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Spirocyclopropanation Reaction of *para*-Quinone Methides with Sulfonium Salts: The Synthesis of Spirocyclopropanyl *para*-Dienones

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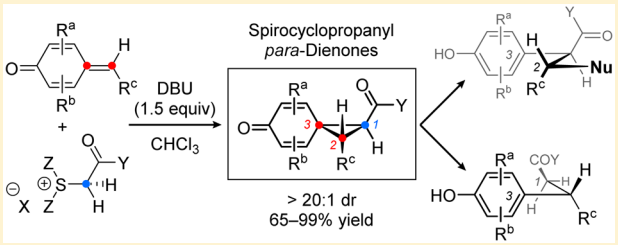
Supporting Information

ABSTRACT: A novel DBU-mediated stereoselective spirocyclopropanation of *para*-quinone methides with sulfonium salts has been developed on the basis of the mode involving a 1,6-conjugate addition/intramolecular dearomatizing cyclization cascade. This reaction provides a mild and effective method for the assembly of synthetically and structurally interesting spirocyclopropanyl *para*-dienones. The feasibility for the enantioselective access to such functionalized *para*-dienones has also been explored by using the axially chiral sulfonium salt. Importantly, the regioselective ring openings of the related spirocyclopropanyl *para*-dienones have been achieved divergently.

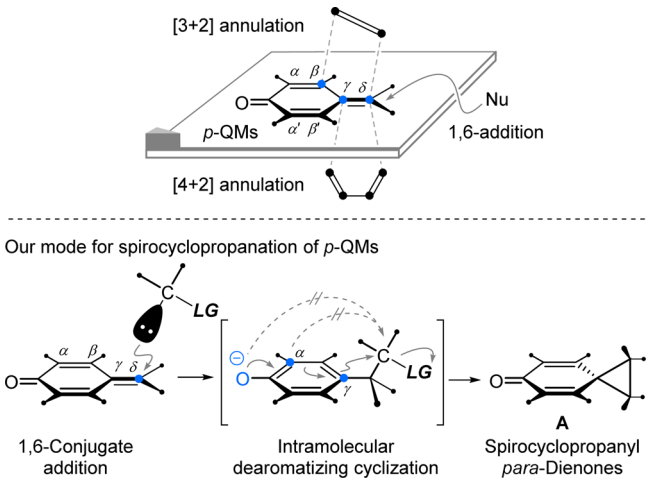


para-Quinone methides (*p*-QMs) as a class of quinonoid compounds, structurally featured by the unique bisvinylogous enone system, have already been documented for more than one century in organic chemistry.[1] Compared with the fact that the functionalized *p*-QM units exist in many natural products,[2] importantly, the transient *p*-QM entities formed *in situ* are also involved in many chemical, medicinal, and biological processes.[3,4] Chemically, the reactivity of *p*-QMs is mostly attributable to the intrinsic electrophilicity, partially enhanced by the aromatization driving force. Notably during the past decades, the development of methodologies of *p*-QMs has received considerable attention,[5] and the elegant pioneering works have led to three main reaction models for 1,6-conjugate additions,[6,7] [4 + 2]-annulations[8] and [3 + 2]-annulations[9] (Scheme 1). In connection with our recent interest in the chemistry of *p*-QMs[6a] and *para*-dienones,[10] a novel model for the spirocyclopropanation of *p*-QMs with a one-carbon nucleophile bearing a nucleofuge (leaving group) could be envisaged, wherein the 1,6-conjugate addition/intramolecular dearomatizing cyclization cascade would proceed to yield the spirocyclopropanyl fused *para*-dienones **A** having a spiro[2.5]-octa-4,7-dien-6-one skeleton. Synthetically, regarding the assembly of such a type of functionalized *para*-dienones, as shown in Scheme 2, some effort has been made and mainly includes (1) intramolecular dearomatizing cyclization of phenol-type precursors,[11] (2) intramolecular cyclization of substituted *para*-dienone precursors,[12] and (3) [2 + 1]-cycloaddition of *para*-quinone diazides with alkenes.[13]

Given the appeal for the development of methodologies of *p*-QMs[5] as well as stimulated by the sulfonium chemistry,[14] as shown in Scheme 3, we recently develop a novel spirocycloaddition reaction of *p*-QMs **1** with sulfonium salts **2**,[15] and this methodology provides an access to synthetically and structurally interesting spirocyclopropanyl *para*-dienones **3**. Herein, we present our preliminary results on this aspect.

Initially, our effort was conducted in the model reaction using *p*-QM **1a** and ethyl dimethylsulfonium acetate bromide

Scheme 1. Methodologies on the Chemistry of *para*-Quinone Methides



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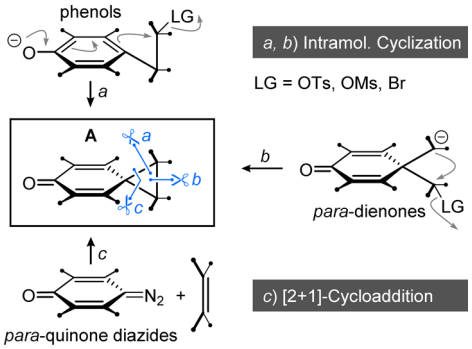
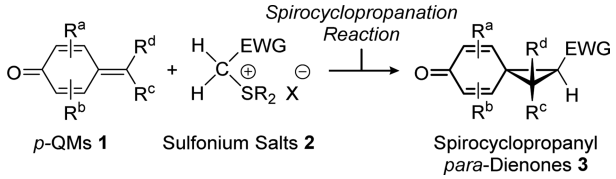
Scheme 2. Known Methods for the Synthesis of Spirocyclopropanyl *para*-Dienones

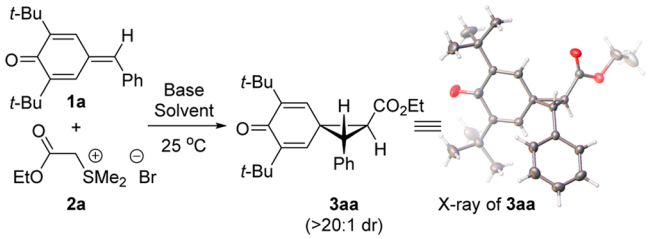


Scheme 3. Spirocyclopropanation Reaction of *para*-Quinone Methides with Sulfonium Salts



2a. Considering the requirement for the *in situ* generation of nucleophilic species via deprotonation of the active methylene proton, as tabulated in Table 1, a series of inorganic bases (e.g., hydroxides, carbonates, the phosphate) and organic ones (e.g., the alkoxide, fused bicyclic amidine, cyclic amine, acyclic amine, guanidine) were first evaluated in CH_2Cl_2 as solvent at room temperature (entries 1−12). Among the inorganic bases screened in this model (entries 1−7), interestingly, it was found that the increasing size of the inorganic cation or anion could give a positive impact to the reaction yield. For example, compared with $LiOH·H_2O$ (9% yield, entry 1) and NaOH (62% yield, entry 2), KOH (entry 3) as base could afford **3aa** in 76% yield. In comparison with the cases using Na_2CO_3 (12% yield, entry 4) and K_2CO_3 (33% yield, entry 5), the reaction with Cs_2CO_3 (entry 6) gave **3aa** in 65% yield. Analogously, when employing the bases with the same inorganic cation such as K_2CO_3 (33% yield, entry 5) and $K_3PO_4·3H_2O$ (66% yield, entry 7), the base having a larger-size anion gave a better reaction yield. As for the organic bases evaluated (entries 8−12), generally the yields were improved by the increase of basicity. For example, the model reactions using *t*-BuONa (entry 8), DBU (entry 9), or TMG (entry 12) as a base could deliver the desired product **3aa** in more than 70% yield, wherein the fused bicyclic amidine DBU demonstrated higher efficiency (3.5 h, 76% yield, >20:1 dr). The *trans* configuration of spirocyclopropanyl *para*-dienone **3aa** was unambiguously assigned by X-ray crystallographic analysis.[16] Following this promising screening result, various solvents were also examined (entries 13−20). Except for THF (entry 19) and DMSO (entry 20), most of solvents are compatible with the current spirocyclopropanation transformation, giving **3aa** in good yields of 72−97% (entries 9, 13−18). In terms of yield and time, $CHCl_3$ as reaction media (entry 16) could give a better yield of **3aa** (97% yield). Further investigation on the influence of amounts of DBU (entries 21−23) revealed that the optimal result (3.5 h, 99% yield, >20:1 dr) could be achieved using 1.5 equiv of DBU as base in $CHCl_3$ as solvent at room temperature (entry 22).

Table 1. Reaction Conditions Optimization[a,b]



entry	base	equiv (base)	solvent	*t* (h)	yield (%)[c]
1[d]	$LiOH·H_2O$	4.0	CH_2Cl_2	70	9
2	NaOH	4.0	CH_2Cl_2	50	62
3	KOH	4.0	CH_2Cl_2	50	76
4[d]	Na_2CO_3	4.0	CH_2Cl_2	70	12
5	K_2CO_3	4.0	CH_2Cl_2	156	33
6	Cs_2CO_3	4.0	CH_2Cl_2	156	65
7	$K_3PO_4·3H_2O$	4.0	CH_2Cl_2	100	66
8	*t*-BuONa	4.0	CH_2Cl_2	50	73
9	**DBU**	**4.0**	**CH_2Cl_2**	**3.5**	**76**
10[d]	DABCO	4.0	CH_2Cl_2	78	7
11	NEt_3	4.0	CH_2Cl_2	96	41
12	TMG	4.0	CH_2Cl_2	96	76
13	DBU	4.0	PhCl	6	83
14	DBU	4.0	$PhCF_3$	12	72
15	DBU	4.0	$PhCH_3$	35	92
16	**DBU**	**4.0**	**$CHCl_3$**	**3**	**97**
17	DBU	4.0	CH_3CN	0.5	84
18	DBU	4.0	EtOAc	1	86
19	DBU	4.0	THF	12	47
20	DBU	4.0	DMSO	3	54
21	DBU	3.0	$CHCl_3$	3	96
22	**DBU**	**1.5**	**$CHCl_3$**	**3.5**	**99**
23	DBU	1.0	$CHCl_3$	4	93

[a]Performed with *p*-QM **1a** (0.1 mmol) and sulfonium salt **2a** (0.14 mmol) in the presence of base (0.4−0.1 mmol) in solvent (2 mL) at 25 °C. [b]Determined by crude NMR. [c]Yield of isolated product. [d]The dr value not determined. DBU = 1,8-diazabicyclo[5.4.0]undec-7-ene, DABCO = 1,4-diazabicyclo[2.2.2]octane, TMG = 1,1,3,3-tetramethylguanidine.

With the above optimized conditions, as tabulated in Table 2, the scope of *para*-quinone methides was explored in this spirocyclopropanation reaction. Generally, the reaction gave good to excellent yields (up to 99% yield) and high diastereoselectivities (>20:1 dr) for a broad range of *p*-QMs. Compared with the model acceptor **1a**, the electronic deficiency of the aromatic R^c group at the δ position of *p*-QMs (e.g., **1c−1g**, **1k**, and **1n**) could facilitate this reaction with decreased reaction time (<3.5 h), giving the products **3ca−3ga**, **3ka**, and **3na** in 85−99% yields. Notably, the spirocyclopropanation using *p*-QM **1n** with the heteroaryl group at the δ position (R^c = 2-pyridinyl) proceeded very quickly (5 min) to deliver the corresponding dienone **3na** (>20:1 dr) in 96% yield. In contrast to the above cases, the prolonged reaction time (>3.5 h), which was required for the formation of the desired products **3ha−3ja**, **3la**, **3ba**, and **3ma** (66−97% yields), was usually observed when *p*-QMs with an R^c

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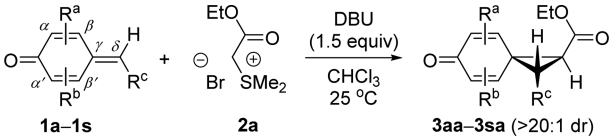
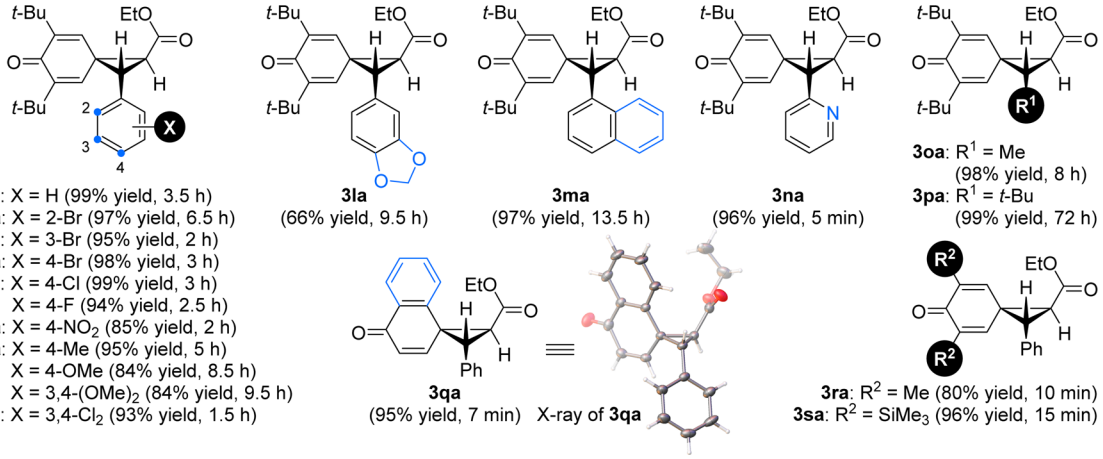
Table 2. Spirocyclopropanation Reaction with Various *para*-Quinone Methides[a]





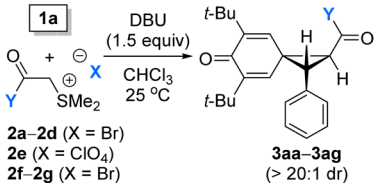
[a]Performd with *p*-QMs **1a**−**1b** (0.2 mmol) and sulfonium salt **2a** (0.28 mmol) in the presence of DBU (0.3 mmol) in $CHCl_3$ (4 mL) at 25 °C. The yields refer to the isolated products, and the dr's were determined by crude NMR.

group having the electronic donating substituents on the aromatic ring (e.g., **1h**−**1j** and **1l**) or containing steric *ortho* substituents on the aromatic ring (e.g., **1b** and **1m**) were subjected to this reaction. In addition, two *p*-QM substrates (**1o** and **1p**) bearing the electron-donating alkyl groups at the δ position (R^c = Me and *t*-Bu) were also investigated, and pleasingly the products **3oa** and **3pa** could be isolated in almost quantitative yields. It should be noted that the prolonged reaction time of 72 h required for the case of **3pa** mainly resulted from the unfavorable steric effect of the bulky *t*-Bu group substituted at the electrophilic position in **1p**. Furthermore, three *p*-QMs (**1q**−**1s**) with substituents at the α,β- or α,α'-position were subjected to the standard conditions, and interestingly, the desired spirocyclopropanyl *para*-dienones **3qa**−**3sa** were obtained with high diastereoselectivities in 80−96% yields. Notably, these reactions with the enhanced reactivity were completed within 15 min, clearly indicating the positive influence of the less bulky substituent (**1q** and **1r**) and the group with α-silicon effect (**1s**) at the α,α'-position of *p*-QMs. Considering the introduction of unsymmetric α,α'-substituents in *p*-QM **1q**, the stereochemistry of product **3qa** was eventually confirmed by X-ray crystallographic analysis.[16]

As another aspect of the methodology, the influence of sulfonium salts to this spirocyclopropanation reaction was also preliminarily tested. As shown in Scheme 4, a series of alkyl, benzyl, and phenyl ester sulfonium salts (**2a**−**2e**) were examined under the controlled conditions, and pleasingly, there was no obvious effect on the reaction yields of the spirocyclopropanyl *para*-dienones **3aa**−**3ae** (93−99% yields). In contrast to the stable sulfonium bromides **2a**−**2d**, it should be noted that the perchlorate, instead of bromide, as a counteranion for the phenyl ester sulfonium salt **2e** was essential to its chemical stability.[17] In addition, when using the ketone sulfonium salts **2f** and **2g**, the decreased reaction efficiency was observed, giving the corresponding products **3af** and **3ag** in 65% and 88% yield, respectively.

In order to have an insight into the stereoselectivity observed in this spirocyclopropanation reaction, a plausible model was proposed on the basis of the *trans* configuration asssigment for **3aa** by X-ray crystallographic analysis.[16] As shown in Scheme 5,

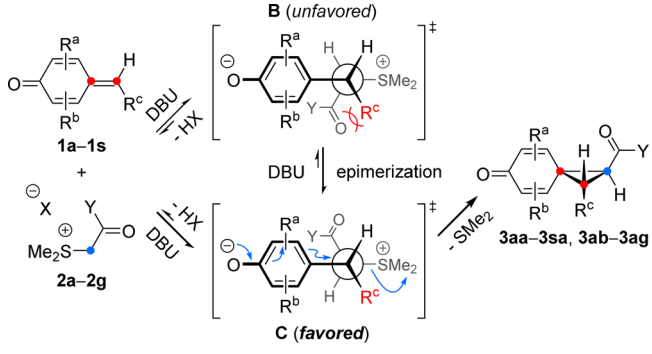
Scheme 4. Spirocyclopropanation Reaction with Various Sulfonium Salts



3aa: Y = OEt (99% yield, 3.5 h)
3ab: Y = OMe (98% yield, 5 h)
3ac: Y = O*t*-Bu (98% yield, 1 h)
3ad: Y = OBn (99% yield, 5.5 h)
3ae: Y = OPh (93% yield, 20 h)

3af: Y = Ph (65% yield, 42 h)
3ag: Y = 4-C_6H_4OMe (88% yield, 14 h)

Scheme 5. Stereoselective Model for Spirocyclopropanation Reaction



the nucleophilic 1,6-addition of *p*-QMs **1a**−**1s** with sulfonium salts **2a**−**2g** took place first in the presence of DBU, delivering the zwitterionic species **B** and **C**. Because of the unfavorable steric interaction in **B**, the desired spirocyclopropanation products were predominantly generated through the intramolecular S_N2 nucleophilic substitution of the intermediate **C**,

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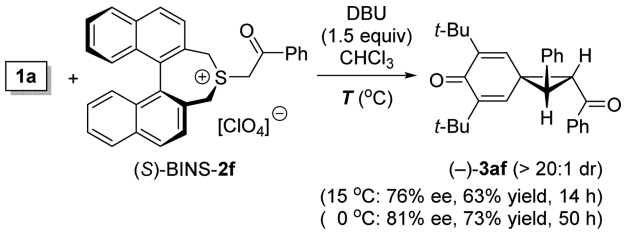
wherein a retro-conjugate addition process or an epimerization sequence might be involved in the consumption of thermodynamically unstable **B**.

To further probe the feasibility to access the asymmetric synthesis of spirocyclopropanyl *para*-dienones,[18] the employment of a chiral BINOL-derived sulfonium perchlorate, (*S*)-BINS-**2f**, developed by Xiao[19] was considered at this stage. By varying the reaction temperature, as shown in Scheme 6, the asymmetric spirocyclopropanation reaction of *p*-QM **1a** with (*S*)-BINS-**2f** at 0 °C delivered the chiral product (−)-**3af** in 73% yield with the optimal enantioselectivity of 81% ee.[20] The current preliminary investigation has shown a possibility of stereocontrol in this spirocyclopropanation reaction of *p*-QMs with C2-symmetric axially chiral auxiliary containing sulfonium salts.

Scheme 6. Asymmetric Spirocyclopropanation Reaction



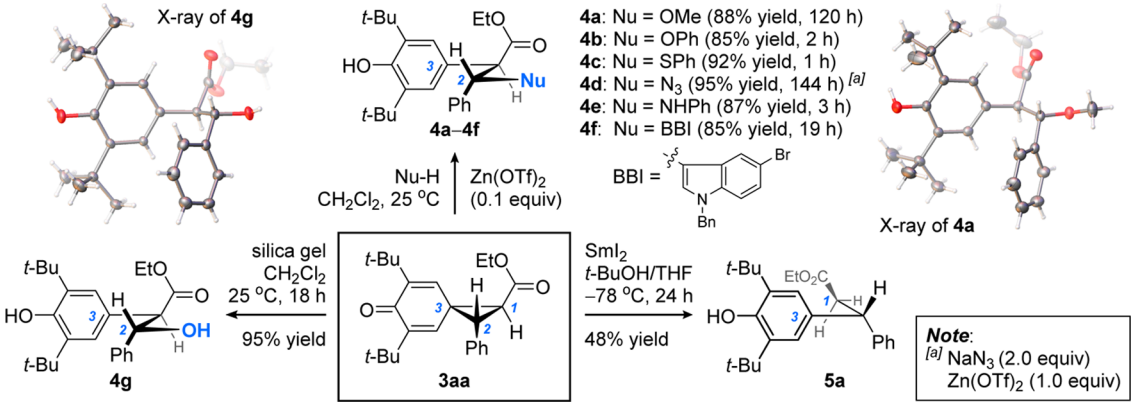
Considering the ring strain release of the cyclopropanyl system and the aromatization of the cyclohexadienone (*para*-dienone) moiety, the synthetic potential of this methodology was further explored.[21] As demonstrated in Scheme 7, a series of ring-opening reactions of spirocyclopropanyl *para*-dienone **3aa** as a model were pursed. First, the Lewis acid $Zn(OTf)_2$-catalyzed cyclopropane openings were conducted in the presence of various heteroatom nucleophiles (e.g., MeOH, PhOH, PhSH, NaN_3, $PhNH_2$) as well as the carbon nucleophiles (e.g., substituted indole). Significantly, such a type of highly stereoselective ring-opening reactions proceeded readily to give the S_N2-type products **4a**−**4f** in good to high yields (85−95% yields), wherein the C2−C3 bond cleavage in **3aa** took place in a stereocontrolled manner. The corresponding stereochemistry inversion was clearly confirmed by X-ray crystallographic analysis of **4a**.[16] Besides, it is worthy to note that **3aa** could undergo a mild water-involving stereoselective ring opening promoted by silica gel in CH_2Cl_2 to afford *β*-hydroxy ester product **4g** (95% yield), and its configuration was analogously determined by X-ray crystallographic analysis.[16] In addition to the above C2−C3 heterolytic bond dissociation, another mode involving the C1−C3 bond cleavage in **3aa** was also demonstrated by SmI_2-mediated reduction, leading to the reductive ring-opening product **5a** in a moderate yield of 48%.

In conclusion, stimulated by the methodology design in the chemistry of *para*-quinone methides, a novel base-promoted spirocyclopropanation reaction of *para*-quinone methides with sulfonium salts was developed, in which a 1,6-conjugate addition/intramolecular dearomatizing cyclization cascade was involved. This methodology provided a useful approach in a one-pot manner to the effective synthesis of various spirocyclopropanyl fused *para*-dienones. Importantly, the asymmetric synthesis of such functionalized *para*-dienones has been preliminarily probed by using the axially chiral BINOL-derived C2-symmetric sulfonium salt. Besides, to demonstrate the synthetic potential of this methodology, two modes for the selective cleavage of C2−C3 and C1−C3 bonds in the related spirocyclopropanyl fused *para*-dienones were divergently accessed, leading to the development of several regioselective ring-opening reactions, especially with oxygen, sulfur, nitrogen, and carbon nucleophiles. Our present spirocyclopropanation methodology not only provides an alternative pathway to the synthetically interesting, functionalized *para*-dienones but also enriches the *para*-quinone methide chemistry in organic synthesis.

EXPERIMENTAL SECTION

General Methods. Unless otherwise noted, all moisture- or oxygen-sensitive reactions were carried out under an argon atmosphere in oven- or heat-dried flasks. All solvents were purified and dried prior to use according to the literature.[22] All other commercial reagents were used as received without further purification unless otherwise stated. All reactions were monitored by thin-layer chromatography (TLC) on silica gel F_{254} plates using UV light as visualizing agent, and a solution of ammonium molybdate tetrahydrate (50 g/L) in EtOH, followed by heating as developing agents. The products were purified by flash column chromatography on silica gel (200−300 meshes). ^1H NMR and ^{13}C NMR spectra were recorded in $CDCl_3$ or acetone-d_6 solution at 400 MHz. Chemical shifts were denoted in ppm (*δ*), and calibrated by using residual undeuterated solvent ($CDCl_3$ (7.27 ppm), acetone-d_6 (2.05 ppm), or tetramethylsilane (0.00 ppm)) as internal reference for ^1H NMR and the deuterated solvent ($CDCl_3$ (77.00 ppm), acetone-d_6 (29.84 ppm), or tetramethylsilane (0.00 ppm)) as internal standard for ^{13}C NMR. Multiplicities are indicated as follows: s (singlet), d (doublet), t (triplet), and m (multiplet). The MS data were obtained with the ESI

Scheme 7. Ring-Opening Reactions of Spirocyclopropanyl *para*-Dienones



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technique, and the relative intensity (%) is given in brackets. High-resolution mass spectral analysis (HRMS) data were obtained using an Orbitrap instrument equipped with an ESI source. The IR spectra were recorded by means of the ATR technique.

General Procedure for the Preparation of *para*-Quinone Methides. In a Dean−Stark apparatus, a solution of phenols (25.0 mmol) and the corresponding aldehydes (25.0 mmol) in toluene (100 mL) was heated to reflux. Piperidine (50.0 mmol, 4.94 mL) was dropwise added over 1 h. The reaction mixture was continued to reflux for 3 h. After cooling just below the boiling point of the reaction mixture, acetic anhydride (50.0 mmol, 2.55g) was added, and stirring was continued for 15 min. Then, the reaction mixture was poured on ice−water (500 mL) and extracted with CH_2Cl_2 (4 × 200 mL). The combined organic phases were dried over anhydrous Na_2SO_4, and the solvent of the filtrate was removed under reduced pressure. The crude products were purified by flash column chromatography and further recrystallized from *n*-hexane, affording the desired *p*-QMs. **1a−1s** were prepared according to the reported literature procedures.[6a]

General Procedure for the Preparation of Sulfonium Bromides. Dimethyl sulfide (55 mmol) was added to a solution of 2-bromoacetates (50 mmol) in acetone (20 mL). After the mixture was stirred for 12 h, the residue was filtered and washed with acetone and dried *in vacuo* to give the related sulfonium bromides. **2a−2d**[14g] and **2f−2g**[23] were prepared according to the reported literature procedures.

General Procedure for the Preparation of Sulfonium Perchlorate 2e. Phenyl 2-bromoacetate (4.6 mmol), dimethyl sulfide (5.1 mmol), and sodium perchlorate monohydrate (9.2 mmol) were stirred in acetone at room temperature for 24 h. The resultant precipitate was then collected by filtration, washed with acetone, and dried *in vacuo* to give the sulfonium perchlorate **2e**.

*Phenoxycarbonylmethyl Dimethylsulfonium Perchlorate (**2e**).* White solid, 1.3 g, 96% yield, mp 133−136 ° C; **^{1}H NMR** (400 MHz, acetone-d_6) δ = 7.45 (t, *J* = 8.0 Hz, 2H), 7.31 (t, *J* = 8.0 Hz, 1H), 7.25 (d, *J* = 8.0 Hz, 2H), 4.95 (s, 2H), 3.22 ppm (s, 6H); **^{13}C NMR** (100 MHz, acetone-d_6) δ = 164.5, 151.0, 130.4, 127.4, 122.3, 46.0, 25.4 ppm; **IR** $\bar{U}$ = 3396, 1924, 1751, 1427, 1120, 1082, 940, 629 cm^{-1}. **HRMS** (ESI): *m*/*z* calcd for $[C_{10}H_{13}O_2S_1]^+$ 197.0631; found 197.0632.

General Procedure for the Spirocyclopropanation Reaction of *para*-Quinone Methides with Sulfonium Salts. To a solution of *para*-quinone methides **1** (0.2 mmol) and sulfonium salts **2** (0.28 mmol) in $CHCl_3$ (4.0 mL) was added DBU (0.3 mmol). The resulting mixture was stirred vigorously at 25 °C for the indicated time. The solvent was concentrated under reduced pressure, and the resulting residue was purified by flash column chromatography on silica gel (*Note: silica gel was neutralized by triethylamine before use*) eluting with petroleum ether/ethyl acetate, giving the spirocyclopropanyl *para*-dienones **3**.

*Ethyl 5,7-Di-tert-butyl-6-oxo-2-phenylspiro[2.5]octa-4,7-diene-1-carboxylate (**3aa**).* White solid: 75.3 mg, 99% yield, mp 136−137 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ = 7.35−7.25 (m, 3H), 7.22 (d, *J* = 8.0 Hz, 2H), 6.90 (d, *J* = 2.8 Hz, 1H), 5.79 (d, *J* = 2.8 Hz, 1H), 4.31−4.20 (m, 2H), 3.71 (d, *J* = 7.6 Hz, 1H), 3.07 (d, *J* = 7.6 Hz, 1H), 1.34 (t, *J* = 7.2 Hz, 1H), 1.28 (s, 9H) 1.07 ppm (s, 9H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ = 185.7, 169.5, 149.4, 149.3, 138.8, 137.6, 134.7, 128.8, 128.5, 127.6, 61.5, 40.0, 37.9, 36.3, 35.2, 35.0, 29.3, 29.1, 14.2 ppm; **IR**: $\bar{U}$ = 2957, 1727, 1647, 1455, 1282, 1184, 1038, 739 cm^{-1}. For X-ray crystallographic analysis of **3aa**, see the Supporting Information.

*Ethyl 2-(2-Bromophenyl)-5,7-di-tert-butyl-6-oxospiro[2.5]octa-4,7-diene-1-carboxylate (**3ba**).* White solid: 88.9 mg, 97% yield; mp 133−135 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ = 7.56 (d, *J* = 7.2 Hz, 1H), 7.33−7.25 (m, 2H), 7.17 (td, *J* = 7.2 Hz, 0.8 Hz, 1H), 6.93 (d, *J* = 2.8 Hz, 1H), 5.59 (d, *J* = 2.8 Hz, 1H), 4.34−4.22 (m, 2H), 3.63 (d, *J* = 7.6 Hz, 1H), 3.02 (d, *J* = 7.6 Hz, 1H), 1.35 (t, *J* = 7.2 Hz, 3H), 1.28 (s, 9H), 1.05 ppm (s, 9H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ = 185.6, 169.3, 150.0, 149.9, 138.0, 137.3, 135.2, 132.9, 129.9, 129.2, 127.2, 126.4, 61.6, 40.9, 37.9, 36.5, 35.2, 34.9, 29.4, 29.0, 14.3 ppm; **IR**: $\bar{U}$ = 2956, 1729, 1623, 1459, 1292, 1184, 1032, 744 cm^{-1}; **HRMS** (ESI): *m*/*z* calcd for $[C_{25}H_{31}BrO_3 + Na]^+$ 481.1349; found 481.1341.

*Ethyl 2-(3-Bromophenyl)-5,7-di-tert-butyl-6-oxospiro[2.5]octa-4,7-diene-1-carboxylate (**3ca**).* White solid: 87.5 mg, 95% yield; mp 130−132 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ = 7.43 (d, *J* = 8.0 Hz, 1H) 7.39 (s, 1H), 7.21 (t, *J* = 8.0 Hz, 1H), 7.15 (d, *J* = 8.0 Hz), 6.84 (d, *J* = 2.8 Hz, 1H), 5.75 (d, 2.8 Hz, 1H), 4.35−4.19 (m, 2H), 3.64 (d, *J* = 7.2 Hz, 1H), 3.00 (d, *J* = 7.2 Hz, 1H), 1.34 (t, *J* = 7.2 Hz, 3H), 1.27 (s, 9H), 1.09 ppm (s, 9H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ = 185.6, 169.2, 149.74, 149.71, 138.2, 137.2, 137.1, 132.0, 130.8, 130.0, 127.6, 122.6, 61.7, 39.2, 37.6, 36.2, 35.3, 35.1, 29.3, 29.1, 14.2 ppm; **IR**: $\bar{U}$ = 2957, 1718, 1623, 1458, 1183, 1092, 884, 697 cm^{-1}; **HRMS** (ESI): *m*/*z* calcd for $[C_{25}H_{31}BrO_3 + Na]^+$ 481.1349; found 481.1341.

*Ethyl 2-(4-Bromophenyl)-5,7-di-tert-butyl-6-oxospiro[2.5]octa-4,7-diene-1-carboxylate (**3da**).* White solid: 89.5 mg, 98% yield; mp 146−148 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ = 7.46 (d, *J* = 8.4 Hz, 2H), 7.10 (d, *J* = 8.4 Hz, 2H), 6.85 (d, *J* = 2.4 Hz, 1H), 5.74 (d, *J* = 2.4 Hz, 1H), 4.31−4.20 (m, 2H), 3.63 (d, *J* = 7.6 Hz, 1H), 3.00 (d, *J* = 7.6 Hz, 1H), 1.34 (t, *J* = 7.2 Hz, 1H), 1.27 (s, 9H), 1,08 ppm (s, 9H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ = 185.6, 169.3, 149.7, 149.6, 138.2, 137.3, 133.9, 131.7, 130.6, 121.7, 61.7, 39.3, 37.7, 36.3, 35.3, 35.1, 29.3, 29.1, 14.2 ppm; **IR**: $\bar{U}$ = 2957, 1727, 1622, 1490, 1182, 1012, 915, 740 cm^{-1}; **HRMS** (ESI): *m*/*z* calcd for $[C_{25}H_{31}BrO_3 + Na]^+$ 481.1349; found 481.1342.

*Ethyl 5,7-Di-tert-butyl-2-(4-chlorophenyl)-6-oxospiro[2.5]octa-4,7-diene-1-carboxylate (**3ea**).* White solid: 82.1 mg, 99% yield; mp 139−141 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ = 7.31 (d, *J* = 8.4 Hz, 2H), 7.17 (d, *J* = 8.4 Hz, 2H), 6.86 (d, *J* = 2.8 Hz, 1H), 5.74 (d, *J* = 2.8 Hz, 1H), 4.31−4.20 (m, 2H), 3.65 (d, *J* = 7.2 Hz, 1H), 3.01 (d, *J* = 7.2 Hz, 1H), 1.34 (t, *J* = 7.2 Hz, 3H), 1.27 (s, 9H), 1.08 ppm (s, 9H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ = 185.6, 169.3, 149.7, 149.6, 138.2, 137.3, 133.6, 133.4, 130.2, 128.7, 61.7, 39.2, 37.7, 36.3, 35.2, 35.0, 29.3, 29.1, 14.2 ppm; **IR**: $\bar{U}$ = 2957, 1729, 1622, 1459, 1183, 1092, 741, 510 cm^{-1}; **HRMS** (ESI): *m*/*z* calcd for $[C_{25}H_{31}ClO_3 + H]^+$ 415.2034; found 415.2030.

*Ethyl 5,7-Di-tert-butyl-2-(4-fluorophenyl)-6-oxospiro[2.5]octa-4,7-diene-1-carboxylate (**3fa**).* White solid: 74.8 mg, 94% yield; mp 125−127 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ = 7.22−7.18 (m, 2H) 7.05−7.01 (m, 2H), 6.87 (d, *J* = 2.8 Hz, 1H), 5.74 (d, *J* = 2.8 Hz), 4.31- 4.20 (m, 2 H), 3.66 (d, 7.2 Hz, 1H), 3.01 (d, *J* = 7.2 Hz, 1H), 1.34 9 (t, *J* = 7.2 Hz, 3H), 1.27 (s, 9H), 1.08 ppm (s, 9H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ = 185.7, 169.4, 163.4, 160.9, 149.6, 149.5, 138.5, 137.4, 130.63, 130.60, 130.53, 130.45, 115.6, 115.4, 61.7, 39.2, 37.7, 36.5, 35.2, 35.0, 29.3, 29.1, 14.2 ppm; **IR**: $\bar{U}$ = 2958, 1728, 1623, 1514, 1183, 915, 741, 539 cm^{-1}; **HRMS** (ESI): *m*/*z* calcd for $[C_{25}H_{31}FO_3 + H]^+$ 399.2330; found 399.2324.

*Ethyl 5,7-Di-tert-butyl-2-(4-nitrophenyl)-6-oxospiro[2.5]octa-4,7-diene-1-carboxylate (**3ga**).* White solid: 73.0 mg, 85% yield; mp 169−171 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ = 8.22 (d, *J* = 8.4 Hz, 2H), 7.44 (d, *J* = 8.4 Hz, 2H), 6.87 (d, *J* = 2.8 Hz, 1H) 5.70 (d, *J* = 2.8 Hz, 1H), 4.32−4.25 (m, 2H), 3.75 (d, *J* = 7.6 Hz, 1H), 3.12 d, *J* = 7.6 Hz, 1H), 1.36 (t, *J* = 7.2 Hz, 3H), 1.28 (s, 9H), 1.07 ppm (s, 9H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ = 185.4, 168.8, 150.3, 150.1, 147.3, 142.4, 137.2, 136.6, 129.8, 123.7, 61.9, 39.0, 37.8, 36.1, 35.3, 35.1, 29.3, 29.0, 14.2 ppm; **IR**: $\bar{U}$ = 2958, 1727, 1523, 1347, 1184, 993, 741, 505 cm^{-1}; **HRMS** (ESI): *m*/*z* calcd for $[C_{25}H_{31}NO_5 + H]^+$ 426.2275; found 426.2269.

*Ethyl 5,7-Di-tert-butyl-6-oxo-2-(p-tolyl)spiro[2.5]octa-4,7-diene-1-carboxylate (**3ha**).* White solid: 74.8 mg, 95% yield; mp 154−157 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ = 7.14−7.08 (m, 4H), 6.88 (d, *J* = 2.8 Hz, 1H) 5.81 (d, *J* = 2.8 Hz, 1H), 4.30−4.19 (m, 2H), 3.67 (d, *J* = 7.2 Hz, 1H), 3.03 (d, *J* = 7.2 Hz, 1H), 2.34 (s, 3H), 1.34 (t, *J* = 7.2 Hz, 3H), 1.27 (s, 9H), 1.08 ppm (s, 9H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ = 185.8, 169.6, 149.24, 149.20, 139.0, 137.8, 137.3, 131.6, 129.2, 128.7, 61.5, 39.9, 38.0, 36.5, 35.2, 35.0, 29.3, 29.1, 21.1, 14.2 ppm; **IR**: $\bar{U}$ = 2957, 1728, 1622, 1457, 1517, 1287, 1181, 740 cm^{-1}; **HRMS** (ESI): *m*/*z* calcd for $[C_{26}H_{34}O_3 + H]^+$ 395.2581; found 395.2574.

*Ethyl 5,7-Di-tert-butyl-2-(4-methoxyphenyl)-6-oxospiro[2.5]octa-4,7-diene-1-carboxylate (**3ia**).* White solid: 69.0 mg, 84% yield; mp 150−153 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ = 7.13 (d, *J* = 8.4 Hz, 2H), 6.87−6.84 (m, 3H), 5.81 (d, *J* = 2.8 Hz, 1H), 4.30−4.19 (m, 2H), 3.81 (s, 3H), 3.65 (d, *J* = 7.2 Hz, 1H), 3.01 (d, *J* = 7.2 Hz, 1H),

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1.34 (t, J = 7.2 Hz, 3H), 1.27 (s, 9H), 1.08 ppm (s, 9H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ = 185.8, 169.6, 159.0, 149.3, 139.0, 137.8, 129.9, 126.8, 113.9, 61.6, 55.3, 39.6, 38.1, 36.7, 35.2, 35.0, 29.4, 29.1, 14.2 ppm; **IR**: $\bar{U}$ = 2957, 1727, 1620, 1517, 1252, 1181, 1037, 740 cm^{-1}; **HRMS** (ESI): m/z calcd for $[C_{26}H_{34}O_4 + H]^+$ 411.2530; found 411.2524.

*Ethyl 5,7-Di-tert-butyl-2-(3,4-dimethoxyphenyl)-6-oxospiro[2.5]-octa-4,7-diene-1-carboxylate (**3ja**).* White solid: 74.5 mg, 84% yield; mp 139−141 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ = 6.87−6.78 (m, 3H), 6.67 (s, 1H), 5.85 (d, J = 2.0 Hz, 1H), 4.28 (q, J = 7.2 Hz, 2H), 3.89 (s, 3H), 3.86 (s, 3H), 3.67 (d, J = 7.2 Hz, 1H), 3.01 (d, J = 7.2 Hz, 1H), 1.35 (t, J = 7.2 Hz, 3H), 1.28 (s, 9H), 1.09 ppm (s, 9H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ = 185.7, 169.5, 149.3, 149.2, 148.9, 148.5, 138.9, 137.7, 127.2, 120.9, 112.0, 110.9, 61.6, 55.9, 55.8, 39.9, 38.0, 36.8, 35.2, 35.0, 29.3, 29.1, 14.2 ppm; **IR**: $\bar{U}$ = 2957, 1727, 1621, 1462, 1254, 1182, 1028, 739 cm^{-1}; **HRMS** (ESI): m/z calcd for $[C_{27}H_{36}O_5 + H]^+$ 441.2636; found 441.2628.

*Ethyl 5,7-Di-tert-butyl-2-(3,4-dichlorophenyl)-6-oxospiro[2.5]-octa-4,7-diene-1-carboxylate (**3ka**).* White solid: 83.8 mg, 93% yield; mp 161−164 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.41 (d, J = 8.4 Hz, 1H), 7.34 (d, J = 1.6 Hz, 1H), 7.06 (dd, J = 8.4, 1.6 Hz, 1H), 6.82 (d, J = 2.8 Hz, 1H), 5.72 (d, J = 2.8 Hz, 1H), 4.34−4.14 (m, 2H), 3.61 (d, J = 7.2 Hz, 1H), 2.96 (d, J = 7.2 Hz, 1H), 1.34 (t, J = 7.2 Hz, 3H), 1.27 (s, 9H), 1.10 ppm (s, 9H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ = 185.6, 169.1, 150.1, 149.9, 137.7, 136.9, 135.2, 132.7, 131.9, 130.9, 130.5, 128.3, 61.8, 38.5, 37.5, 36.3, 35.3, 35.1, 29.3, 29.1, 14.2 ppm; **IR**: $\bar{U}$ = 2951, 1729, 1624, 1476, 1255, 1185, 883, 741 cm^{-1}; **HRMS** (ESI): m/z calcd for $[C_{25}H_{30}Cl_2O_3 + Na]^+$ 471.1464; found 471.1454.

*Ethyl 2-(Benzo[d][1,3]dioxol-5-yl)-5,7-di-tert-butyl-6-oxospiro-[2.5]octa-4,7-diene-1-carboxylate (**3la**).* White solid: 56.0 mg, 66% yield; mp 130−132 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ = 6.84 (d, J = 2.8 Hz, 1H), 6.76 (d, J = 8.4 Hz, 1H), 6.69−6.67 (m, 2H), 5.97 (s, 2H), 5.82 (d, J = 2.8 Hz, 1H), 4.30−4.19 (m, 2H), 3.62 (d, J = 7.2 Hz, 1H), 2.97 (d, J = 7.2 Hz, 1H), 1.34 (t, J = 7.2 Hz, 3H), 1.27 (s, 9H), 1.10 ppm (s, 9H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ = 185.8, 169.5, 149.39, 149.35, 147.8, 147.1, 138.8, 137.6, 128.5, 122.0, 109.3, 108.2, 101.2, 61.6, 39.9, 38.1, 36.7, 35.2, 35.0, 29.3, 29.2, 14.2 ppm; **IR**: $\bar{U}$ = 2955, 1727, 1621, 1454, 1251, 1177, 1038, 932, 740 cm^{-1}; **HRMS** (ESI): m/z calcd for $[C_{26}H_{32}O_5 + H]^+$ 425.2323; found 425.2317.

*Ethyl 5,7-Di-tert-butyl-2-(naphthalen-1-yl)-6-oxospiro[2.5]octa-4,7-diene-1-carboxylate (**3ma**).* Light yellow solid: 83.5 mg, 97% yield; mp 141−143 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ = 7.83−7.76 (m, 2 H), 7.49−7.38 (m, 4H), 7.38−7.34 (m, 1H) 7.11 (d, J = 2.8 Hz, 1H), 5.51 (d, J = 2.8 Hz, 1H), 4.38−4.26 (m, 2H), 3.97 (d, J = 7.2 Hz, 1H), 3.20 (d, J = 7.2 Hz, 1H), 1.38 (t, J = 7.2 Hz, 3H), 1.36 (s, 9H), 0.75 ppm (s, 9H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ = 185.4, 169.7, 150.4, 149.6, 139.0, 137.2, 133.4, 132.7, 132.0, 128.5, 128.4, 126.4, 126.2, 124.9, 123.8, 61.7, 38.4, 37.9, 36.8, 35.4, 34.6, 29.5, 28.6, 14.3 ppm; **IR**: $\bar{U}$ = 2956, 1728, 1622, 1459, 1387, 1255, 1176, 779 cm^{-1}; **HRMS** (ESI): m/z calcd for $[C_{29}H_{34}O_3 + K]^+$ 469.2140; found 469.2132.

*Ethyl 5,7-Di-tert-butyl-6-oxo-2-(pyridin-2-yl)spiro[2.5]octa-4,7-diene-1-carboxylate (**3na**).* White solid: 73.2 mg, 96% yield; mp 116−119 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ = 8.57 (d, J = 4.3 Hz, 1H), 7.62 (td, J = 7.7, 1.7 Hz, 1H), 7.33 (d, J = 7.8 Hz, 1H), 7.19−7.16 (m, 1H), 6.87 (d, J = 2.6 Hz, 1H), 6.66 (d, J = 2.6 Hz, 1H), 4.34−4.10 (m, 2H), 3.73 (d, J = 7.2 Hz, 1H), 3.66 (d, J = 7.2 Hz, 1H), 1.31 (t, J = 7.2 Hz, 4H), 1.27 (s, 9H), 1.10 ppm (s, 9H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ = 185.8, 169.6, 154.2, 149.50, 149.3, 148.9, 137.50, 137.1, 136.3, 124.8, 122.1, 61.50, 40.9, 39.50, 35.9, 35.2, 35.1, 29.3, 29.1, 14.2 ppm; **IR**: $\bar{U}$ = 2957, 1723, 1620, 1475, 1190, 993, 741 cm^{-1}; **HRMS** (ESI): m/z calcd for $[C_{24}H_{31}NO_3 + H]^+$ 382.2377; found 382.2373.

*Ethyl 5,7-Di-tert-butyl-2-methyl-6-oxospiro[2.5]octa-4,7-diene-1-carboxylate (**3oa**).* Light yellow solid: 62.3 mg, 98% yield; mp 123−125 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ = 6.69 (d, J = 2.8 Hz, 1H), 6.22 (d, J = 2.8 Hz, 1H), 4.21−4.09 (m, 2H), 2.42−2.35 (m, 2H), 1.35 (d, J = 6.0 Hz, 3H), 1.27−1.23 (m, 12H), 1.20 ppm (s, 9H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ = 185.8, 169.9, 150.0, 148.7, 139.0, 137.9, 61.3, 39.9, 36.9, 35.2, 35.1, 31.6, 29.34, 29.26, 14.2, 13.8 ppm; **IR**: $\bar{U}$ = 2957, 1726, 1621, 1458, 1298, 1182, 1054, 743 cm^{-1}; **HRMS** (ESI): m/z calcd for $[C_{20}H_{30}O_3 + Na]^+$ 341.2087; found 341.2080.

*Ethyl 2,5,7-Tri-tert-butyl-6-oxospiro[2.5]octa-4,7-diene-1-carboxylate (**3pa**).* White solid: 71.2 mg, 99% yield; mp 98−100 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ = 6.70 (d, J = 2.8 Hz, 1H), 6.51 (d, J = 2.8 Hz, 1H), 4.25−4.13 (m, 2H), 2.66 (d, J = 8.4 Hz, 1H), 2.35 (d, J = 8.4 Hz, 1H), 1.31 (t, J = 7.2 Hz, 3H), 1.26 (s, 9H), 1.24 (s, 9H), 1.04 ppm (s, 9H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ = 186.1, 170.1, 148.7, 148.3, 139.5, 137.8, 61.3, 48.7, 38.5, 36.6, 35.2, 35.0, 31.5, 29.8, 29.30, 29.25, 14.2 ppm; **IR**: $\bar{U}$ = 2958, 1728, 1622, 1460, 1255, 1180, 883, 675 cm^{-1}; **HRMS** (ESI): m/z calcd for $[C_{23}H_{36}O_3 + Na]^+$ 383.2557; found 383.2553.

*Ethyl 4′-Oxo-3-phenyl-4′H-spiro[cyclopropane-1,1′-naphthalene]-2-carboxylate (**3qa**).* White solid: 60.5 mg, 95% yield, mp 90−91 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ = 8.31−8.29 (m, 1H), 7.61−7.56 (m, 2H), 7.50−7.46 (m, 1H), 7.39−7.28 (m, 6H), 6.50 (d, J = 10.4 Hz, 1H), 6.26 (d, J = 10.4 Hz, 1H), 4.22 (d, J = 8.0 Hz, 1H), 4.13−4.00 (m, 2H), 3.19 (d, J = 8.0 Hz, 1H), 1.06 ppm (t, J = 7.2 Hz, 3H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ = 184.6, 167.2, 149.0, 139.0, 134.8, 133.5, 131.8, 129.1, 128.9, 128.8, 127.9, 127.23, 127.22, 123.9, 61.6, 39.7, 39.0, 36.8, 14.0 ppm; **IR**: $\bar{U}$ = 2982, 1728, 1656, 1461, 1303, 1190, 985, 764 cm^{-1}. For X-ray crystallographic analysis of **3qa**, see the Supporting Information.

*Ethyl 5,7-Dimethyl-6-oxo-2-phenylspiro[2.5]octa-4,7-diene-1-carboxylate (**3ra**).* Colorless oil: 47.4 mg, 80% yield; **^{1}H NMR** (400 MHz, $CDCl_3$) δ = 7.36−7.29 (m, 3H), 7.22 (d, J = 6.8 Hz, 2H), 6.96 (s, 1H), 5.93 (s, 1H), 4.31−4.18 (m, 2H), 3.74 (d, J = 7.2 Hz, 1H), 3.12 (d, J = 7.2 Hz, 1H), 1.99 (s, 3H), 1.81 (s, 3H), 1.33 ppm (t, J = 7.2 Hz); **^{13}C NMR** (100 MHz, $CDCl_3$) δ = 186.6, 169.4, 142.0, 141.3, 137.6, 137.4, 134.5, 128.73, 128.67, 127.8, 61.7, 40.0, 38.4, 35.8, 16.5, 16.3, 14.1 ppm; **IR**: $\bar{U}$ = 2923, 1726, 1625, 1449, 1279, 1181, 911, 738 cm^{-1}; **HRMS** (ESI): m/z calcd for $[C_{19}H_{20}O_3 + Na]^+$ 319.1305; found 319.1299.

*Ethyl 6-Oxo-2-phenyl-5,7-bis(trimethylsilyl)spiro[2.5]octa-4,7-diene-1-carboxylate (**3sa**).* White solid: 80.0 mg, 96% yield; mp 114−116 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ = 7.36−7.29 (m, 3H), 7.26−7.23 (m, 3H), 6.17 (d, J = 3.2 Hz, 1H), 4.30−4.22 (m, 2H), 3.80 (d, J = 7.2 Hz, 1H), 3.18 (d, J = 7.2 Hz, 1H), 1.35 (t, J = 7.2 Hz, 3H), 0.23 (s, 9H), 0.02 ppm (s, 9H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ = 191.7, 169.1, 154.0, 152.9, 143.8, 143.7, 134.2, 128.7, 128.6, 127.8, 61.8, 41.0, 39.2, 37.2, 14.2, −1.5, −1.7 ppm; **IR**: $\bar{U}$ = 2954, 1728, 1613, 1449, 1278, 1185, 861, 699, 613 cm^{-1}; **HRMS** (ESI): m/z calcd for $[C_{23}H_{32}O_3\ Si_2 + Na]^+$ 435.1782; found 435.1773.

*Methyl 5,7-Di-tert-butyl-6-oxo-2-phenylspiro[2.5]octa-4,7-diene-1-carboxylate (**3ab**).* Light yellow solid: 72.0 mg, 98% yield; mp 134−136 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ = 7.35−7.26 (m, 3H), 7.21 (d, J = 7.2 Hz, 2H), 6.90 (d, J = 2.4 Hz, 1H), 5.78 (d, J = 2.4 Hz, 1H), 3.80 (s, 3H), 3.72 (d, J = 7.2 Hz, 1H), 3.08 (d, J = 7.2 Hz, 1H), 1.28 (s, 9H), 1.07 ppm (s, 9H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ = 185.7, 170.0, 149.3, 138.7, 137.6, 134.6, 128.8, 128.5, 127.7, 52.5, 40.1, 37.9, 36.0, 35.2, 35.0, 29.3, 29.0 ppm; **IR**: $\bar{U}$ = 2924, 1722, 1611, 1259, 1071, 1039, 743, 488 cm^{-1}; **HRMS** (ESI): m/z calcd for $[C_{24}H_{30}O_3 + Na]^+$ 389.2087; found 389.2083.

*tert-Butyl 5,7-Di-tert-butyl-6-oxo-2-phenylspiro[2.5]octa-4,7-diene-1-carboxylate (**3ac**).* White solid: 80.5 mg, 98% yield; mp 174−177 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ = 7.34−7.24 (m, 3H), 7.22 (d, J = 7.2 Hz, 2H), 6.85 (d, J = 2.8 Hz, 1H), 5.79 (d, J = 2.8 Hz, 1H), 3.68 (d, J = 7.2 Hz, 1H), 3.01 (d, J = 7.2 Hz, 1H), 1.52 (s, 9H), 1.28 (s, 9H), 1.07 ppm (s, 9H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ = 185.8, 168.4, 149.3, 149.1, 139.1, 137.8, 134.9, 128.8, 128.4, 127.5, 82.1, 39.7, 37.8, 37.4, 35.2, 35.0, 29.4, 29.1, 28.0 ppm; **IR**: $\bar{U}$ = 2923, 1707, 1619, 1459, 1369, 1255, 1152, 743 cm^{-1}; **HRMS** (ESI): m/z calcd for $[C_{27}H_{36}O_3 + Na]^+$ 431.2557; found 431.2549.

*Benzyl 5,7-Di-tert-butyl-6-oxo-2-phenylspiro[2.5]octa-4,7-diene-1-carboxylate (**3ad**).* White solid: 88.2 mg, 99% yield; mp 108−111 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ = 7.39−7.24 (m, 8H), 7.20 (d, J = 7.2 Hz, 2H), 6.87 (d, J = 2.0 Hz, 1H), 5.77 (d, J = 2.0 Hz, 1H), 5.23 (d, J = 1.6 Hz, 1H), 3.74 (d, J = 7.2 Hz, 1H), 3.13 (d, J = 7.2 Hz, 1H), 1.25 (s, 9H), 1.06 ppm (s, 9H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ = 185.6, 169.4, 149.4, 149.3, 138.7, 137.4, 135.2, 134.6, 128.8, 128.7,

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128.6, 128.5, 127.6, 67.4, 40.1, 38.0, 36.2, 35.2, 35.0, 29.3, 29.0 ppm; **IR**: $\bar{U}$ = 2955, 1730, 1623, 1457, 1281, 1164, 698 cm^{-1}; **HRMS** (ESI): *m*/*z* calcd for $[C_{30}H_{34}O_3 + Na]^+$ 465.2400; found 465.2391.

*Phenyl 5,7-Di-tert-butyl-6-oxo-2-phenylspiro[2.5]octa-4,7-diene-1-carboxylate (**3ae**).* White solid: 80.0 mg, 93% yield; mp 151−154 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ = 7.44−7.25 (m, 8H), 7.13 (d, *J* = 7.6 Hz, 2H), 6.93 (d, *J* = 2.0 Hz, 1H), 5.86 (d, *J* = 2.0 Hz, 1H), 3.82 (d, *J* = 7.2 Hz, 1H), 3.30 (d, *J* = 7.2 Hz, 1H), 1.29 (s, 9H), 1.10 ppm (s, 9H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ = 185.7, 168.4, 150.5, 149.9, 149.7, 138.4, 137.1, 134.4, 129.6, 128.8, 128.6, 127.8, 126.2, 121.3, 40.3, 38.4, 36.1, 35.3, 35.1, 29.4, 29.1 ppm; **IR**: $\bar{U}$ = 2957, 1739, 1621, 1457, 1195, 1138, 964, 744 cm^{-1}; **HRMS** (ESI): *m*/*z* calcd for $[C_{29}H_{32}O_3 + Na]^+$ 451.2244; found 451.2233.

*1-Benzoyl-5,7-di-tert-butyl-2-phenylspiro[2.5]octa-4,7-dien-6-one (**3af**).* White solid: 53.7 mg, 65% yield; mp 167−169 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ = 7.87 (d, *J* = 7.6 Hz, 2H), 7.60 (t, *J* = 7.6 Hz, 1H), 7.49 (t, *J* = 7.6 Hz, 2H), 7.36−7.26 (m, 5H), 6.62 (d, *J* = 2.4 Hz, 1H), 6.03 (d, *J* = 2.4 Hz, 1H), 4.09 (d, *J* = 7.2 Hz, 1H), 3.97 (d, *J* = 7.2 Hz, 1H), 1.16 (s, 9H), 1.14 ppm (s, 9H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ = 194.6, 185.6, 150.1, 149.8, 138.5, 137.53, 137.49, 135.2, 133.5, 129.1, 128.8, 128.6, 128.2, 127.7, 40.8, 40.4, 40.0, 35.1, 29.2 ppm; **IR**: $\bar{U}$ = 2956, 1648, 1451, 1367, 1220, 1089, 898, 694 cm^{-1}; **HRMS** (ESI): *m*/*z* calcd for $[C_{29}H_{32}O_2 + Na]^+$ 435.2295; found 435.2286.

*5,7-Di-tert-butyl-1-(4-methoxybenzoyl)-2-phenylspiro[2.5]octa-4,7-dien-6-one (**3ag**).* White solid: 78.3 mg, 88% yield; mp 168−171 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ = 7.87 (d, *J* = 8.4 Hz, 2H), 7.36−7.26 (m, 5H), 6.94 (d, *J* = 8.4 Hz, 2H), 6.62 (d, *J* = 2.0 Hz, 1H), 6.04 (d, *J* = 2.0 Hz, 1H), 4.08 (d, *J* = 7.6 Hz, 1H), 3.94 (d, *J* = 7.6 Hz, 1H), 3.86 (s, 3H), 1.16 (s, 9H), 1.14 ppm (s, 9H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ = 192.7, 185.6, 163.8, 149.8, 149.5, 138.7, 137.9, 135.3, 130.5, 130.4, 129.0, 128.5, 127.5, 113.9, 55.5, 40.5, 40.0, 39.8, 35.1, 35.0, 29.2 ppm; **IR**: $\bar{U}$ = 2956, 1646, 1600, 1426, 1233, 1167, 1041, 702 cm^{-1}; **HRMS** (ESI): *m*/*z* calcd for $[C_{30}H_{34}O_3 + Na]^+$ 465.2400; found 465.2391.

General Procedure for the Preparation of 1-Benzoyl-5,7-di-*tert*-butyl-2-phenylspiro[2.5]octa-4,7-dien-6-one (−)-3af. To a solution of *para*-quinone methide **1a** (14.7 mg, 0.05 mmol) and chiral sulfonium salt (*S*)-BINS-**2f** (37.0 mg, 0.07 mmol) in $CHCl_3$ (1.0 mL) was added DBU (11.4 mg, 0.075 mmol). The resulting mixture was stirred vigorously at the 0 °C for 50 h. The solvent was concentrated under reduced pressure, and the resulting residue was purified by flash column chromatography on silica gel (*Note: silica gel was neutralized by triethylamine before use*) eluting with petroleum ether/ethyl acetate (petroleum ether/ethyl acetate = 50/1) giving the product (−)-**3af** (15.0 mg, 73% yield, 81% ee, $[\alpha]_D^{22}$ −180 (*c* 1, $CHCl_3$)). The enantiomeric ratio was determined by Chiralpak IB-3, *n*-hexane/2-propanol = 99/1, *v* = 1.0 mL·min^{-1}, λ = 260.0 nm, t_R (major) = 7.4 min, t_R (minor) = 5.2 min.

General Procedure for $Zn(OTf)_2$-Catalyzed Ring-Opening Reactions of the Spirocyclopropanyl *para*-Dienone. To a 10 mL Schlenk tube were sequentially added anhydrous $Zn(OTf)_2$ (unless otherwise noted, 3.6 mg, 0.01 mmol), *para*-dienone **3aa** (0.1 mmol), and CH_2Cl_2 (1.0 mL) under argon. Then, the specified nucleophile (unless otherwise noted, 2.0 equiv) was added to the resulting mixture. After stirring vigorously under a nitrogen atmosphere at room temperature for the indicated time, the reaction was quenched with H_2O (10 mL), extracted with ethyl acetate (3 × 10 mL), and dried over anhydrous Na_2SO_4. The solvent was concentrated under reduced pressure, and the residue was purified by flash column chromatography on silica gel, giving the ring-opening product.

*Ethyl 2-(3,5-Di-tert-butyl-4-hydroxyphenyl)-3-methoxy-3-phenyl Propanoate(**4a**).* Following the above-mentioned general procedure, MeOH (0.5 mL) as the specified nucleophile was used in this case to afford the product **4a** (white solid, 36.4 mg, 88% yield, mp 102−103 °C); **^{1}H NMR** (400 MHz, $CDCl_3$) δ = 7.13−7.12 (m, 3H), 6.93−6.91(m, 2H), 6.74 (s, 2H), 5.01 (s, 1H), 4.53 (d, *J* = 10.4 Hz, 1H), 4.32−4.16 (m, 2H), 3.64 (d, *J* = 10.4 Hz, 1H), 3.24 (s, 3H), 1.32−1.28 ppm (m, 21H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ = 172.9, 152.8, 139.0, 135.4, 127.7, 127.4, 125.3, 125.2, 86.5, 60.7, 59.5, 57.0, 34.1, 30.1, 14.2 ppm; **IR**: $\bar{U}$ = 2957, 1732, 1436, 1369, 1238, 1158, 1103, 701 cm^{-1}. For X-ray crystallographic analysis of **4a**, see the Supporting Information.

*Ethyl 2-(3,5-Di-tert-butyl-4-hydroxyphenyl)-3-phenoxy-3-phenyl Propanoate (**4b**).* Following the above-mentioned general procedure, PhOH (0.2 mmol) as the specified nucleophile was used in this case to afford the product **4b** (light yellow solid, 40.5 mg, 85% yield, mp 101−103 °C); **^{1}H NMR** (400 MHz, $CDCl_3$) δ = 7.17−7.08 (m, 5H), 6.96−6.94 (m, 2H), 6.87−6.84 (m, 3H), 6.78 (s, 2H), 5.43 (d, *J* = 10.4 Hz, 1H), 5.08 (s, 1H), 4.35−4.27 (m, 1H), 4.20−4.09 (m, 1H), 3.91 (d, *J* = 10.4 Hz, 1H), 1.29−1.25 ppm (m, 21H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ = 172.3, 158.0, 153.1, 138.7, 135.6, 129.2, 127.9, 127.5, 126.9, 125.5, 124.4, 121.0, 116.4, 83.2, 60.9, 59.7, 34.1, 30.1, 14.2 ppm; **IR**: $\bar{U}$ = 2956, 1733, 1597, 1493, 1236, 1159, 1033, 753 cm^{-1}; **HRMS** (ESI): *m*/*z* calcd for $[C_{31}H_{38}O_4 + Na]^+$ 497.2662; found 497.2652.

*Ethyl 2-(3,5-Di-tert-butyl-4-hydroxyphenyl)-3-phenyl-3-(phenylthio) Propanoate (**4c**).* Following the above-mentioned general procedure, PhSH (0.2 mmol) as the specified nucleophile was used in this case to afford the product **4c** (white solid, 45.0 mg, 92% yield, mp 102−104 °C); **^{1}H NMR** (400 MHz, $CDCl_3$) δ = 7.28−7.25 (m, 2H), 7.19−7.17 (m, 3H), 7.02−6.99 (m, 3H), 6.92−6.89 (m, 2H), 6.84 (s, 2H), 4.98 (s, 1H), 4.63 (d, *J* = 11.2 Hz, 1H), 4.35−4.27 (m, 1H), 4.19−4.11 (m, 1H), 3.90 (d, *J* = 11.2 Hz, 1H), 1.33 (t, *J* = 7.2 Hz, 3H), 1.27 ppm (s, 18H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ = 172.5, 152.8, 139.8, 135.3, 134.3, 132.9, 128.6, 128.5, 127.6, 127.4, 126.6, 126.5, 125.3, 61.0, 57.6, 57.2, 34.1, 30.1, 14.2 ppm; **IR**: $\bar{U}$ = 2958, 1732, 1587, 1436, 1263, 1153, 1031, 741 cm^{-1}; **HRMS** (ESI): *m*/*z* calcd for $[C_{31}H_{38}O_3S_1 + Na]^+$ 513.2434; found 513.2419.

*Ethyl 3-Azido-2-(3,5-di-tert-butyl-4-hydroxyphenyl)-3-phenyl Propanoate (**4d**).* Following the above-mentioned general procedure, anhydrous $Zn(OTf)_2$ (0.1 mmol) as catalyst and NaN_3 (0.2 mmol) as the specified nucleophile were used in this case to afford the product **4d** (colorless oil, 40.2 mg, 95% yield); **^{1}H NMR** (400 MHz, $CDCl_3$) δ = 7.19−7.17 (m, 3H), 6.97−6.94 (m, 2H), 6.73 (s, 2H), 5.06 (s, 1H), 4.93 (d, *J* = 11.2 Hz, 1H), 4.37−4.16 (m, 2H), 3.65 (d, *J* = 11.2 Hz, 1H), 1.33 (t, *J* = 7.2 Hz, 3H), 1.27 ppm (s, 18H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ = 172.2, 153.2, 137.1, 135.7, 128.2, 128.0, 127.6, 125.1, 124.8, 69.2, 61.2, 58.2, 34.2, 30.1, 14.2 ppm; **IR**: $\bar{U}$ = 2958, 2105, 1731, 1436, 1238, 1159, 700 cm^{-1}; **HRMS** (ESI): *m*/*z* calcd for $[C_{25}H_{33}N_3O_3 + Na]^+$ 446.2414; found 446.2406.

*Ethyl 2-(3,5-Di-tert-butyl-4-hydroxyphenyl)-3-phenyl-3-(phenylamino)propanoate (**4e**).* Following the above-mentioned general procedure, $PhNH_2$ (0.2 mmol) as the specified nucleophile was used in this case to afford the product **4e** (white solid, 41.3 mg, 87% yield, mp 130−132 °C); **^{1}H NMR** (400 MHz, $CDCl_3$) δ = 7.17−7.11 (m, 3H), 7.07−7.03 (m, 4H), 6.97 (s, 2H), 6.61 (t, *J* = 7.2 Hz, 1H), 6.53 (d, *J* = 8.0 Hz, 2H), 5.09 (s, 1H), 4.90−4.79 (m, 2H), 4.23−4.06 (m, 2H), 3.80 (d, *J* = 8.0 Hz, 1H), 1.33 (s, 18H), 1.20 ppm (t, *J* = 7.2 Hz, 3H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ = 172.7, 153.1, 146.9, 140.9, 135.5, 129.0, 128.1, 127.0, 126.9, 125.9, 125.5, 117.4, 113.6, 61.4, 60.9, 58.6, 34.2, 30.2, 14.1 ppm; **IR**: $\bar{U}$ = 2958, 1724, 1602, 1435, 1264, 1157, 741, 699 cm^{-1}; **HRMS** (ESI): *m*/*z* calcd for $[C_{31}H_{39}N_1O_3 + H]^+$ 474.3003; found: 474.2994.

*Ethyl 3-(1-Benzyl-5-bromo-1H-indol-3-yl)-2-(3,5-di-tert-butyl-4-hydroxyphenyl)-3-phenylpropanoate (**4f**).* Following the above-mentioned general procedure, *N*-benzyl-5-bromoindole (BBI-H, 0.2 mmol) as the specified nucleophile was used in this case to afford the product **4f** (white solid, 56.5 mg, 85% yield, mp 163−165 °C); **^{1}H NMR** (400 MHz, $CDCl_3$) δ = 7.57 (s, 1H), 7.32−7.24 (m, 4H), 7.16 (d, *J* = 8.8 Hz, 1H), 7.06−6.97 (m, 6H), 6.88−6.86 (m, 4H), 5.29 (s, 2H), 5.02 (s, 1H), 4.67 (d, *J* = 12.0 Hz, 1H), 4.07 (d, *J* = 12.0 Hz, 1H), 4.02−3.96 (m, 1H), 3.92−3.84 (m, 1H), 1.31 (s, 18H), 1.02 ppm (t, *J* = 7.2 Hz, 3H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ = 173.2, 152.8, 141.7, 137.3, 135.43, 135.40, 129.5, 128.8, 128.4, 127.8, 127.7, 127.4, 126.5, 126.0, 125.9, 125.2, 124.9, 122.3, 117.6, 112.5, 110.9, 60.5, 57.8, 50.2, 47.4, 34.2, 30.2, 14.0 ppm; **IR**: $\bar{U}$ = 2958, 1728, 1494, 1436, 1254, 1154, 738, 700 cm^{-1}; **HRMS** (ESI): *m*/*z* calcd for $[C_{40}H_{44}Br_1N_1O_3 + Na]^+$ 688.2397; found 688.2381.

General Procedure for the Silica Gel-Promoted Ring-Opening Reaction of the Spirocyclopropanyl *para*-Dienone.

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To a solution of *para*-dienone **3aa** (19.0 mg, 0.05 mmol) in CH_2Cl_2 (4.0 mL) was added silica gel (500 mg). The resulting mixture was stirred vigorously at room temperature for 18 h. The mixture was purified by flash column chromatography on silica gel eluting with CH_2Cl_2, giving the product **4g**.

*Ethyl 2-(3,5-Di-tert-butyl-4-hydroxyphenyl)-3-hydroxy-3-phenyl Propanoate (**4g**).* White solid: 19.0 mg, 95% yield, mp 145−146 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ = 7.18−7.16 (m, 3H), 7.02−7.00 (m, 2H), 6.74 (s, 2H), 5.05 (s, 1H), 5.02 (dd, J = 4.0 Hz, 9.2 Hz, 1H), 4.31−4.15 (m, 2H), 3.73 (d, J = 9.2 Hz, 1H), 3.11 (d, J = 4.0 Hz, 1H), 1.30 (s, 9H), 1.27 ppm (t, J = 7.2 Hz, 1H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ = 173.9, 153.0, 141.3, 135.7, 127.8, 127.5, 126.6, 125.8, 125.1, 77.1, 61.01, 59.95, 34.2, 30.2, 14.1 ppm; **IR**: $\bar{U}$ = 2954, 1730, 1433, 1213, 1148, 1042, 766, 699 cm^{-1}. For X-ray crystallographic analysis of **4g**, see the Supporting Information.

General Procedure for the SmI_2-Mediated Ring-Opening Reaction of the Spirocyclopropanyl *para*-Dienone. To a 10 mL Schlenk tube were added *para*-dienone **3aa** (0.1 mmol) and THF (1.0 mL). Then, the solution of SmI_2 in THF (0.1 mmol/mL, 2 mL) and *t*-BuOH (0.5 mL) was dropwise added at −78 °C. The resulting mixture was stirred vigorously under an argon atmosphere at −78 °C for 25 h. The reaction was quenched with saturated aqueous $NaHCO_3$ solution (10 mL), extracted with CH_2Cl_2 (3 × 10 mL), and dried over anhydrous Na_2SO_4. The solvent was concentrated under reduced pressure, and the residue was purified by flash column chromatography on silica gel, giving the product **5a**.

*Ethyl 3-(3,5-Di-tert-butyl-4-hydroxyphenyl)-3-phenylpropanoate (**5a**).* White solid: 18.3 mg, 48% yield; mp 83−84 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ = 7.29−7.25 (m, 4H), 7.19−7.15 (m, 1H), 7.02 (s, 2H), 5.04 (s, 1H), 4.46 (t, J = 8.0 Hz, 1H), 4.03 (q, J = 7.2 Hz, 2H), 3.00 (dd, J = 6.0 Hz, 8.4 Hz, 2H), 1.39 (s, 18H), 1.09 ppm (t, 7.2 Hz, 3H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ = 172.1, 152.2, 144.0, 135.7, 134.1, 128.4, 127.7, 126.3, 124.2, 60.3, 47.2, 41.6, 34.4, 30.3, 14.1 ppm; **IR**: $\bar{U}$ = 2925, 1734, 1436, 1372, 1157, 1030, 739, 701 cm^{-1}; **HRMS** (ESI): m/z calcd for $[C_{25}H_{34}O_3 + Na]^+$ 405.2400; found 405.2393.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.joc.5b02725.

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

X-ray crystallographic data for **3aa** (CIF)

X-ray crystallographic data for **3qa** (CIF)

X-ray crystallographic data for **4a** (CIF)

X-ray crystallographic data for **4g** (CIF)

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Notes

The authors declare no competing financial interest.

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