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Copper-catalyzed asymmetric silylative cyclization of cyclohexadienone-containing 1,6-enynes

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ABSTRACT

The first copper-catalyzed asymmetric silylative cyclization of cyclohexadienone-containing 1,6-enynes has been accomplished through a tandem process: regioselective silylcupration of terminal unactivated alkynes and subsequently enantioselective conjugate addition to cyclohexadienones. This reaction proceeded smoothly to afford the *cis*-hydrobenzofuran and *cis*-hydroindole frameworks bearing two consecutive chiral carbon centers in high to excellent yields and moderate enantioselectivities. Additionally, the cyclization products could be readily subjected to several transformations for elaborating synthetic utilities.

1. Introduction

Alkenylsilanes have found widespread applications in modern organic synthesis community as versatile building blocks, which could be efficiently utilized in Fleming-Tamao oxidation, palladium-catalyzed cross-coupling reactions, etc [1]. In recent years, transition-metal-catalyzed tandem silylation of alkynes by trapping the alkenylsilyl-metal intermediates with various electrophiles has been extensively studied, affording a variety of functionalized alkenylsilanes [2]. Among these works, the silylative cyclization of 1,6-enynes has spurred substantial interests of chemists for its applications in the construction of five-membered carbocyclic and heterocyclic frameworks since its first report by Ojima and coworkers in 1992 [3]. Subsequently, several research groups have made contributions in this field [4]. However, the asymmetric variants still remain extremely rare [5,6]until 2003 Widenhoefer and co-workers disclosed the first example of the asymmetric silylative cyclization of 1,6-enynes catalyzed by a cationic rhodium bis(phosphine) complex to offer silylated alkylidenecyclopentanes in good to excellent enantioselectivities (Scheme 1a) [5]. Soon afterwards, Zhou and coworkers achieved the excellent enantioselectivities in the same reaction using a powerful catalyst, namely the rhodium complex of spiro diphosphine SDP (Scheme 1a) [6]. Although these elegant reports have exerted a significant impact in this field [7], the non-noble metal catalysis, including Cu-catalyzed asymmetric silylative cyclization of cyclohexadienone-containing 1,6-enynes is under developed, which generates more than one stereocenters to gain access to more complicated bicyclic scaffolds.

Recently, we have devoted to the subject of transition-metal-catalyzed desymmetrization of cyclohexadienone-containing 1,6-enynes and 1,6-enallenes [8]. Encouraged by these advances, we decide to investigate the Cu-catalyzed asymmetric silylative cyclization of cyclohexadienone-containing 1,6-enynes (Scheme 1b). In the presence of a silylboronate reagent ($PhMe_2Si$-Bpin) introduced by Suginome and Ito [9], the direct conjugate silylation of enone need to be minimized in order to obtain the cyclization products, and such pathway is supposed to be suppressed by the neighboring

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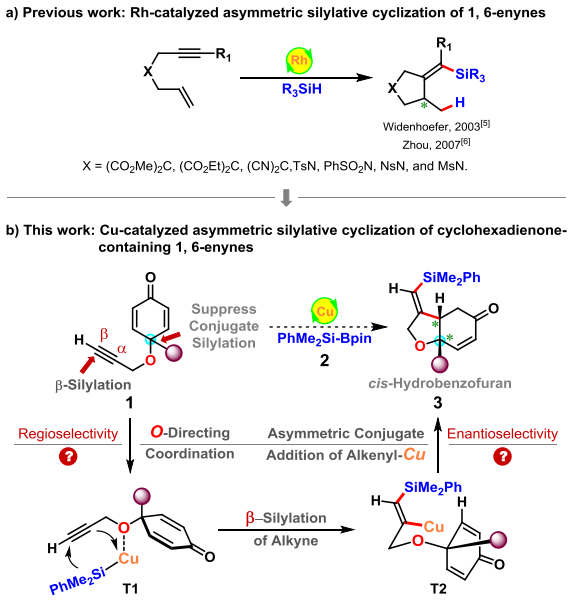


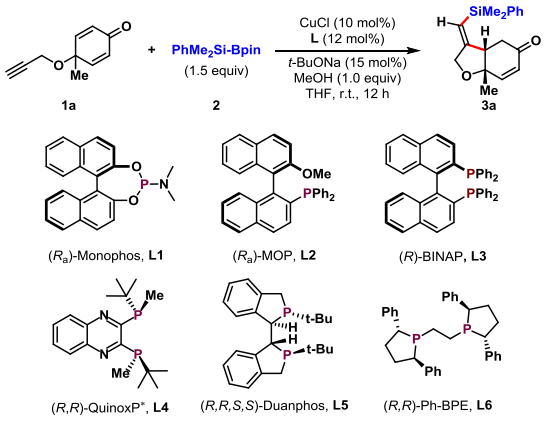
Scheme 1. Strategic design of Cu-catalyzed asymmetric silylative cyclization of cyclohexadienone-containing 1,6-enynes.

steric hindrance [10]. The regioselective α-silylcupration over β-silylcupration process has been found in the Cu-catalyzed hydrosilylation of terminal unactivated alkynes [11]. However, the regioselective β-silylcupration of terminal alkynes is supposed to take place due to the O-coordination between copper and the propargyl ether unit in our case (Scheme 1, **T1**). Then, the resulting silylated alkenyl-copper intermediates (**T2**) undergo enantioselective conjugate addition to the cyclohexadienone moieties in a *syn*-fashion to generate the desired silylative cyclization products. Nevertheless, the enantioselective control remains quite challenging during the cyclization process.

2. Results/discussion

With these considerations in mind, we commenced to investigate the silylative cyclization of the model substrate **1a** with PPh_3 as the ligand. To our delight, the desired racemic product **3a** was obtained in almost quantitative yield (Table 1, entry 1). In order to gain the enantioenriched product, chiral monophosphine ligands, including (R_a)-Monophos (**L1**) and (R_a)-MOP (**L2**) were immediately examined. However, low yields and no enantioselectivities were observed to our disappointment (Table 1, entries 2 and 3). Next, a set of privileged nonracemic bisphosphine ligands were evaluated and selected results were summarized in Table 1 [12]. As for the commonly used bisphosphine ligand, (*R*)-BINAP (**L3**), high yield and poor enantioselectivity (16% *ee*) was obtained (Table 1, entry 4). When electronically biased bisphosphine ligand, (*R, R*)-Quinoxp* (**L4**) was used in this reaction, the desired product was formed in very low yield (Table 1, entry 5). Electron-rich bisphosphine ligand, (*R,R,S,S*)-Duanphos (**L5**), promoted the reaction with good yield, but showed almost invalid in the enantioselective control (Table 1, entry 6). Eventually, (*R,R*)-Ph-BPE (**L6**) was found to be an optimal choice for the Cu-catalyzed silylative cyclization of 1,6-enyne (Table 1, entry 7). Other solvents, including toluene and diethyl ether, were used instead of THF, but no further improvement was observed (Table 1, entries 8 and 9). When *t*-BuOH and KF were used instead of MeOH and *t*-BuONa, respectively, a slightly better enantioselectivity (71% *ee*) was achieved (Table 1, entry 10).

Table 1
Selected optimization studies.[a]



Entry	L	Solvent	Yield [%][b]	*ee*[c]
1	PPh_3	THF	98	0
2	**L1**	THF	35	0
3	**L2**	THF	<10	–
4	**L3**	THF	77	16
5	**L4**	THF	<10	–
6	**L5**	THF	80	5
7	**L6**	THF	99[d]	68
8	**L6**	Toluene	99[d]	53
9	**L6**	Et_2O	95[d]	50
10[e]	**L6**	THF	96[d]	71

[a] Reactions were performed under an Ar atmosphere.
[b] Determined by ^1H NMR (400 MHz) analysis of crude mixtures.
[c] Determined by HPLC analysis.
[d] Yield of isolated product **3a**.
[e] *t*-BuOH and KF were used instead of MeOH and *t*-BuONa, respectively.

With the optimal reaction condition identified, various substrates were investigated and the results are summarized in Table 2. With the R substituent as alkyl, cycloalkyl, phenyl, benzyl, vinyl, and allyl group, the reactions proceeded smoothly with excellent yields (88–98%) and moderate enantioselectivities (up to 71% *ee*, Table 2, **3a**–**3j**). With a heteroatom (Br, I, O, Si, S, and N) as part of R in the substrates **1**, the outcome of the reactions remained promising, and the absolute configuration of (*S,S*)-**3k** was unambiguously determined by X-ray crystallography (Table 2, **3k**–**3r**) [12,13]. It is a remarkable fact that the bromo- and iodopropyl groups in substrates **1k** and **1m** could be tolerated in this reaction, which implied that the silylated alkenyl-copper intermediates selectively underwent conjugate addition to enone rather than nucleophilic substitution in both cases [14]. As for the pharmaceutical compound, estrone-tethered 1,6-enyne **1s**, the cyclization occurred uneventfully with high yield and moderate diastereoselectivity (80:20 d.r., Table 2, **3s**). In consistence with O-linked substrates, the N-linked 1,6-enyne **1t** also afforded the corresponding *cis*-hydroindole product. However, the C-linked 1,6-enyne **1u** underwent direct protonation after silylcupration of alkyne and failed to generate the cyclization product, presumably due to the absence of the Thorpe-Ingold effect [15]. As for the cyclohexadienone-tethered internal alkyne substrate **1v**, the silylative cyclization also happened with 32% yield but low enantioselectivity (31% *ee*). The main byproduct is the further conjugate silylation product.

To demonstrate the utility of the cyclization products, their further transformations were elaborated in Scheme 2. The alkenylsilane **3a** was readily converted, through Hiyama cross-coupling with phenyl iodide, to a known compound (*S,S*)-**4a** [16]. When **3m**

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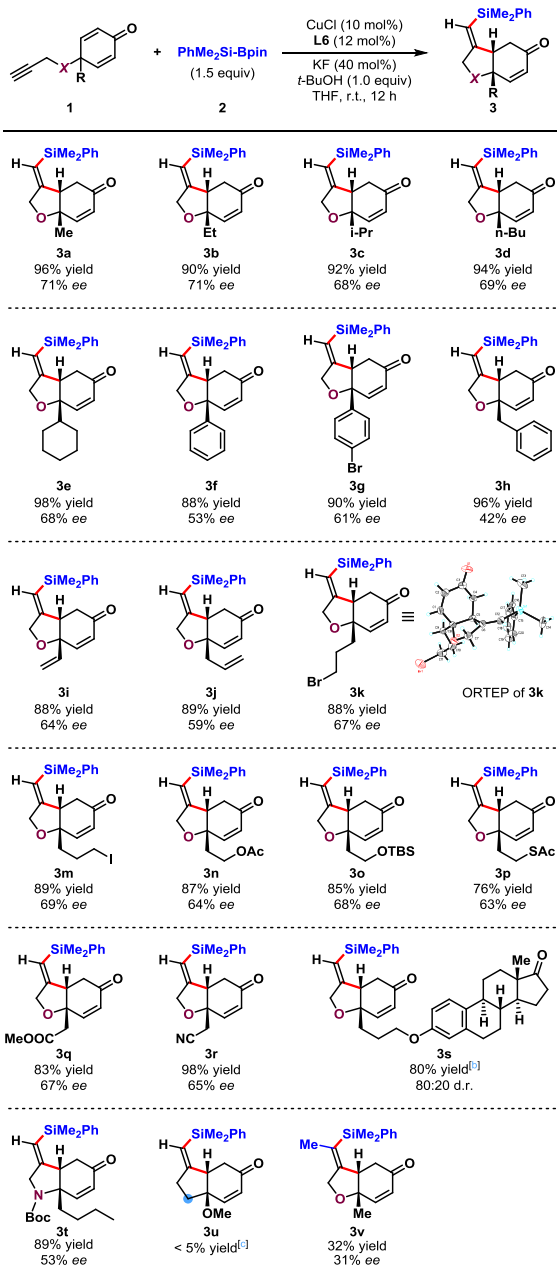
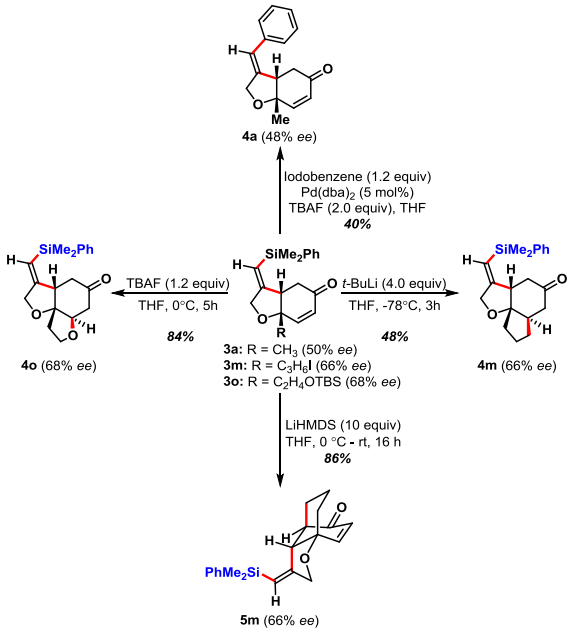
Table 2
Substrate scope.[a]



[a] Reaction with 0.1 mmol **1** and performed under an Ar atmosphere. Yields correspond to isolated and purified products. Ee values were determined by chiral HPLC analysis. [b] Reaction was performed at 0 °C. [c] Determined by ^{1}H NMR analysis of crude mixtures.

was treated with *t*-BuLi, the resulting alkyllithium underwent an intramolecular Michael addition to deliver the tricyclic ketone **4m**. Alternatively, a weaker base LiHMDS could promoted an intramolecular alkylation reaction to afford the bridged ring product **5m**. Additionally, an intramolecular oxa-Michael addition reaction occurred equally well *in situ* in a syn fashion to furnish **4o** after removing the *t*-butyldimethylsilyl protecting group in **3o** under TBAF conditions. All transformations as above proceeded smoothly with almost no loss of the enantiomeric excesses.



Scheme 2. Synthetic transformation.

3. Conclusion

In summary, through tandem regioselective silylcupration of terminal unactivated alkynes and enantioselective conjugate addition to cyclohexadienones, copper-catalyzed asymmetric silylative cyclization of cyclohexadienone-containing 1,6-enynes has been developed with high efficiency, thus providing enantioenriched *cis*-hydrobenzofuran and *cis*-hydroindole frameworks with high to excellent yields (up to 98%) and moderate enantioselectivities (up to 71% *ee*). Meanwhile, this mild transformation is well compatible with a wide range of functional groups, which allows further conversion of the cyclization products to the bridged and tricyclic ring structures. Further studies on the applications of the cyclohexadienone-containing 1,6-enynes are in progress in our laboratories and will be reported in due course.

4. Experimental section

4.1. General methods

All solvents were dried before use following the standard procedures. Unless otherwise indicated, all starting materials were obtained from commercial suppliers and were used without further purification. The ^{1}H and ^{13}C NMR spectra were recorded on Bruker AV-400 MHz in the indicated solvents. Chemical shifts are reported in δ (ppm) referenced to an internal TMS standard for ^{1}H NMR and $CDCl_3$ ($\delta = 77.0$ ppm) for ^{13}C NMR. Coupling constants (J) are quoted in Hz. Optical rotations were measured on a JASCO P-1030 polarimeter. IR spectra were recorded on Nicolet iN 10 MX. ESI mass spectra were recorded on Agilent1200/G6100A.

4.2. General procedure for the synthesis of *3a-3v*

A dried Schlenk flask was charged with CuCl (1.0 mg, 0.01 mmol, 10 mol%), ligand **L6** (6.1 mg, 0.012 mmol, 12 mol%), $PhMe_2Si$-Bpin (**2**, 41 μL, 0.15 mmol, 1.5 equiv), KF (2.4 mg, 0.040 mmol, 40 mol%) and anhydrous THF (1.0 mL) under argon atmosphere. After the mixture was stirred at room temperature for 10 min, a solution of

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substrate **1** (0.10 mmol) in anhydrous THF (1.0 mL) was added, followed by anhydrous *t*-BuOH (9 μL, 0.10 mmol, 1.0 equiv). The resulting mixture was stirred at room temperature for 12 h. Then the reaction mixture was filtered, washed with EtOAc (5 mL × 3), dried over anhydrous Na_2SO_4, filtered and concentrated in vacuo. The residue was purified by flash silica gel (300–400 mesh) chromatography to afford the desired products **3**.

*4.2.1. (3aS,7aS,E)-3-((Dimethyl(phenyl)silyl)methylene)-7a-methyl-2,3,3a,4-tetrahydrobenzofuran-5(7aH)-one (**3a**)*

Colorless oil. 28.5 mg, 96% yield. $[\alpha]_D^{25.0}$ -119.2 (*c* 0.75, $CHCl_3$) for 71% *ee*. ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.55–7.52 (m, 2H), 7.38–7.35 (m, 3H), 6.55 (d, *J* = 10.0 Hz, 1H), 5.96 (d, *J* = 10.0 Hz, 1H), 5.60–5.59 (m, 1H), 4.47–4.35 (m, 2H), 2.70–2.67 (m, 1H), 2.55–2.49 (m, 1H), 2.25–2.16 (m, 1H), 1.33 (s, 3H), 0.46 (s, 3H), 0.37 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 197.3, 159.6, 149.6, 138.2, 133.7, 129.6, 129.3, 128.0, 118.6, 79.3, 72.5, 47.3, 38.8, 24.3, −0.7, −1.8. HRMS (ESI): $[M+H]^{\oplus}$ calcd for $C_{18}H_{23}O_2Si^{\oplus}$ 299.1462, found 299.1463. IR (KBr) ν (cm^{-1}) 3336, 3068, 2964, 2855, 1686, 1427, 1389, 1276, 1111, 1000, 817, 702, 473.

*4.2.2. (3aS,7aS,E)-3-((Dimethyl(phenyl)silyl)methylene)-7a-ethyl-2,3,3a,4-tetrahydrobenzofuran-5(7aH)-one (**3b**)*

Colorless oil. 28.0 mg, 90% yield. $[\alpha]_D^{25.6}$ -95.4 (*c* 1.15, $CHCl_3$) for 71% *ee*. ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.55–7.53 (m, 2H), 7.37–7.34 (m, 3H), 6.57 (d, *J* = 10.0 Hz, 1H), 6.01 (d, *J* = 10.0 Hz, 1H), 5.59–5.58 (m, 1H), 4.48–4.31 (m, 2H), 2.77–2.73 (m, 1H), 2.53–2.47 (m, 1H), 2.25–2.20 (m, 1H), 1.62 (q, *J* = 6.4 Hz, 2H), 0.81 (t, *J* = 6.4 Hz, 3H), 0.46 (s, 3H), 0.37 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 197.6, 160.1, 148.4, 138.2, 133.7, 130.6, 129.3, 128.0, 118.5, 82.0, 72.4, 44.6, 39.3, 30.3, 8.0, −0.8, −1.7. HRMS (ESI): $[M+H]^{\oplus}$ calcd for $C_{19}H_{25}O_2Si^{\oplus}$ 313.1618, found 313.1618. IR (KBr) ν (cm^{-1}) 2965, 1763, 1685, 1459, 1427, 1250, 1114, 1038, 935, 837, 734, 702.

*4.2.3. (3aS,7aS,E)-3-((Dimethyl(phenyl)silyl)methylene)-7a-isopropyl-2,3,3a,4-tetrahydrobenzofuran-5(7aH)-one (**3c**)*

Colorless oil. 30.0 mg, 92% yield. $[\alpha]_D^{24.6}$ -97.6 (*c* 0.50, $CHCl_3$) for 68% *ee*. ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.56–7.53 (m, 2H), 7.38–7.35 (m, 3H), 6.56 (d, *J* = 10.0 Hz, 1H), 6.07 (d, *J* = 10.0 Hz, 1H), 5.56 (m, 1H), 4.45–4.26 (m, 2H), 2.83–2.79 (m, 1H), 2.50–2.45 (m, 1H), 2.26–2.20 (m, 1H), 1.89–1.82 (m, 1H), 0.94 (d, *J* = 7.0 Hz, 3H), 0.72 (d, *J* = 7.0 Hz, 3H), 0.46 (s, 3H), 0.37 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 197.7, 160.8, 146.6, 138.0, 133.7, 131.2, 129.3, 128.0, 118.1, 84.0, 72.1, 42.8, 34.1, 17.2, 16.6, −0.9, −1.8. HRMS (ESI): $[M+H]^{\oplus}$ calcd for $C_{20}H_{27}O_2Si^{\oplus}$ 327.1775, found 327.1774. IR (KBr) ν (cm^{-1}), 3068, 2959, 1689, 1635, 1465, 1386, 1250, 1113, 1104, 848, 834, 701, 414.

*4.2.4. (3aS,7aS,E)-7a-Dutyl-3-((dimethyl(phenyl)silyl)methylene)-2,3,3a,4-tetrahydrobenzofuran-5(7aH)-one (**3d**)*

Colorless oil. 31.9 mg, 94% yield. $[\alpha]_D^{25.5}$ -97.5 (*c* 1.30, $CHCl_3$) for 69% *ee*. ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.55–7.53 (m, 2H), 7.37–7.36 (m, 3H), 6.57 (d, *J* = 10.0 Hz, 1H), 6.00 (d, *J* = 10.0 Hz, 1H), 5.58 (m, 1H), 4.47–4.30 (m, 2H), 2.76–2.73 (m, 1H), 2.53–2.47 (m, 1H), 2.26–2.20 (m, 1H), 1.57 (m, 2H), 1.32–1.01 (m, 4H), 0.88 (t, *J* = 7.0 Hz, 3H), 0.46 (m, 3H), 0.37 (m, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 197.6, 160.0, 148.8, 138.2, 133.7, 130.3, 129.3, 128.0, 118.5, 81.7, 72.4, 45.0, 39.2, 37.4, 26.0, 23.1, 13.9, −0.8, −1.8. HRMS (ESI): $[M+H]^{\oplus}$ calcd for $C_{21}H_{29}O_2Si^{\oplus}$ 341.1931, found 341.1932. IR (KBr) ν (cm^{-1}) 2956, 2871, 1763, 1689, 1427, 1250, 1114, 837, 701.

*4.2.5(3aS,7aS,E)-7a-Cyclohexyl-3-((dimethyl(phenyl)silyl) methylene)-2,3,3a,4-tetrahydrobenzofuran-5(7aH)-one (**3e**)*

White solid. 37.2 mg, 98% yield. mp 59–61 °C $[\alpha]_D^{25.0}$ -147.98 (*c* 1.0, $CHCl_3$) for 68% *ee*. ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.56–7.54 (m, 2H), 7.38–7.37 (m, 3H), 6.56 (d, *J* = 10.0 Hz, 1H), 6.02 (d, *J* = 10.0 Hz, 1H), 5.56 (s, 1H), 4.27 (d, *J* = 14.0 Hz, 1H), 4.38 (d, *J* = 14.0 Hz, 1H), 2.83–2.80 (m, 1H), 2.49–2.43 (m, 1H), 2.26–2.20 (m, 1H), 1.83–0.74 (m, 11H), 0.46 (s, 3H), 0.38 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 197.8, 160.9, 147.3, 138.0, 133.7, 130.7, 129.3, 127.9, 118.0, 83.8, 72.0, 44.6, 42.8, 40.3, 31.6, 29.6, 27.5, 26.6, 26.3, −1.0, −1.7. HRMS (ESI): $[M+H]^{\oplus}$ calcd for $C_{23}H_{31}O_2Si^{\oplus}$ 367.2088, found 367.2077. IR (KBr) ν (cm^{-1}) 3079, 3045, 2941, 2855, 1693, 1630, 1392, 1267, 1043, 847, 810, 471.

*4.2.6. (3aS,7aS,E)-3-((Dimethyl(phenyl)silyl)methylene)-7a-phenyl-2,3,3a,4-tetrahydrobenzofuran-5(7aH)-one (**3f**)*

White solid. 31.7 mg, 88% yield. mp 60–63 °C $[\alpha]_D^{25.0}$ -132.90 (*c* 1.0, $CHCl_3$) for 53% *ee*. ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.39–7.25 (m, 10H), 6.57–6.55 (d, *J* = 10.0 Hz, 1H), 6.09–6.06 (d, *J* = 10.0 Hz, 1H), 5.52 (m, 1H), 4.70–4.66 (m, 1H), 4.51–4.47 (m, 1H), 3.15–3.12 (m, 1H), 2.63–2.57 (m, 1H), 2.37–2.32 (m, 1H), 0.37 (m, 3H), 0.29 (m, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 197.6, 158.5, 147.8, 141.9, 137.9, 133.6, 129.5, 129.2, 128.7, 128.0, 127.9, 125.3, 118.7, 83.2, 73.1, 48.7, 39.0, −1.1, −1.6. HRMS (ESI): $[M+H]^{\oplus}$ calcd for $C_{23}H_{25}O_2Si^{\oplus}$ 361.1618, found 361.1617. IR (KBr) ν (cm^{-1}) 3066, 2952, 2852, 1770, 1688, 1489, 1426, 1250, 1052, 833, 700, 470.

*4.2.7. (3aS,7aS,E)-7a-(4-Bromophenyl)-3-((dimethyl(phenyl)silyl) methylene)-2,3,3a,4-tetrahydrobenzofuran-5(7aH)-one (**3g**)*

White soild. 39.4 mg, 90% yield. mp 95–97 °C $[\alpha]_D^{24.9}$ -161.18 (*c* 1.0, $CHCl_3$) for 61% *ee*. ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.46–7.44 (d, *J* = 7.6 Hz, 2H), 7.38–7.28 (m, 5H), 7.11–7.09 (d, *J* = 7.6 Hz, 2H), 6.50 (d, *J* = 10.0 Hz, 1H), 6.07 (d, *J* = 10.0 Hz, 1H), 5.53 (m, 1H), 4.70–4.66 (m, 1H), 4.47–4.44 (m, 1H), 3.07–3.03 (m, 1H), 2.61–2.55 (m, 1H), 2.35–2.30 (m, 1H), 0.39 (s, 3H), 0.29 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 197.2, 157.9, 147.0, 141.2, 137.7, 133.6, 131.8, 129.6, 129.3, 128.0, 127.0, 122.0, 119.3, 83.8, 73.1, 48.6, 39.0, −1.1, −1.6. HRMS (ESI): $[M+H]^{\oplus}$ calcd for $C_{23}H_{24}O_2BrSi^{\oplus}$ 439.0723, found 439.0723. IR (KBr) ν (cm^{-1}) 3446, 3065, 2955, 2856, 1767, 1492, 1423, 1245, 1051, 839, 711, 478.

*4.2.8. (3aS,7aS,E)-7a-Benzyl-3-((dimethyl(phenyl)silyl)methylene)-2,3,3a,4-tetrahydrobenzofuran-5(7aH)-one (**3h**)*

White soild. 35.9 mg, 96% yield. mp 53–55 °C $[\alpha]_D^{25.2}$ -78.40 (*c* 1.0, $CHCl_3$) for 42% *ee*. ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.53–7.51 (m, 2H), 7.41–7.34 (m, 3H), 7.26–7.23 (m, 3H), 7.07–7.05 (m, 2H), 6.51 (d, *J* = 10.0 Hz, 1H), 5.96 (d, *J* = 10.0 Hz, 1H), 5.59 (m, 1H), 4.40 (s, 2H), 3.02–2.99 (m, 1H), 2.84–2.80 (m, 2H), 2.44–2.39 (m, 1H), 1.94–1.88 (m, 1H), 0.45 (s, 3H), 0.34 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 197.2, 159.5, 148.3, 138.0, 135.3, 133.7, 130.5, 130.1, 129.2, 128,3, 128.0, 126.9, 118.4, 82.0, 72,5, 45.1, 43.9, 39.1, −0.7, −2.0. HRMS (ESI): $[M+H]^{\oplus}$ calcd for $C_{24}H_{27}O_2Si^{\oplus}$ 375.1775, found 375.1775. IR (KBr) ν (cm^{-1}) 3065, 2953, 2915, 2837, 1688, 1427, 1384, 1249, 1043, 849, 832, 701, 472.

*4.2.9. (3aS,7aS,E)-3-((Dimethyl(phenyl)silyl)methylene)-7a-vinyl-2,3,3a,4-tetrahydrobenzofuran-5(7aH)-one (**3i**)*

Yellow oil. 27.0 mg, 88% yield. $[\alpha]_D^{24.5}$ -95.60 (*c* 1.25, $CHCl_3$) for 64% *ee*. ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.54–7.51 (m, 2H). 7.37–7.35 (m, 3H), 6.49 (d, *J* = 10.0 Hz, 1H), 6.05 (d, *J* = 10.0 Hz, 1H), 5.82–5.75 (m, 1H), 5.58 (m, 1H), 5.27–5.22 (m, 2H), 4.51–4.47 (m, 1H), 4.40–4.37 (m, 1H), 2.83–2.80 (m, 1H), 2.55–2.49 (m, 1H), 2.26–2.21 (m, 1H), 0.45 (s, 3H), 0.36 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 197.3, 158.7, 147.0, 138.2, 138.1, 133.7, 130.6, 129.3, 128.0, 118.4, 116.6, 81.9. 72.9, 46.3, 38.3, −0.7, −1.8. HRMS (ESI): $[M+H]^{\oplus}$ calcd for $C_{19}H_{23}O_2Si^{\oplus}$ 311.1462, found 311.1461. IR (KBr) ν (cm^{-1}) 3068, 2954, 1689, 1636, 1427, 1329, 1249, 1112, 1025, 935, 834, 733, 701, 418.

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*4.2.10. (3aS,7aS,E)-7a-Allyl-3-((dimethyl(phenyl)silyl)methylene)-2,3,3a,4-tetrahydrobenzofuran-5(7aH)-one (**3j**)*

Colorless oil. 28.6 mg, 89% yield. $[\alpha]_D^{24.8}$ -191.33 (*c* 0.35, $CHCl_3$) for 59% *ee*. ^1H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.54–7.52 (m, 2H), 7.37–7.35 (m, 3H), 6.58 (d, $J = 10.0$ Hz, 1H), 6.01 (d, $J = 10.0$ Hz, 1H), 5.69–5.60 (m, 2H), 5.11–5.01 (m, 2H), 4.50–4.46 (m, 1H), 4.36–4.33 (m, 1H), 2.82–2.79 (m, 1H), 2.51–2.18 (m, 4H), 0.45 (s, 3H), 0.37 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 197.4, 159.4, 148.0, 138.1, 133.7, 131.9, 130.5, 129.3, 128.0, 119.3, 118.7, 81.0, 72,5, 44.9, 42.2, 39.1, −0.8, −1.8. HRMS (ESI): $[M+H]^{\oplus}$ calcd for $C_{10}H_{25}O_2Si^{\oplus}$ 325.1618, found 325.1618. IR (KBr) ν (cm^{-1}) 3069, 2954, 1690, 1638, 1427, 1249, 1112, 1042, 927, 833, 782, 701, 427.

*4.2.11. (3aS,7aS,E)-7a-(3-Bromopropyl)-3-((dimethyl(phenyl)silyl) methylene)-2,3,3a,4-tetrahydrobenzofuran-5(7aH)-one (**3k**)*

Yellow solid. 35.6 mg, 88% yield. mp 82–84 °C $[\alpha]_D^{25.1}$ -52.24 (*c* 1.00, $CHCl_3$) for 67% *ee*. ^1H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.55–7.53 (m, 2H), 7.38–7.36 (m, 3H), 6.55 (d, $J = 10.0$ Hz, 1H), 6.00 (d, $J = 10.0$ Hz, 1H), 5.61 (m, 1H), 4.49–4.44 (m, 1H), 4.35–4.31 (m, 1H), 3.37–3.34 (m, 2H), 2.72–2.68 (m, 1H), 2.53–2.47 (m, 1H), 2.25–2.17 (m, 1H), 1.85–1.66 (m, 4H), 0.46 (s, 3H), 0.37 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 197.2, 159.3, 147.7, 138.0, 133.7, 130.6, 129.4, 128.0, 119.0, 81.0, 72.4, 45.1, 39.0, 36.0, 33.4, 27.1, −0.8, −1.8. HRMS (ESI): $[M+H]^{\oplus}$ calcd for $C_{20}H_{26}O_2BrSi^{\oplus}$ 405.0880, found 405.0880. IR (KBr) ν (cm^{-1}) 3069, 2950, 2908, 1682, 1444, 1245, 1112, 1080, 835, 704, 474.

*4.2.12. (3aS,7aS,E)-3-((Dimethyl(phenyl)silyl)methylene)-7a-(3-iodopropyl)-2,3,3a,4-tetrahydrobenzofuran-5(7aH)-one (**3m**)*

White solid. 40.2 mg, 89% yield. mp 66–68 °C $[\alpha]_D^{25.1}$ -21.15 (*c* 1.00, $CHCl_3$) for 69% *ee*. ^1H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.55–7.53 (m, 2H), 7.39–7.36 (m, 3H), 6.56–6.53 (d, $J = 10.0$ Hz, 1H), 6.01–6.98 (d, $J = 10.0$ Hz, 1H), 5.61 (m, 1H), 4.48–4.44 (m, 1H), 4.35–4.31 (m, 1H), 3.13–3.10 (m, 2H), 2.71–2.67 (m, 1H), 2.52–2.46 (m, 1H), 2.25–2.20 (m, 1H), 1.81–1.60 (m, 4H), 0.46 (s, 3H), 0.37 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 197.2, 159.3, 147.7, 138.0, 133.7, 130.6, 129.4, 128.0, 119.0, 80.9, 72.4, 45.1, 39.0, 38.3, 27.8, 6.2, −0.8, −1.8. HRMS (ESI): $[M+H]^{\oplus}$ calcd for $C_{20}H_{26}O_2ISi^{\oplus}$ 453.0741, found 453.0741. IR (KBr) ν (cm^{-1}) 2953, 2853, 1689, 1427, 1249, 1112, 1040, 849, 833, 733, 701.

*4.2.13. 2-((3aS,7aS,E)-3-((Dimethyl(phenyl)silyl)methylene)-5-oxo-2,3,3a,4,5,7a-hexahydrobenzofuran-7a-yl)ethyl acetate (**3n**)*

Colorless oil. 32.6 mg, 87% yield. $[\alpha]_D^{24.2}$ -28.08 (*c* 1.25, $CHCl_3$) for 64% *ee*. ^1H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.55–7.52 (m, 2H), 7.37–7.35 (m, 3H), 6.60 (d, $J = 10.0$ Hz, 1H), 6.00 (d, $J = 10.0$ Hz, 1H), 5.61–5.60 (m, 1H), 4.45–4.41 (m, 1H), 4.35–4.31 (m, 1H), 4.17–4.03 (m, 2H), 2.80–2.77 (m, 1H), 2.55–2.49 (m, 1H), 2.27–2.21 (m, 1H), 1.99 (s, 3H), 1.97–1.93 (m, 2H), 0.46 (s, 3H), 0.37 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 197.0, 170.7, 159.0, 147.6, 138.0, 133.7, 130.4, 129.4, 128.0, 119.0, 80.4, 72,4, 59.8, 45.6, 38.8, 36.0, 20.9, −0.7, −1.9. HRMS (ESI): $[M+H]^{\oplus}$ calcd for $C_{21}H_{27}O_4Si^{\oplus}$ 371.1673, found 371.1673. IR (KBr) ν (cm^{-1}) 3067, 2955, 2849, 1740, 1689, 1437, 1247, 849, 834, 701, 542, 472.

*4.2.14. (3aS,7aS,E)-7a-(2-((Tert-butyldimethylsilyl)oxy)ethyl)-3-((dimethyl(phenyl)silyl)methylene)-2,3,3a,4-tetrahydrobenzofuran-5(7aH)-one (**3o**)*

Colorless oil. 37.8 mg, 85% yield. $[\alpha]_D^{25.2}$ -25.34 (*c* 1.10, $CHCl_3$) for 68% *ee*. ^1H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.54–7.51 (m, 2H), 7.37–7.35 (m, 3H), 6.66 (d, $J = 10.0$ Hz, 1H), 5.98 (d, $J = 10.0$ Hz 1H), 5.58 (m, 1H), 4.43–4.39 (m, 1H), 4.32–4.29 (m, 1H), 3.72–3.60 (m, 2H), 2.90–2.87 (m, 1H), 2.57–2.41 (m, 1H), 2.38–2.33 (m, 1H), 1.86 (t, $J = 6.4$ Hz, 2H), 0.85 (s, 9H), 0.45 (s, 3H), 0.37 (s, 3H), 0.01 (s, 3H), 0.00 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 197.4, 160.0, 149.0, 138.3, 133.7, 129.9, 129.3, 128.0, 118.5, 81.1, 72.4, 58.6, 45.8, 40.4, 39.0, 25.9, 18.2, −0.8, −1.7, −5.4. HRMS (ESI): $[M+H]^{\oplus}$ calcd for $C_{25}H_{39}O_3Si_2^{\oplus}$ 443.2432, found 443.2433. IR (KBr) ν (cm^{-1}) 3068, 2953, 2855, 1690, 1635, 1471, 1388, 1251, 1111, 1042, 835, 776, 471.

*4.2.15. S-(2-((3aS,7aS,E)-3-((Dimethyl(phenyl)silyl)methylene)-5-oxo-2,3,3a,4,5,7a-hexahydrobenzofuran-7a-yl)ethyl) ethanethioate (**3p**)*

Colorless oil. 29.3 mg, 76% yield. $[\alpha]_D^{23.1}$ -30.51 (*c* 0.60, $CHCl_3$) for 63% *ee*. ^1H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.55–7.53 (m, 2H), 7.37–7.35 (m, 3H), 6.64 (d, $J = 10.0$ Hz, 1H), 6.03 (d, $J = 10.0$ Hz, 1H), 5.61 (m, 1H), 4.49–4.46 (m, 1H), 4.36–4.34 (m, 1H), 2.84–2.76 (m, 2H), 2.69–2.61 (m, 1H), 2.53–2.46 (m, 1H), 2.32 (s, 3H), 2.26–2.20 (m, 1H), 1.85–1.80 (m, 2H), 0.46 (s, 3H), 0.38 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 197.1, 195.3, 159.0, 147.1, 138.0, 133.7, 130.8, 129.4, 128.0, 119.2, 80.9, 72.5, 45.1, 39.0, 37.4, 30.5, 23.4, −0.8, −1.8. HRMS (ESI): $[M+H]^{\oplus}$ calcd for $C_{21}H_{27}O_3SSi^{\oplus}$ 387.1445, found 387.1444. IR (KBr) ν (cm^{-1}) 3367, 3068, 2954, 1766, 1690, 1427, 1250, 1113, 836, 734, 625, 471.

*4.2.16. Methyl2-((3aS,7aS,E)-3-((dimethyl(phenyl)silyl)methylene)-5-oxo-2,3,3a,4,5,7a-hexahydrobenzofuran-7a-yl)acetate (**3q**)*

Colorless oil. 29.6 mg, 83% yield. $[\alpha]_D^{24.0}$ -97.96 (*c* 1.00, $CHCl_3$) for 67% *ee*. ^1H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.54–7.52 (m, 2H), 7.38–7.36 (m, 3H), 6.82 (d, $J = 10.0$ Hz, 1H), 6.03 (d, $J = 10.0$ Hz, 1H), 5.65 (m, 1H), 4.57–4.53 (m, 1H), 4.38–4.35 (m, 1H), 3.65 (s, 3H), 3.07–3.03 (m, 1H), 2.67–2.55 (m, 2H), 2.50–2.43 (m, 1H), 2.26–2.21 (m, 1H), 0.45 (s, 3H), 0.39 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 197.0, 169.6, 158.2, 146.1, 138.0, 133.7, 130.5, 129.4, 128.0, 119.8, 79.3, 72.6, 51,9, 45.8, 42.5, 38.9, −1.1, −1.8. HRMS (ESI): $[M+H]^{\oplus}$ calcd for $C_{20}H_{24}O_4Si^{\oplus}$ 357.1517, found 357.1517. IR (KBr) ν (cm^{-1}) 3048, 2952, 1737, 1690, 1435, 1250, 1141, 1112, 1028, 848, 835, 734, 698.

*4.2.17. 2-((3aS,7aS,E)-3-((Dimethyl(phenyl)silyl)methylene)-5-oxo-2,3,3a,4,5,7a-hexahydrobenzofuran-7a-yl)acetonitrile (**3r**)*

Yellow oil. 31.7 mg, 98% yield. $[\alpha]_D^{24.0}$ -20.10 (*c* 1.00, $CHCl_3$) for 65% *ee*. ^1H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.55–7.52 (m, 2H), 7.39–7.36 (m, 3H), 6.65 (d, $J = 10.0$ Hz, 1H), 6.10 (d, $J = 10.0$ Hz, 1H), 5.71 (m, 1H), 4.61–4.57 (m, 1H), 4.42–4.38 (m, 1H), 2.87–2.84 (m, 1H), 2.65–2.44 (m, 3H), 2.27–2.21 (m, 1H), 0.47 (m, 3H), 0.40 (m, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 195.8, 156.5, 143.8, 137.5, 133.6, 131.9, 129.6, 128.2, 121.4, 115.4, 78.5, 72.9, 45.6, 38.6, 29.6, 29.6, 27.1, −1.1, −1.9. HRMS (ESI): $[M+H]^{\oplus}$ calcd for $C_{19}H_{22}O_2NSi^{\oplus}$ 324.1414, found 324.1412. IR (KBr) ν (cm^{-1}) 3445, 3068, 2958, 2251, 1772, 1694, 1427, 1250, 1160, 1114, 999, 836,702, 471.

*4.2.18. (3aS,7aS,Z)-3-((Dimethyl(phenyl)silyl)methylene)-7a-(3-(((8R,9S,13S,14S)-13-methyl-17-oxo-7,8,9,11,12,13,14,15,16,17-decahydro-6H-cyclopenta[a]phenanthren-3-yl)oxy)propyl)-2,3,3a,7a-tetrahydrobenzofuran-5(4H)-one (**3s**)*

Viscous oil. 95.0 mg, 80% yield. $[\alpha]_D^{27.9}$ 41.63 (*c* 1.00, $CHCl_3$) for 61% *de*. ^1H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.54 (dd, $J = 6.4$, 3.0 Hz, 2H), 7.38–7.33 (m, 3H), 7.20 (d, $J = 8.6$ Hz, 1H), 6.69 (dd, $J = 8.6$, 2.6 Hz, 1H), 6.60 (d, $J = 10.2$ Hz, 2H), 6.02 (d, $J = 10.3$ Hz, 1H), 5.61 (d, $J = 1.7$ Hz, 1H), 4.47 (d, $J = 13.7$ Hz, 1H), 4.34 (dd, $J = 13.8$, 1.4 Hz, 1H), 3.89 (t, $J = 5.1$ Hz, 2H), 2.89 (dd, $J = 10.8$, 4.6 Hz, 2H), 2.77 (t, $J = 6.8$ Hz, 1H), 2.56–2.47 (m, 2H), 2.42–2.38 (m, 1H), 2.28–2.22 (m, 2H), 2.19–1.08 (m, 1H), 2.06–1.94 (m, 3H), 1.78–1.71 (m, 3H), 1.66–1.60 (m, 3H), 1.54 (m, 1H), 1.51–1.48 (m, 2H), 1.26 (m, 1H), 0.91 (s, 3H), 0.46 (s, 3H), 0.37 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 221.1, 197.5, 159.8, 157.0, 148.4, 138.3, 137.9, 133.9, 132.3, 130.7, 129.5, 128.2, 126.5, 118.9, 114.7, 112.2, 81.5, 72.6, 67.7, 50.5, 48.1, 45.3, 44.1, 39.3, 38.5, 36.0, 34.2, 31.7, 29.8, 26.7, 26.1, 24.1, 21.7, 14.0, −0.6, −1.7. HRMS (ESI): $[M + NH_4]^{\oplus}$ calcd for $C_{38}H_{50}NO_4Si^{\oplus}$ 612.3504, found

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612.3502. IR (thin film) ν (cm^{-1}) 2929, 1738, 1690, 1499, 1280, 1248, 1112, 1055, 848, 834, 701.

4.2.19. Tert-butyl(3aS,7aS,E)-7a-butyl-3-((dimethyl(phenyl)silyl) methylene)-5-oxo-2,3,3a,4,5,7a-hexahydro-1H-indole-1-carboxylate (**3t**)

Colorless oil. 39.0 mg, 89% yield. $[\alpha]_D^{25.4}$ -4.13 (*c* 0.4, $CHCl_3$) for 53% *ee*. ^1H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.53–7.50 (m, 2H), 7.37–7.35 (m, 3H), 6.94 (d, $J = 10.0$ Hz, 1H), 5.92 (d, $J = 10.0$ Hz, 1H), 5.65 (m, 1H), 4.39–4.30 (m, 1H), 4.00–3.90 (m, 1H), 2.92–2.87 (m, 1H), 2.42–2.35 (m, 1H), 2.19–2.14 (m, 1H), 1.40 (s, 9H), 1.37–0.73 (m, 9H), 0.42 (s, 3H), 0.38 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 197.9, 154.9, 153.8, 150.1, 138.2, 133.6, 129.5, 128.1, 128.1, 122.1, 80.0, 63.2, 53.7, 46.9, 39.5, 36.2, 28.5, 26.9, 23.0, 13.9, −1.1, −1.3. HRMS (ESI): $[M+H]^{\oplus}$ calcd for $C_{26}H_{38}O_3NSi^{\oplus}$ 440.2615, found 440.2615. IR (KBr) ν (cm^{-1}) 2957, 2871, 1700, 1457, 1368, 1307, 1252, 1164, 1113, 839, 733, 701.

4.2.20. (3aS,7aS,E)-3-(1-(dimethyl(phenyl)silyl)ethylidene)-7a-methyl-2,3,3a,7a-tetrahydrobenzofuran-5(4H)-one(**3v**)

Colorless oil. 20.0 mg, 32% yield. $[\alpha]_D^{25.0}$ -44.34 (*c* 1.0, $CHCl_3$) for 31% *ee*. ^1H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.52–7.50 (m, 2H), 7.37–7.33 (m, 3H), 6.59 (d, $J = 10.1$ Hz, 1H), 5.93 (d, $J = 10.1$ Hz, 1H), 4.59–4.49 (m, 2H), 2.70 (dd, $J = 10.6$, 5.6 Hz, 1H), 2.42 (dd, $J = 16.0$, 10.7 Hz, 1H), 2.12 (dd, $J = 16.1$, 5.6 Hz, 1H), 1.66 (d, $J = 0.7$ Hz, 3H), 1.22 (s, 3H), 0.45 (s, 3H), 0.40 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 198.4, 152.4, 148.6, 138.4, 133.9, 129.6, 129.5, 128.1, 126.3, 78.4, 70.0, 47.3, 40.2, 24.7, 19.0, −1.4, −1.6. HRMS (ESI): $[M+H]^{\oplus}$ calcd for $C_{19}H_{25}O_2Si^{\oplus}$ 313.1618, found 313.1615. IR (KBr) ν (cm^{-1}) 3068, 2964, 2926, 1686, 1427, 1373, 1251, 1111, 1073, 999, 818, 776, 702.

4.3. (3aS,7aS)-3-((E)-Benzylidene)-7a-methyl-2,3,3a,7a-tetrahydrobenzofuran-5(4H)-one (**4a**)

To the well-stirred solution of **3a** (60 mg, 0.2 mmol) and $Pd(dba)_2$ (6 mg, 0.01 mmol, 5% equiv) in THF (2.0 mL) was added TBAF (1 M in THF, 0.4 mL, 0.4 mmol, 2.0 equiv) and Iodobenzene (27 μL, 0.24 mmol, 1.2 equiv) under argon atmosphere. The resulting mixture continued to react for 16 h at room temperature. It was quenched by aqueous saturated $NaHCO_3$ (10 mL), extracted with DCM (10 mL × 3), washed with brine (30 mL), dried over anhydrous Na_2SO_4 and concentrated under reduced pressure. The residue was purified by flash silica gel (300–400 mesh) chromatography to afford the desired products **4a** as a colorless oil. 19.0 mg, 40% yield. $[\alpha]_D^{27.9}$ -11.78 (*c* 0.50, $CHCl_3$) for 48% *ee*. ^1H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.35–7.32 (m, 2H), 7.25–7.19 (m, 3H), 6.57 (d, $J = 10.2$ Hz, 1H), 6.42 (s, 1H), 5.99 (d, $J = 10.2$ Hz, 1H), 4.49 (dd, $J = 36.3$, 13.3 Hz, 2H), 3.42 (s, 1H), 2.65–2.59 (m, 1H), 2.49–2.43 (m, 1H), 1.51 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 197.3, 150.1, 142.2, 136.1, 129.8, 128.6, 128.2, 127.1, 122.4, 80.4, 71.4, 46.2, 36.4, 24.2. HRMS (ESI): $[M + NH_4]^{\oplus}$ calcd for $C_{16}H_{20}NO_2^{\oplus}$ 258.1489, found 258.1491. IR (thin film) ν (cm^{-1}) 2920, 1690, 1382, 1280, 1227, 1162, 1114, 1044, 877, 726, 697, 562.

4.4. (3aS,6aR,9aS,E)-3-((Dimethyl(phenyl)silyl)methylene) octahydroindeno[3a,4-b]furan-5(6H)-one (**4m**)

To a solution of **3m** (30 mg, 0.066 mmol) in dry THF (2 mL) was added *t*-BuLi (1.3 M in pentane, 0.2 mL, 4.0 equiv) in 10 min at −78 °C. The resulting mixture was stirred for 0.5 h. The reaction mixture was quenched by MeOH (0.2 mL) and water (10 mL), extracted with EtOAc (10 mL × 3), dried over anhydrous Na_2SO_4, filtered and concentrated in vacuo. The residue was purified by flash column chromatography to afford **4m** as a colorless oil. 10.4 mg, 48% yield. $[\alpha]_D^{24.4}$ -124.70 (*c* 0.20, $CHCl_3$) for 66% *ee*. ^1H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.54–7.51 (m, 2H), 7.36–7.34 (m, 3H), 5.56 (s, 1H), 4.53–4.50 (m, 1H), 4.28–4.24 (m, 1H), 2.45–1.10 (m, 12H), 0.40 (s, 3H), 0.37 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 211.4, 160.3, 138.5, 133.7, 129.3, 128.0, 118.0, 92.5, 70.8, 45.7, 43.2, 42.1, 42.0, 36.2, 31.5, 22.8, −1.2, −1.4. HRMS (ESI): $[M+H]^{\oplus}$ calcd for $C_{20}H_{27}O_2Si^{\oplus}$ 327.1775, found 327.1775. IR (KBr) ν (cm^{-1}) 2953, 2924, 1718, 1461, 1376, 1248, 1199, 1113, 1037, 833, 732, 469.

4.5. (3aS,4R,7aS,E)-3-((Dimethyl(phenyl)silyl)methylene)-2,3,3a,4-tetrahydro-5H-4,7a-propanobenzofuran-5-one (**5m**)

To a solution of **3m** (30.0 mg, 0.066 mmol) in dry THF (2 mL) was added a solution of LiHMDS (1 M THF solution, 0.66 mL, 10.0 equiv) at 0 °C. The resulting mixture was stirred at 0 °C for 1 h and at room temperature for 15 h. The reaction mixture was quenched by aqueous saturated NH_4Cl (10 mL) and extracted with EtOAc (10 mL × 3). The combined organic phases were dried over anhydrous Na_2SO_4, filtered and concentrated in vacuo. The residue was purified by flash column chromatography to afford **5m** as a colorless oil. 18.6 mg, 86% yield. $[\alpha]_D^{25.8}$ -54.61 (*c* 0.90, $CHCl_3$) for 66% *ee*. ^1H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.54–7.52 (m, 2H), 7.36–7.35 (m, 3H), 6.55 (d, $J = 10.0$ Hz, 1H), 6.11 (d, $J = 10.0$ Hz, 1H), 5.57–5.55 (m, 1H), 4.47–4.43 (d, $J = 13.8$ Hz, 1H), 4.27–4.24 (d, $J = 13.8$ Hz, 1H), 2.70 (s, 1H), 2.21 (s, 1H), 1.87–1.41 (m, 5H), 1.03–0.94 (m, 1H), 0.41 (s, 3H), 0.26 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 198.8, 157.2, 152.1, 138.5, 133.7, 133.0, 129.0, 128.0, 116.8, 81.8, 73.4, 54.4, 47.0, 31.0, 28.4 19.3, 0.2, −2.3. HRMS (EI): $[M]^{\oplus}$ calcd for $C_{20}H_{24}O_2Si^{\oplus}$ 324.1546, found 324.1553. IR (KBr) ν (cm^{-1}) 3356, 3185, 2919, 2849, 1683, 1634, 1470, 1427, 1377, 1247, 1149, 1005, 834, 732, 420.

4.6. (3aS,9aR,E)-3-((Dimethyl(phenyl)silyl)methylene)-2,3,3a,4,8,9-hexahydro-5H-benzo[1,2-b:6,1-b']difuran-5-one (**4o**)

To a well-stirred solution of **3o** (44.2 mg, 0.1 mmol) in dry THF (5 mL) was added 0.3 mL TBAF (1 M in THF, 1.2 equiv) at 0 °C. The resulting mixture was stirred at 0 °C for 0.5 h, then warmed to room temperature, stirred for 9 h. The reaction mixture was quenched by aqueous saturated NH_4Cl (10 mL) and extracted with EtOAc (10 mL × 3). The combined organic phases were dried over anhydrous Na_2SO_4, filtered and concentrated in vacuo. The residue was purified by flash column chromatography to afford **4o** as a colorless oil. 66.1 mg, 84% yield. $[\alpha]_D^{21.1}$ -141.71 (*c* 0.50, $CHCl_3$) for 68% *ee*.^1H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.54–7.51 (m, 2H), 7.37–7.32 (m, 3H), 5.63 (s, 1H), 4.57 (d, $J = 14.0$ Hz, 1H), 4.32 (d, $J = 14.0$ Hz, 1H). 4.11–4.07 (m, 1H), 3.86–3.82 (m, 2H), 2.69–2.63 (m, 1H). 2.54–2.50 (m, 1H), 2.16–2.01 (m, 4H), 1.57–1.49 (m, 1H). 0.41 (s, 3H), 0.38 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 208.3, 158.4, 138.1, 133.7, 129.5, 128.0, 119.2, 90.9, 79.6, 71.1, 66.7, 45.0, 43.6, 41.7, 36.4, −1.2, −1.5. HRMS (ESI): $[M + NH_4]^{\oplus}$ calcd for $C_{19}H_{28}NO_3Si^{\oplus}$ 346.1833, found 346.1829. IR (KBr) ν (cm^{-1}) 3065, 2953, 2871, 1717, 1639, 1425, 1251, 1197, 1112, 1082, 1037, 836, 731, 702, 467.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at

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[12] For more details, see the Supporting Information.

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