86.4, 80.3, 55.3, 48.0, 47.7, 40.4, 38.2; HRMS (TOF-ESI): $[M + H]^+$ calcd for $C_{34}H_{27}O_4$: 499.1909; found: 499.1902.

(3*S*,3*aS*,8*R*,8*aS*)-8-(Benzoylmethyl)-5-fluoro-3-(2-(phenylethynyl)phenyl)-3,3a,8,8a-tetrahydroindeno[1,2-*c*]-furan-1-one 4l. White solid, 198 mg, 82%, ee >99%, $[\alpha]^{20}_D$ = −160.1 (CH_2Cl_2, c = 0.50), mp 115−116 °C (recrystallization from AcOEt/hexane); IR ν (cm^{-1}) 1773, 1686; ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.09 (d, J = 7.5 Hz, 2H), 7.68 (d, J = 7.5 Hz, 1H), 7.60 (t, J = 7.3 Hz, 1H), 7.55−7.57 (m, 2H), 7.50 (t, J = 7.5 Hz, 2H), 7.40−7.43 (m, 4H), 7.31 (t, J = 7.6 Hz, 1H), 7.18 (d, J = 7.8 Hz, 1H), 7.07 (dd, J = 8.0, 5.3 Hz, 1H), 6.86 (t, J = 8.2 Hz, 1H), 6.29 (d, J = 6.1 Hz, 1H), 5.47 (d, J = 9.3 Hz, 1H), 4.69 (t, J = 6.6 Hz, 1H), 4.10−4.12 (m, 1H), 4.00−4.07 (m, 2H), 3.50 (dd, J = 17.8, 4.0 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 199.1, 176.1, 161.8 (d, J_{C-F} = 243 Hz), 140.6 (d, J_{C-F} = 2 Hz), 139.7 (d, J_{C-F} = 8 Hz), 137.5, 137.0, 133.1, 132.1, 131.5, 129.0, 128.7, 128.64, 128.62, 128.4, 128.2, 126.2, 123.7 (d, J_{C-F} = 9 Hz), 122.5, 120.3, 115.2 (d, J_{C-F} = 23 Hz), 113.7 (d, J_{C-F} = 23 Hz), 95.4, 86.2, 80.0, 48.6, 47.5, 39.8, 38.3; HRMS (TOF-ESI): $[M + H]^+$ calcd for $C_{33}H_{24}FO_3$: 487.1709; found: 487.1704.

(3*S*,3*aS*,8*R*,8*aS*)-8-(Benzoylmethyl)-5-methyl-3-(2-(phenylethynyl)phenyl)-3,3a,8,8a-tetrahydroindeno[1,2-*c*]-furan-1-one 4m. White solid, 191 mg, 79%, ee 99%, $[\alpha]^{20}_D$ = −159.1 (CH_2Cl_2, c = 0.50), mp 83−84 °C (recrystallization from AcOEt/hexane); IR ν (cm^{-1}) 1770, 1687; ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.09 (d, J = 7.4 Hz, 2H), 7.68 (d, J = 7.4 Hz, 1H), 7.59 (t, J = 7.3 Hz, 1H), 7.55−7.57 (m, 2H), 7.50 (t, J = 7.5 Hz, 2H), 7.37−7.43 (m, 4H), 7.27 (t, J = 7.7 Hz, 1H), 7.15 (d, J = 7.8 Hz, 1H), 7.02 (d, J = 7.8 Hz, 1H), 6.97 (d, J = 7.8 Hz, 1H), 6.30 (d, J = 6.2 Hz, 1H), 5.53 (s, 1H), 4.67 (t, J = 6.7 Hz, 1H), 4.10−4.15 (m, 1H), 3.98−4.06 (m, 2H), 3.52 (dd, J = 17.9, 4.4 Hz, 1H), 1.97 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 199.5, 176.6, 142.2, 138.2, 137.6, 137.2, 136.4, 133.0, 131.9, 131.5, 128.9, 128.7, 128.64, 128.59, 128.3, 128.2, 128.0, 127.6, 126.5, 122.6, 122.4, 120.4, 95.2, 86.4, 80.2, 48.6, 47.4, 40.1, 38.4, 21.1; HRMS (TOF-ESI): $[M + H]^+$ calcd for $C_{34}H_{27}O_3$: 483.1960; found: 483.1957.

(3*S*,3*aS*,8*R*,8*aS*)-8-(Benzoylmethyl)-5-methoxy-3-(2-(phenylethynyl)phenyl)-3,3a,8,8a-tetrahydroindeno[1,2-*c*]-furan-1-one 4n. White solid, 201 mg, 81%, ee >99%, $[\alpha]^{20}_D$ = −150.8 (CH_2Cl_2, c = 0.50), mp 97−98 °C (recrystallization from AcOEt/hexane); IR ν (cm^{-1}) 1769, 1684; ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.09 (d, J = 7.3 Hz, 2H), 7.68 (dd, J = 7.6, 0.9 Hz, 1H), 7.59 (td, J = 7.3, 1.2 Hz, 1H), 7.55−7.57 (m, 2H), 7.50 (t, J = 7.2 Hz, 2H), 7.40−7.45 (m, 3H), 7.38 (dd, J = 7.6, 1.3 Hz, 1H), 7.31 (td, J = 7.8, 1.2 Hz, 1H), 7.22 (d, J = 7.7 Hz, 1H), 7.02 (d, J = 8.4 Hz, 1H), 6.72 (dd, J = 8.4, 2.1 Hz, 1H), 6.29 (d, J = 6.2 Hz, 1H), 5.53 (d, J = 2.1 Hz, 1H), 4.68 (t, J = 6.6 Hz, 1H), 4.08−4.14 (m, 1H), 3.97−4.04 (m, 2H), 3.50 (dd, J = 18.0, 4.5 Hz, 1H), 3.33 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 199.4, 176.4, 158.6, 138.9, 138.1, 137.2, 137.1, 133.0, 131.9, 131.5, 129.0, 128.64, 128.58, 128.2, 128.0, 127.5, 123.3, 122.5, 120.4, 115.6, 110.7, 95.4, 86.2, 80.1, 55.0, 48.5, 47.5, 39.6, 38.5; HRMS (TOF-ESI): $[M + H]^+$ calcd for $C_{34}H_{27}O_4$: 499.1903; found: 499.1905.

(3*S*,3*aS*,8*R*,8*aS*)-8-((4-Bromobenzoyl)methyl)-3-(2-(phenylethynyl)phenyl)-3,3a,8,8a-tetrahydroindeno[1,2-*c*]-furan-1-one 4o. White solid, 175 mg, 64%, ee 99%, $[\alpha]^{20}_D$ = −126.7 (CH_2Cl_2, c = 0.50), mp 101−102 °C (recrystallization from AcOEt/hexane); IR ν (cm^{-1}) 1769, 1686; ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.95 (d, J = 8.2 Hz, 2H), 7.67 (d, J = 7.9 Hz, 1H), 7.64 (d, J = 8.3 Hz, 2H), 7.55−7.56 (m, 2H), 7.37−7.41 (m, 4H), 7.27 (t, J = 7.7 Hz, 1H), 7.15−7.19 (m, 3H), 6.85 (t, J = 7.2 Hz, 1H), 6.31 (d, J = 6.2 Hz, 1H), 5.83 (d, J = 7.8 Hz, 1H), 4.72 (t, J = 6.7 Hz, 1H), 4.13−4.19 (m, 1H), 3.96−4.02 (m, 2H), 3.49 (dd, J = 18.0, 4.4 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 198.3, 176.4, 144.9, 137.9, 137.6, 135.9, 132.0, 131.9, 131.5, 129.7, 128.9, 128.6, 128.5, 128.15, 128.12, 128.0, 126.9, 126.8, 126.3, 122.7, 122.6, 120.4, 95.2, 86.3, 80.4, 48.7, 47.0, 40.3, 38.3; HRMS (TOF-ESI): $[M + H]^+$ calcd for $C_{33}H_{24}BrO_3$: 547.0903; found: 547.0901.

(3*S*,3*aS*,8*R*,8*aS*)-8-((4-Methylbenzoyl)methyl)-3-(2-(phenylethynyl)phenyl)-3,3a,8,8a-tetrahydroindeno[1,2-*c*]-furan-1-one 4p. White solid, 164 mg, 68%, ee >99%, $[\alpha]^{20}_D$ = −163.2 (CH_2Cl_2, c = 0.50), mp 78−79 °C (recrystallization from AcOEt/hexane); IR ν (cm^{-1}) 2212 (w), 1773, 1686; ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.00 (d, J = 8.2 Hz, 2H), 7.67 (dd, J = 7.6, 0.8 Hz, 1H), 7.54−7.56 (m, 2H), 7.37−7.44 (m, 4H), 7.30 (d, J = 8.0 Hz, 2H), 7.25−7.27 (m, 1H), 7.13−7.18 (m, 3H), 6.84 (td, J = 7.8, 2.3 Hz, 1H), 6.30 (d, J = 6.2 Hz, 1H), 5.81 (d, J = 7.7 Hz, 1H), 4.72 (t, J = 6.8 Hz, 1H), 4.14−4.20 (m, 1H), 4.03 (dd, J = 18.0, 10.0 Hz, 1H), 4.01 (t, J = 8.0 Hz, 1H), 3.53 (dd, J = 18.0, 4.8 Hz, 1H), 2.44 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 199.0, 176.5, 145.3, 143.8, 138.1, 137.6, 134.7, 132.0, 131.5, 129.3, 128.9, 128.7, 128.5, 128.3, 128.1, 128.0, 126.8, 126.3, 122.9, 122.6, 120.4, 95.2, 86.4, 80.3, 48.7, 47.3, 40.4, 38.1, 21.7; HRMS (TOF-ESI): $[M + H]^+$ calcd for $C_{34}H_{27}O_3$: 483.1960; found: 483.1957.

(3*S*,3*aS*,8*R*,8*aS*)-8-((4-Methoxybenzoyl)methyl)-3-(2-(phenylethynyl)phenyl)-3,3a,8,8a-tetrahydroindeno[1,2-*c*]-furan-1-one 4q. White solid, 126 mg, 51%, ee >99%, $[\alpha]^{20}_D$ = −140.8 (CH_2Cl_2, c = 0.50), mp 86−87 °C (recrystallization from AcOEt/hexane); IR ν (cm^{-1}) 2201 (w), 1775, 1773, 1680; ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.09 (d, J = 8.0 Hz, 2H), 7.67 (d, J = 7.6 Hz, 1H), 7.54−7.55 (m, 2H), 7.37−7.41 (m, 4H), 7.27 (t, J = 7.8 Hz, 1H), 7.14−7.17 (m, 3H), 6.98 (d, J = 7.9 Hz, 2H), 6.84 (t, J = 6.6 Hz, 1H), 6.30 (d, J = 6.1 Hz, 1H), 5.82 (t, J = 7.8 Hz, 1H), 4.72 (t, J = 6.7 Hz, 1H), 4.14−4.20 (m, 1H), 3.98−4.05 (m, 2H), 3.89 (s, 3H), 3.50 (dd, J = 17.9, 4.6 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 197.8, 176.4, 163.5, 145.4, 138.1, 137.6, 131.9, 131.5, 130.4, 130.2, 128.9, 128.6, 128.5, 128.1, 128.0, 126.73, 126.70, 126.3, 122.8, 122.6, 120.4, 113.7, 95.2, 86.3, 80.2, 55.5, 48.7, 47.3, 40.4, 37.8; HRMS (TOF-ESI): $[M + H]^+$ calcd for $C_{34}H_{27}O_4$: 499.1909; found: 499.1902.

(3*S*,3*aS*,8*R*,8*aS*)-8-(Benzoylmethyl)-3-(2-((*E*)-styryl)phenyl)-3,3a,8,8a-tetrahydroindeno[1,2-*c*]furan-1-one 9a:[12] White solid, 161 mg, 69%, ee >99%, $[\alpha]^{20}_D$ = −212.5 (CH_2Cl_2, c = 0.50), mp 162−163 °C (recrystallization from AcOEt/hexane); IR ν (cm^{-1}) 1773, 1734, 1692; ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.09 (d, J = 7.6 Hz, 2H), 7.68 (d, J = 7.7 Hz, 1H), 7.59 (t, J = 7.2 Hz, 1H), 7.48−7.55 (m, 4H), 7.39−7.43 (m, 4H), 7.32 (t, J = 7.2 Hz, 1H), 7.22 (t, J = 7.5 Hz, 1H), 7.06−7.15 (m, 4H), 6.83 (t, J = 7.2 Hz, 1H), 6.20 (d, J = 6.0 Hz, 1H), 5.72 (d, J = 7.7 Hz, 1H), 4.40 (t, J = 6.6 Hz, 1H), 4.11−4.13 (m, 1H), 3.99−4.06 (m, 2H), 3.52 (dd, J = 18.0, 3.4 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 199.3, 176.4, 145.2, 137.4, 137.1, 137.0, 135.0, 133.5, 133.1, 132.6, 128.9, 128.6, 128.5, 128.25, 128.19, 128.0, 127.7, 126.79, 126.75, 126.6, 126.3, 126.2, 124.5, 122.8, 79.4, 49.6, 47.2, 40.3, 38.3; HRMS (TOF-ESI): $[M + H]^+$ calcd for $C_{33}H_{27}O_3$: 471.1960; found: 471.1958.

(3*S*,3*aS*,8*R*,8*aS*)-8-(Benzoylmethyl)-3-(4-fluoro-2-((*E*)-styryl)-phenyl)-3,3a,8,8a-tetrahydroindeno[1,2-*c*]furan-1-one 9b. White solid, 199 mg, 82%, ee >99%, $[\alpha]^{20}_D$ = −179.2 (CH_2Cl_2, c = 0.50), mp 94−95 °C (recrystallization from AcOEt/hexane); IR ν (cm^{-1}) 1773, 1730, 1690; ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.08 (d, J = 7.7 Hz, 2H), 7.59 (t, J = 7.1 Hz, 1H), 7.53 (d, J = 8.4 Hz, 2H), 7.50 (t, J = 7.5 Hz, 2H), 7.33−7.43 (m, 5H), 7.06−7.19 (m, 4H),

DOI: 10.1021/acs.joc.6b01362
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6.86−6.93 (m, 2H),6.16 (d, J = 6.1 Hz, 1H), 5.78 (d, J = 7.8 Hz, 1H), 4.38 (t, J = 6.7 Hz, 1H), 4.11−4.16 (m, 1H), 3.98−4.05 (m, 2H), 3.52 (dd, J = 18.2, 4.0 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 199.2, 176.1, 162.8 (d, J_{C-F} = 245 Hz), 145.2, 137.10, 137.07, 136.4, 133.7, 133.1, 129.3 (d, J_{C-F} = 3 Hz), 128.9, 128.6, 128.5, 128.4, 128.2, 126.88, 126.85, 126.5, 123.2, 122.9, 114.5 (d, J_{C-F} = 21 Hz), 112.7 (d, J_{C-F} = 22 Hz), 79.0, 49.6, 47.2, 40.3, 38.3; HRMS (TOF-ESI): [M + H]$^+$ calcd for $C_{33}H_{26}FO_3$: 489.1866; found: 489.1862.

(3*S*,3*aS*,8*R*,8*aS*)-8-(Benzoylmethyl)-3-(4-methyl-2-((*E*)-styryl)phenyl)-3,3a,8,8a-tetrahydroindeno[1,2-*c*]furan-1-one 9c. White solid, 97 mg, 40%, ee >99%, $[\alpha]^{20}_D$ = −210.8 (CH_2Cl_2, c = 0.50), mp 114−115 °C (recrystallization from AcOEt/hexane); IR ν (cm^{-1}) 1773, 1732, 1690; ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.08 (d, J = 7.6 Hz, 2H), 7.59 (t, J = 7.1 Hz, 1H), 7.48−7.54 (m, 5H), 7.36−7.41 (m, 3H), 7.31 (t, J = 7.2 Hz, 1H), 7.12−7.17 (m, 3H), 6.99−7.09 (m, 1H), 7.02 (s, 1H), 6.85 (t, J = 7.3 Hz, 1H), 6.17 (d, J = 6.1 Hz, 1H), 5.78 (d, J = 7.7 Hz, 1H), 4.37 (t, J = 6.5 Hz, 1H), 4.11−4.14 (m, 1H), 3.96−4.06 (m, 2H), 3.51 (dd, J = 17.5, 3.9 Hz, 1H), 2.43 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 199.3, 176.5, 145.2, 138.1, 137.5, 137.1, 137.0, 134.8, 133.0, 132.2, 130.5, 128.8, 128.6, 128.5, 128.2, 128.1, 128.0, 126.8, 126.7, 126.4, 124.6, 122.7, 79.5, 49.6, 47.3, 40.3, 38.3, 21.3; HRMS (TOF-ESI): [M + H]$^+$ calcd for $C_{34}H_{29}O_3$: 485.2117; found: 485.2112.

(3*S*,3*aS*,8*R*,8*aS*)-8-(Benzoylmethyl)-3-(4-methoxy-2-((*E*)-styryl)phenyl)-3,3a,8,8a-tetrahydroindeno[1,2-*c*]furan-1-one 9d. White solid, 115 mg, 46%, ee >99%, $[\alpha]^{20}_D$ = −155.4 (CH_2Cl_2, c = 0.46), mp 97−98 °C (recrystallization from AcOEt/hexane); IR ν (cm^{-1}) 1773, 1728, 1686; ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.08 (d, J = 7.6 Hz, 2H), 7.59 (t, J = 7.3 Hz, 1H), 7.48−7.54 (m, 4H), 7.35−7.42 (m, 3H), 7.30 (t, J = 7.1 Hz, 1H), 7.19 (s, 1H), 7.07−7.18 (m, 3H), 7.04 (d, J = 8.6 Hz, 1H), 6.87 (t, J = 7.3 Hz, 1H), 6.76 (d, J = 8.6 Hz, 1H), 6.15 (d, J = 6.2 Hz, 1H), 5.81 (d, J = 7.7 Hz, 1H), 4.35 (t, J = 6.7 Hz, 1H), 4.10−4.16 (m, 1H), 3.96−4.05 (m, 2H), 3.89 (s, 3H), 3.51 (dd, J = 17.7, 3.7 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 199.3, 176.5, 159.6, 145.2, 137.5, 137.1, 136.8, 136.3, 133.1, 132.7, 128.9, 128.6, 128.3, 128.2, 128.0, 127.8, 126.8, 125.9, 124.4, 122.8, 113.0, 111.6, 79.4, 55.4, 49.8, 47.2, 40.3, 38.4; HRMS (TOF-ESI): [M + H]$^+$ calcd for $C_{34}H_{29}O_4$: 501.2066; found: 501.2063.

(3*S*,3*aS*,8*R*,8*aS*)-8-(Benzoylmethyl)-6-fluoro-3-(2-((*E*)-styryl)-phenyl)-3,3a,8,8a-tetrahydroindeno[1,2-*c*]furan-1-one 9e. White solid, 137 mg, 56%, ee 99%, $[\alpha]^{20}_D$ = −206.0 (CH_2Cl_2, c = 0.50), mp 96−97 °C (recrystallization from AcOEt/hexane); IR ν (cm^{-1}) 1761, 1724, 1682; ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.07 (d, J = 7.5 Hz, 2H), 7.67 (d, J = 7.6 Hz, 1H), 7.60 (t, J = 7.3 Hz, 1H), 7.49−7.54 (m, 4H), 7.37−7.42 (m, 4H), 7.32 (t, J = 7.3 Hz, 1H), 7.23 (t, J = 7.4 Hz, 1H), 7.14−7.17 (m, 1H), 6.99−7.09 (br, 1H), 6.79 (d, J = 8.4 Hz, 1H), 6.53 (t, J = 8.6 Hz, 1H), 6.18 (d, J = 6.2 Hz, 1H), 5.63 (dd, J = 8.4, 5.4 Hz, 1H), 4.35 (t, J = 6.6 Hz, 1H), 4.09−4.14 (m, 1H), 3.99−4.06 (m, 2H), 3.44 (dd, J = 18.1, 3.9 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 198.8, 176.1, 163.0 (d, J_{C-F} = 245 Hz), 147.6 (d, J_{C-F} = 8 Hz), 136.93, 136.85, 135.0, 133.22, 133.16, 132.8, 132.7, 128.9, 128.7, 128.6, 128.3, 128.2, 127.8, 127.7, 126.7, 126.3, 126.2, 124.3, 114.0 (d, J_{C-F} = 22 Hz), 110.0 (d, J_{C-F} = 22 Hz), 79.3, 48.9, 47.7, 40.2, 38.1; HRMS (TOF-ESI): [M + H]$^+$ calcd for $C_{33}H_{26}FO_3$: 489.1866; found: 489.1859.

(3*S*,3*aS*,8*R*,8*aS*)-8-(Benzoylmethyl)-6-methyl-3-(2-((*E*)-styryl)phenyl)-3,3a,8,8a-tetrahydroindeno[1,2-*c*]furan-1-one 9f. White solid, 128 mg, 53%, ee 99%, $[\alpha]^{20}_D$ = −289.9 (CH_2Cl_2, c = 0.50), mp 181−182 °C (recrystallization from AcOEt/hexane); IR ν (cm^{-1}) 1761, 1688; ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.09 (d, J = 7.2 Hz, 2H), 7.67 (d, J = 7.7 Hz, 1H), 7.59 (t, J = 7.3 Hz, 1H), 7.48−7.54 (m, 4H), 7.40 (t, J = 7.5 Hz, 4H), 7.31 (t, J = 7.3 Hz, 1H), 7.22 (t, J = 7.4 Hz, 1H), 7.16 (d, J = 7.6 Hz, 1H), 7.06 (brd, J = 15.6 Hz, 1H), 6.92 (s, 1H), 6.64 (d, J = 7.9 Hz, 1H), 6.17 (d, J = 6.2 Hz, 1H), 5.60 (d, J = 7.9 Hz, 1H), 4.36 (t, J = 6.7 Hz, 1H), 4.08−4.12 (m, 1H), 4.01 (dd, J = 17.6, 9.9 Hz, 1H), 3.98 (t, J = 8.0 Hz, 1H), 3.50 (dd, J = 17.6, 4.0 Hz, 1H), 2.24 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 199.3, 176.5, 145.3, 137.9, 137.2, 137.0, 135.0, 134.4, 133.6, 133.0, 132.6, 128.9, 128.6, 128.4, 128.2, 127.8, 127.7, 126.7, 126.34, 126.26, 126.1, 124.5, 123.4, 79.4, 49.2, 47.5, 40.1, 38.3, 21.3; HRMS (TOF-ESI): [M + H]$^+$ calcd for $C_{34}H_{29}O_3$: 485.2117; found: 485.2112.

(3*S*,3*aS*,8*R*,8*aS*)-8-(Benzoylmethyl)-6-methoxy-3-(2-((*E*)-styryl)phenyl)-3,3a,8,8a-tetrahydroindeno[1,2-*c*]furan-1-one 9g. White solid, 98 mg, 39%, ee 99%, $[\alpha]^{20}_D$ = −294.6 (CH_2Cl_2, c = 0.50), mp 178−179 °C (recrystallization from AcOEt/hexane); IR ν (cm^{-1}) 1761, 1688; ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.08 (d, J = 7.4 Hz, 2H), 7.67 (d, J = 7.6 Hz, 1H), 7.59 (t, J = 7.3 Hz, 1H), 7.48−7.54 (m, 4H), 7.40 (t, J = 7.9 Hz, 4H), 7.32 (t, J = 7.3 Hz, 1H), 7.22 (t, J = 7.5 Hz, 1H), 7.16 (d, J = 7.7 Hz, 1H), 7.06 (brd, J = 15.7 Hz, 1H), 6.62 (s, 1H), 6.38 (dd, J = 8.6, 2.1 Hz, 1H), 6.16 (d, J = 6.1 Hz, 1H), 5.60 (d, J = 8.5 Hz, 1H), 4.34 (t, J = 6.6 Hz, 1H), 4.06−4.12 (m, 1H), 3.97−4.04 (m, 2H), 3.70 (s, 3H), 3.46 (dd, J = 17.2, 3.6 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 199.2, 176.5, 159.9, 146.8, 137.1, 137.0, 135.0, 133.6, 133.0, 132.5, 129.2, 128.9, 128.6, 128.5, 128.20, 128.17, 127.7, 127.3, 126.7, 126.4, 126.1, 124.5, 112.9, 108.1, 79.4, 55.3, 48.9, 47.7, 40.3, 38.3; HRMS (TOF-ESI): [M + H]$^+$ calcd for $C_{34}H_{29}O_4$: 501.2066; found: 501.2058.

(3*S*,3*aS*,8*R*,8*aS*)-8-((4-Bromobenzoyl)methyl)-3-(2-((*E*)-styryl)phenyl)-3,3a,8,8a-tetrahydroindeno[1,2-*c*]furan-1-one 9h. White solid, 149 mg, 54%, ee 97%, $[\alpha]^{20}_D$ = −186.0 (CH_2Cl_2, c = 0.50), mp 107−108 °C (recrystallization from AcOEt/hexane); IR ν (cm^{-1}) 1773, 1692; ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.94 (d, J = 8.4 Hz, 2H), 7.67 (d, J = 7.8 Hz, 1H), 7.64 (d, J = 8.5 Hz, 2H), 7.53 (d, J = 7.5 Hz, 2H), 7.41 (d, J = 7.4 Hz, 2H), 7.39 (d, J = 7.8 Hz, 2H), 7.32 (t, J = 7.3 Hz, 1H), 7.21 (t, J = 7.5 Hz, 1H), 7.10−7.17 (m, 4H), 6.83 (t, J = 7.4 Hz, 1H), 6.20 (d, J = 6.3 Hz, 1H), 5.72 (d, J = 7.7 Hz, 1H), 4.40 (t, J = 6.8 Hz, 1H), 4.09−4.15 (m, 1H), 3.98 (t, J = 7.7 Hz, 1H), 5.95 (dd, J = 18.0, 9.6 Hz, 1H), 3.45 (dd, J = 17.9, 4.2 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 198.3, 176.4, 144.9, 137.4, 136.9, 135.8, 133.4, 132.6, 131.9, 129.7, 128.9, 128.6, 128.25, 128.16, 128.1, 127.7, 126.9, 126.73, 126.65, 126.3, 126.2, 124.5, 122.7, 79.4, 49.5, 47.1, 40.2, 38.3; HRMS (TOF-ESI): [M + H]$^+$ calcd for $C_{33}H_{26}BrO_3$: 549.1059; found: 549.1059.

(3*S*,3*aS*,8*R*,8*aS*)-8-((4-Methylbenzoyl)methyl)-3-(2-((*E*)-styryl)phenyl)-3,3a,8,8a-tetrahydroindeno[1,2-*c*]furan-1-one 9i. White solid, 119 mg, 49%, ee >99%, $[\alpha]^{20}_D$ = −195.9 (CH_2Cl_2, c = 0.50), mp 89−90 °C (recrystallization from AcOEt/hexane); IR ν (cm^{-1}) 1757, 1682; ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.99 (d, J = 8.1 Hz, 2H), 7.68 (d, J = 7.7 Hz, 1H), 7.54 (d, J = 7.5 Hz, 2H), 7.39−7.42 (m, 4H), 7.33 (t, J = 7.4 Hz, 1H), 7.30 (d, J = 8.0 Hz, 2H), 7.22 (t, J = 7.8 Hz, 1H), 7.10−7.17 (m, 4H), 6.82 (t, J = 7.4 Hz, 1H),6.20 (d, J = 6.2 Hz, 1H), 5.72 (d, J = 7.7 Hz, 1H), 4.40 (t, J = 6.8 Hz, 1H), 4.11−4.17 (m, 1H), 3.96−4.04 (m, 2H), 3.50 (dd, J = 18.0, 4.8 Hz, 1H), 2.44 (s, 3H);^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 198.8, 176.3, 145.3, 137.7, 137.0, 135.1, 134.7, 133.5, 132.6, 129.3, 128.8, 128.5, 128.3, 128.2, 128.0, 127.7, 126.7, 126.6, 126.4, 126.1, 124.5, 122.8, 79.3, 49.6, 47.3, 40.3, 38.1, 21.6; HRMS (TOF-ESI): [M + H]$^+$ calcd for $C_{34}H_{29}O_3$: 485.2111; found: 485.2113.

(3*S*,3*aS*,8*R*,8*aS*)-8-((4-Methoxybenzoyl)methyl)-3-(2-((*E*)-styryl)phenyl)-3,3a,8,8a-tetrahydroindeno[1,2-*c*]furan-1-one 9j. White solid, 117 mg, 47%, ee >99%, $[\alpha]^{20}_D$ = −220.2 (CH_2Cl_2, c = 0.50), mp 93−94 °C (recrystallization from AcOEt/hexane); IR ν (cm^{-1}) 1766, 1675; ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.08 (d, J = 8.8 Hz, 2H), 7.68 (d, J = 7.6 Hz, 1H), 7.54 (d, J = 7.5 Hz, 2H), 7.39−7.42 (m, 4H), 7.31 (t, J = 7.3 Hz, 1H), 7.21 (t, J = 7.6 Hz, 1H), 7.10−7.16 (m, 4H), 6.98 (d, J = 8.8 Hz, 2H), 6.82 (t, J = 7.2 Hz, 1H), 6.20 (d, J = 6.2 Hz, 1H), 5.72 (d, J = 7.7 Hz, 1H), 4.40 (t, J = 6.8 Hz, 1H), 4.11−4.17 (m, 1H), 3.95−4.02 (m, 2H), 3.89 (s, 3H), 3.48 (dd, J = 17.9, 4.7 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 197.7, 176.4, 163.5, 145.3, 137.3, 136.9, 135.0, 133.5, 132.6, 130.4, 130.2, 128.8, 128.5, 128.2, 128.0, 127.7, 126.7, 126.6, 126.3, 126.1, 124.5, 122.8, 113.7, 79.3, 55.5, 49.5, 47.4, 40.3, 37.8; HRMS (TOF-ESI): [M + H]$^+$ calcd for $C_{34}H_{29}O_4$: 501.2060; found: 501.2061.

(3*S*,3*aS*,8*R*,8*aS*)-8-(Benzoylmethyl)-3-phenyl-3,3a,8,8a-tetrahydroindeno[1,2-*c*]furan-1-one 11a. White solid, 96 mg, 52%, ee >99%, $[\alpha]^{20}_D$ = −210.4 (CH_2Cl_2, c = 0.50), mp 167−168 °C (recrystallization from AcOEt/hexane); IR ν (cm^{-1}) 1766, 1685; ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.10 (d, J = 7.4 Hz, 2H), 7.60 (t, J = 7.3 Hz, 1H), 7.51 (t, J = 7.5 Hz, 2H), 7.37−7.39 (m, 3H), 7.24−7.26 (m, 2H), 7.14−7.19 (m, 2H), 6.83 (t, J = 7.5 Hz, 1H), 5.89 (d, J = 6.2

DOI: 10.1021/acs.joc.6b01362
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Hz, 1H), 5.70 (d, J = 7.7 Hz, 1H), 4.32 (t, J = 6.7 Hz, 1H), 4.13−4.19 (m, 1H), 4.06 (dd, J = 18.0, 10.0 Hz, 1H), 3.97 (t, J = 7.7 Hz, 1H), 3.55 (dd, J = 18.0, 4.6 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 199.4, 176.7, 145.2, 137.3, 137.1, 135.8, 133.1, 128.6, 128.44, 128.40, 128.2, 128.1, 127.0, 126.7, 126.1, 122.8, 81.5, 50.7, 47.3, 40.3, 38.3; HRMS (TOF-ESI): $[M + H]^+$ calcd for $C_{25}H_{21}O_3$: 369.1485; found: 369.1485.

(3*S*,3*aS*,8*R*,8*aS*)-8-(Benzoylmethyl)-3-(2-ethylphenyl)-3,3a,8,8a-tetrahydroindeno[1,2-*c*]furan-1-one 11b. White solid, 97 mg, 49%, ee >99%, $[\alpha]^{20}_D$ = −199.6 (CH_2Cl_2, c = 0.50), mp 129−130 °C (recrystallization from AcOEt/hexane); IR ν (cm^{-1}) 1767, 1687, 1680; ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.10 (d, J = 8.6 Hz, 2H), 7.60 (tt, J = 7.3, 2.0 Hz, 1H), 7.51 (t, J = 7.5 Hz, 2H), 7.30−7.36 (m, 2H), 7.13−7.18 (m, 2H), 7.06−7.12 (m, 1H), 7.01 (d, J = 7.7 Hz, 1H), 6.80−6.84 (m, 1H), 6.08 (d, J = 6.2 Hz, 1H), 5.67 (d, J = 7.8 Hz, 1H), 4.38 (t, J = 6.8 Hz, 1H), 4.15−4.20 (m, 1H), 4.06 (dd, J = 18.0, 10.0 Hz, 1H), 3.99 (t, J = 8.0 Hz, 1H), 3.55 (dd, J = 18.0, 4.7 Hz, 1H), 2.73−2.91 (m, 2H), 1.37 (t, J = 7.5 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 199.4, 176.5, 145.2, 139.8, 137.3, 137.1, 133.1, 128.6, 128.4, 128.2, 128.1, 128.0, 126.9, 126.7, 126.6, 125.9, 122.8, 79.0, 49.4, 47.3, 40.3, 38.4, 25.1, 15.2; HRMS (TOF-ESI): $[M + H]^+$ calcd for $C_{27}H_{25}O_3$: 397.1798; found: 397.1797.

(3*S*,3*aS*,8*R*,8*aS*)-8-(Benzoylmethyl)-3-(2-methoxyphenyl)-3,3a,8,8a-tetrahydroindeno[1,2-*c*]furan-1-one 11c:[12] White solid, 88 mg, 44%, ee 99%, $[\alpha]^{20}_D$ = −226.1 (CH_2Cl_2, c = 0.45), mp 172−173 °C (recrystallization from AcOEt/hexane); IR ν (cm^{-1}) 1769, 1735, 1686; ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.10 (d, J = 7.4 Hz, 2H), 7.59 (t, J = 7.3 Hz, 1H), 7.50 (t, J = 7.5 Hz, 2H), 7.36 (t, J = 7.7 Hz, 1H), 7.13−7.17 (m, 2H), 7.08 (d, J = 7.4 Hz, 1H), 6.99 (d, J = 8.2 Hz, 1H), 6.89 (t, J = 7.5 Hz, 1H), 6.81−6.85 (m, 1H), 6.06 (d, J = 5.9 Hz, 1H), 5.84 (d, J = 7.8 Hz, 1H), 4.49 (t, J = 6.6 Hz, 1H), 4.13−4.19 (m, 1H), 4.05 (dd, J = 18.0, 9.9 Hz, 1H), 3.95 (s, 3H), 3.92−3.95 (m, 1H), 3.54 (dd, J = 18.0, 4.7 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 199.5, 176.7, 155.9, 145.2, 138.1, 137.1, 133.0, 129.1, 128.6, 128.2, 127.8, 126.8, 126.7, 126.5, 124.4, 122.7, 120.6, 109.6, 77.9, 55.5, 48.5, 47.2, 40.2, 38.4; HRMS (TOF-ESI): $[M + H]^+$ calcd for $C_{26}H_{23}O_4$: 399.1590; found: 399.1590.

(3*S*,3*aS*,8*R*,8*aS*)-8-(Benzoylmethyl)-3-(3-methoxyphenyl)-3,3a,8,8a-tetrahydroindeno[1,2-*c*]furan-1-one 11d. White solid, 97 mg, 49%, ee 97%, $[\alpha]^{20}_D$ = −154.5 (CH_2Cl_2, c = 0.50), mp 64−65 °C (without recrystallization); IR ν (cm^{-1}) 1771, 1682; ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.10 (d, J = 7.4 Hz, 2H), 7.60 (t, J = 7.3 Hz, 1H), 7.51 (t, J = 7.6 Hz, 2H), 7.30 (t, J = 7.9 Hz, 1H), 7.14−7.20 (m, 2H), 6.92 (dd, J = 8.2, 2.4 Hz, 1H), 6.85−6.89 (m, 2H), 6.75 (s, 1H), 5.86 (d, J = 6.2 Hz, 1H), 5.80 (d, J = 7.8 Hz, 1H), 4.31 (t, J = 6.7 Hz, 1H), 4.13−4.19 (m, 1H), 4.06 (dd, J = 17.9, 10.0 Hz, 1H), 3.96 (t, J = 7.7 Hz, 1H), 3.74 (s, 3H), 3.56 (dd, J = 17.9, 4.6 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 199.3, 176.7, 159.7, 145.2, 137.34, 137.28, 137.1, 133.1, 129.5, 128.6, 128.2, 128.1, 127.0, 126.7, 122.8, 118.4, 114.4, 111.3, 81.4, 55.4, 50.6, 47.3, 40.3, 38.3; HRMS (TOF-ESI): $[M + H]^+$ calcd for $C_{26}H_{23}O_4$: 399.1590; found: 399.1591.

(3*S*,3*aS*,8*R*,8*aS*)-8-(Benzoylmethyl)-3-(4-methoxyphenyl)-3,3a,8,8a-tetrahydroindeno[1,2-*c*]furan-1-one 11e. White solid, 74 mg, 37%, ee >99%, $[\alpha]^{20}_D$ = −216.2 (CH_2Cl_2, c = 0.50), mp 164−165 °C (recrystallization from AcOEt/hexane); IR ν (cm^{-1}) 1775, 1688; ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.10 (d, J = 8.6 Hz, 2H), 7.59 (t, J = 7.3 Hz, 1H), 7.50 (t, J = 7.5 Hz, 2H), 7.16−7.20 (m, 2H), 7.14 (d, J = 8.8 Hz, 2H), 6.90 (d, J = 8.7 Hz, 2H), 6.88 (t, J = 7.4 Hz, 1H), 5.85 (d, J = 6.3 Hz, 1H), 5.81 (d, J = 7.8 Hz, 1H), 4.27 (t, J = 6.8 Hz, 1H), 4.13−4.19 (m, 1H), 4.05 (dd, J = 18.0, 10.0 Hz, 1H), 3.95 (t, J = 7.8 Hz, 1H), 3.85 (s, 3H), 3.55 (dd, J = 18.0, 4.6 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 199.4, 176.7, 159.6, 145.2, 137.5, 137.1, 133.1, 128.6, 128.2, 128.0, 127.8, 127.4, 127.2, 126.6, 122.8, 113.7, 81.4, 55.3, 50.8, 47.2, 40.3, 38.3; HRMS (TOF-ESI): $[M + H]^+$ calcd for $C_{26}H_{23}O_4$: 399.1590; found: 399.1592.

(3*S*,3*aS*,8*R*,8*aS*)-8-(Benzoylmethyl)-3-(2-bromophenyl)-3,3a,8,8a-tetrahydroindeno[1,2-*c*]furan-1-one 11f. White solid, 161 mg, 72%, ee >99%, $[\alpha]^{20}_D$ = −176.7 (CH_2Cl_2, c = 0.50), mp 125−126 °C (recrystallization from AcOEt/hexane); IR ν (cm^{-1}) 1774, 1681; ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.10 (d, J = 7.6 Hz, 2H), 7.68 (d, J = 7.5 Hz, 1H), 7.60 (t, J = 7.2 Hz, 1H), 7.51 (t, J = 7.5 Hz, 2H), 7.20−7.28 (m, 2H), 7.15−7.19 (m, 2H), 7.10 (d, J = 7.3 Hz, 1H), 6.83−7.86 (m, 1H), 6.06 (d, J = 6.1 Hz, 1H), 5.79 (d, J = 7.7 Hz, 1H), 4.71 (t, J = 6.7 Hz, 1H), 4.15−4.21 (m, 1H), 4.04 (dd, J = 18.2, 10.0 Hz, 1H), 4.01 (t, J = 7.5 Hz, 2H), 3.56 (dd, J = 18.0, 4.5 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 199.2, 176.3, 145.2, 137.3, 137.1, 135.5, 133.1, 132.5, 129.9, 128.6, 128.5, 128.2, 128.1, 127.4, 126.9, 126.6, 122.9, 121.0, 81.0, 48.0, 47.0, 40.3, 38.3; HRMS (TOF-ESI): $[M + H]^+$ calcd for $C_{25}H_{20}BrO_3$: 447.0590; found: 447.0591.

(3*S*,3*aS*,8*R*,8*aS*)-8-(Benzoylmethyl)-3-(2-(trifluoromethyl)-phenyl)-3,3a,8,8a-tetrahydroindeno[1,2-*c*]furan-1-one 11g:[12] White solid, 124 mg, 57%, ee 99%, $[\alpha]^{20}_D$ = −155.8 (CH_2Cl_2, c = 0.50), mp 134−135 °C (recrystallization from AcOEt/hexane); IR ν (cm^{-1}) 1773, 1686; ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.10 (d, J = 8.5 Hz, 2H), 7.80 (d, J = 7.8 Hz, 1H), 7.60 (t, J = 7.3 Hz, 1H), 7.47−7.53 (m, 3H), 7.41 (t, J = 7.6 Hz, 1H), 7.16−7.19 (m, 3H), 6.78−6.84 (m, 1H), 6.23 (d, J = 6.5 Hz, 1H), 5.64 (d, J = 7.7 Hz, 1H), 4.47 (t, J = 7.0 Hz, 1H), 4.15−4.21 (m, 1H), 4.04 (dd, J = 18.1, 10.0 Hz, 1H), 4.02 (t, J = 8.2 Hz, 1H), 3.57 (dd, J = 18.1, 4.7 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 199.0, 176.2, 145.2, 137.1, 137.0, 134.5, 133.1, 131.7, 129.0, 128.6, 128.5, 128.2, 128.1, 127.1 (q, J_{C-F} = 31 Hz), 126.7, 126.6, 125.8 (q, J_{C-F} = 6 Hz), 123.01, 122.97, 77.9, 50.4, 46.8, 40.4, 38.4; HRMS (TOF-ESI): $[M + H]^+$ calcd for $C_{26}H_{20}F_3O_3$: 437.1359; found: 437.1359.

(3*S*,3*aS*,8*R*,8*aS*)-8-(Benzoylmethyl)-3-(3-(trifluoromethyl)-phenyl)-3,3a,8,8a-tetrahydroindeno[1,2-*c*]furan-1-one 11h. White solid, 97 mg, 45%, ee 94%, $[\alpha]^{20}_D$ = −151.0 (CH_2Cl_2, c = 0.50), mp 98−99 °C (recrystallization from AcOEt/hexane); IR ν (cm^{-1}) 1778, 1684; ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.09 (d, J = 8.6 Hz, 2H), 7.65 (d, J = 7.7 Hz, 1H), 7.59 (t, J = 7.3 Hz, 1H), 7.48−7.53 (m, 4H), 7.44 (d, J = 7.8 Hz, 1H), 7.15−7.20 (m, 2H), 6.83 (td, J = 7.1, 2.2 Hz, 1H), 5.91 (d, J = 6.3 Hz, 1H), 5.61 (d, J = 7.7 Hz, 1H), 4.35 (t, J = 6.8 Hz, 1H), 4.13−4.19 (m, 1H), 4.04 (dd, J = 18.0, 10.1 Hz, 1H), 4.00 (t, J = 8.0 Hz, 1H), 3.56 (dd, J = 18.0, 4.7 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 199.3, 176.3, 145.2, 137.0, 136.7, 133.2, 130.9 (q, J_{C-F} = 33 Hz),129.7, 129.0, 128.7, 128.4, 128.2, 126.8, 126.6, 125.3 (q, J_{C-F} = 4 Hz), 125.2, 123.3 (q, J_{C-F} = 4 Hz), 123.1, 122.5, 80.8, 50.5, 47.2, 40.3, 38.2; HRMS (TOF-ESI): $[M + H]^+$ calcd for $C_{26}H_{20}F_3O_3$: 437.1359; found: 437.1360.

(3*S*,3*aS*,8*R*,8*aS*)-8-(Benzoylmethyl)-3-(4-(trifluoromethyl)-phenyl)-3,3a,8,8a-tetrahydroindeno[1,2-*c*]furan-1-one 11i. White solid, 115 mg, 53%, ee 99%, $[\alpha]^{20}_D$ = −193.8 (CH_2Cl_2, c = 0.50), mp 153−154 °C (recrystallization from AcOEt/hexane); IR ν (cm^{-1}) 1771, 1688; ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.10 (d, J = 7.5 Hz, 2H), 7.66 (d, J = 7.9 Hz, 2H), 7.60 (t, J = 7.2 Hz, 1H), 7.51 (t, J = 7.5 Hz, 2H), 7.39 (d, J = 7.8 Hz, 2H), 7.18−7.21 (m, 2H), 6.86 (t, J = 6.7 Hz, 1H), 5.92 (d, J = 6.1 Hz, 1H), 5.68 (d, J = 7.7 Hz, 1H), 4.37 (t, J = 6.6 Hz, 1H), 4.14−4.17 (m, 1H), 4.04 (dd, J = 18.8, 10.2 Hz, 1H), 4.01 (t, J = 7.4 Hz, 1H), 4.04 (dd, J = 18.1, 4.4 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 199.2, 176.2, 145.2, 140.0, 137.0, 136.8, 133.2, 130.7 (q, J_{C-F} = 33 Hz), 128.6, 128.3, 128.2, 126.9, 126.6, 125.4 (q, J_{C-F} = 3 Hz), 123.1, 122.6, 80.8, 50.4, 47.2, 40.3, 38.2; HRMS (TOF-ESI): $[M + H]^+$ calcd for $C_{26}H_{20}F_3O_3$: 437.1359; found: 437.1358.

(1*R*,2*R*)-Isopropyl 1-(Benzoylmethyl)-2,3-dihydroindene-2-carboxylate 6a. Colorless oil, 4−14%, ee 95%, $[\alpha]^{20}_D$ = +33.2 (CH_2Cl_2, c = 0.40); IR ν (cm^{-1}) 1719, 1686; ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.93 (dd, J = 8.6, 1.4 Hz, 2H), 7.54 (t, J = 7.4 Hz, 1H), 7.44 (t, J = 7.5 Hz, 2H), 7.24 (d, J = 7.4 Hz, 1H), 7.11−7.19 (m, 3H), 4.87−4.96 (m, 1H), 4.24 (q, J = 7.5 Hz, 1H), 3.54 (dd, J = 16.4, 8.2 Hz, 1H), 3.43 (dd, J = 17.6, 7.2 Hz, 1H), 3.35 (dd, J = 15.9, 8.4 Hz, 1H), 3.16 (dd, J = 17.6, 6.8 Hz, 1H), 3.10 (dd, J = 15.9, 8.0 Hz, 1H), 1.19 (d, J = 6.3 Hz, 3H), 1.15 (d, J = 6.3 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 198.3, 173.5, 144.8, 141.5, 137.1, 133.1, 128.6, 128.1, 127.2, 126.7, 124.5, 124.2, 68.0, 47.9, 42.3, 40.4, 34.6, 21.9, 21.7; HRMS (TOF-ESI): $[M + H]^+$ calcd for $C_{21}H_{23}O_3$: 323.1647; found: 323.1645.

(1*R*,2*R*)-Isopropyl 1-((4-bromobenzoyl)methyl)-2,3-dihydroindene-2-carboxylate 6h. Colorless oil, 6%−8%, ee 96%, $[\alpha]^{20}_D$ = +25.5 (CH_2Cl_2, c = 0.50); IR ν (cm^{-1}) 1721, 1688; ^{1}H NMR (400

DOI: 10.1021/acs.joc.6b01362
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MHz, $CDCl_3$) δ (ppm) 7.79 (dt, J = 8.6, 2.0 Hz, 2H), 7.58 (dt, J = 8.6, 2.0 Hz, 2H), 7.24 (d, J = 7.2 Hz, 1H), 7.18 (dd, J = 6.4, 2.2 Hz, 1H), 7.12−7.17 (m, 2H), 4.85−4.94 (m, 1H), 4.21 (q, J = 7.2 Hz, 1H), 3.53 (q, J = 8.3 Hz, 1H), 3.42 (dd, J = 17.6, 7.5 Hz, 1H), 3.34 (dd, J = 15.9, 8.7 Hz, 1H), 3.11 (dd, J = 15.9, 8.0 Hz, 1H), 3.09 (dd, J = 17.7, 6.4 Hz, 1H), 1.19 (d, J = 6.3 Hz, 3H), 1.15 (d, J = 6.2 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 197.3, 173.5, 144.6, 141.4, 135.7, 131.9, 129.5, 128.2, 127.3, 126.8, 124.5, 124.1, 68.0, 47.8, 42.2, 40.4, 34.6, 21.8, 21.7; HRMS (TOF-ESI): $[M + H]^+$ calcd for $C_{21}H_{22}BrO_3$: 401.0746; found: 401.0748.

Bis(*o*-phenylethynyl)benzil 7a:[15] White solid, 18−20% isolated from the reaction of **1a** or **1i** with **2a** under the same conditions as those in Method C; mp 132−133 °C (without recrystallization); IR ν (cm^{-1}) 2214 (w), 1667; ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.09 (dd, J = 7.8, 0.9 Hz, 1H), 7.58 (dd, J = 8.4, 0.7 Hz, 1H), 7.51 (td, J = 7.4, 1.3 Hz, 1H),7.40 (td, J = 7.8, 1.2 Hz, 1H), 7.20 (t, J = 7.5 Hz, 1H), 7.10 (t, J = 7.8 Hz, 2H), 6.94 (d, J = 7.1 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 192.9, 135.5, 133.6, 133.1, 131.1, 130.4, 128.6, 128.3, 127.9, 124.9, 122.1, 98.5, 88.3; HRMS (Orbitrap-APCI): $[M + H]^+$ calcd for $C_{30}H_{19}O_2$: 411.1380; found: 411.1371.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.joc.6b01362.

Copies of ^{1}H NMR,^{13}C NMR spectra and HPLC chromatographs for all major products **4**, **9**, and **11** and byproducts **6a**, **6h** and **7a**; single crystal data for **9h** (PDF)

Crystallographic data for **9h** (CIF)

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Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This work was supported by the National Natural Science Foundation of China (No. 21372030).

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DOI: 10.1021/acs.joc.6b01362
J. Org. Chem. 2016, 81, 8276−8286