Organic & Biomolecular Chemistry

PAPER

View Article Online
View Journal | View Issue

Cite this: *Org. Biomol. Chem.*, 2019, **17**, 2258

A hydrate salt-promoted reductive coupling reaction of nitrodienes with unactivated alkenes†

Mengmeng Zhang,[a] Liming Yang,[a] Chao Tian,[a] Meng Zhou,[a] Guanghui An *[a,b] and Guangming Li *[a]

Received 18th January 2019,
Accepted 30th January 2019

DOI: 10.1039/c9ob00136k

rsc.li/obc

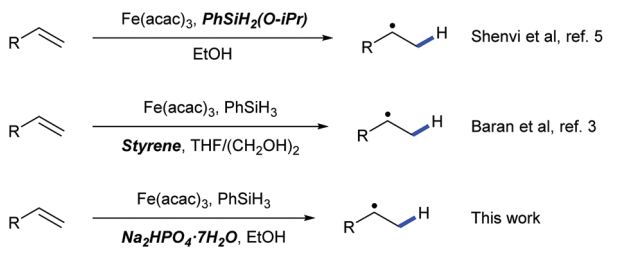
Transition metal-catalyzed reductive coupling has emerged as a powerful method for the construction of C–C bonds. Herein, a crystalline hydrate, $Na_2HPO_4{\cdot}7H_2O$, has been disclosed as an effective promoter for the reductive coupling of nitrodienes with unactivated alkenes to afford diverse dienes with various functionalities in an open-flask manner. The mechanism study has revealed that $Na_2HPO_4{\cdot}7H_2O$ accelerates the *in situ* generation of active silane $PhSi(OEt)H_2$ and prevents the deactivation of catalyst. The approach can increase the efficiency of previous reductive coupling reactions as well.

Introduction

The transition metal-catalyzed reductive cross coupling of unactivated alkenes has emerged as a powerful and distinct method for the facile construction of C–C bonds that allows divergent functionalization.[1] These transformations revealed that unactivated alkenes could be converted to a nucleophilic radical species *via* an initial hydrogen atom transfer (HAT) from a transition metal hydride to an olefin, which is then trapped by a suitable electrophile. They also provide rapid access to many compounds that were difficult or impossible to access using other methods. Baran *et al*. have reported recently practical methods for olefin cross-coupling and hydromethylation of unactivated alkenes[2] with subsequent discovery of a versatile sulfone acceptor for homologation and a Minisci-type functionalization.[3] Shenvi disclosed a branch selective hydroarylation of olefins *via* iodoarenes.[4] To elevate the efficiency in manganese and iron-catalyzed reactions, Shenvi *et al*. revealed isopropoxy(phenyl)silane ($Ph(i\text{-}PrO)SiH_2$) as an efficient reductant.[5] An alternative improvement has been disclosed by a second-generation set of olefin cross-coupling conditions *via* addition of styrene from Baran's group.[3] Despite these advances,[6–11] the development of alternative protocols to prevent catalyst deactivation and other issues problematic for interfacing the direct radical generation method with existing organometallic catalysts still remains highly desirable. Herein, we report an inexpensive crystalline hydrate promoted $Fe(acac)_3$-catalyzed reductive coupling reaction *via in situ* generation of reactive silanes (Scheme 1).

Results and discussion

Baran demonstrated that ethoxy(phenyl)silane $PhSi(OEt)H_2$ would be the most effective silane species for the hydrogen transfer process in the coupling reactions.[3] The isolation of $PhSi(OEt)H_2$ was not successful due to the moisture sensitivity of this adduct according to Shenvi's report.[5] Thus, the *in situ* formed active silane would promote the reactivity of the HAT process. According to the literature, Na_2HPO_4 and its crystal hydrates would potentially benefit the solvolysis of silanes in alcohol solvents.[12] Hence, we commenced our investigation using the reductive cross-coupling reaction of nitrodiene **1** and styrene as a model reaction and Na_2HPO_4 as an additive. This process would afford important synthetic targets, conjugated dienes, which are key structural motifs of many natural products[13] and pharmaceuticals and play important roles in



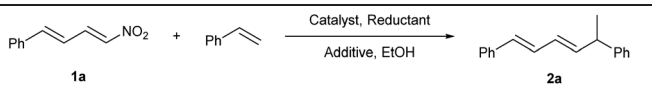
Scheme 1 Strategies for the promotion of reductive cross coupling of unactivated alkenes.

[a]*Key Laboratory of Functional Inorganic Material Chemistry (MOE), School of Chemistry and Materials Science, Heilongjiang University, No. 74, Xuefu Road, Nangang District, Harbin 150080, P. R. China. E-mail: gmli@hlju.edu.cn, chemagh@163.com*
[b]*College of Materials Science and Chemical Engineering, Harbin Engineering University, Harbin, Heilongjiang 150001, P.R. China*
†Electronic supplementary information (ESI) available. See DOI: 10.1039/c9ob00136k

organic synthesis[14] and materials science.[15] To our delight, the diene formation process indeed occurred with Na_2HPO_4 as an additive, providing **2** in 48% yield in an open flask manner. To further improve the reactivity, various catalysts were applied for the coupling reaction, and $Fe(acac)_3$ exhibited the highest yields among all catalysts (Table 1, entries 1 and 2, and Table S1,† entries 1–7). $Ni(acac)_2$[11b] and $Fe(dibm)_3$[2c] (Table S1,† entries 4 and 5), which have been used previously, afforded lower reactivity. The reaction was less efficient with other silane reductants than $PhSiH_3$ (Table 1, entry 1 *vs.* entries 8–11). Further experiments on Na_2HPO_4 and its crystal hydrates revealed that $Na_2HPO_4{\cdot}7H_2O$ could significantly enhance the yield (Table 1, entry 9). A remarkable difference was observed when the reaction was carried out in the absence of $Na_2HPO_4{\cdot}7H_2O$, indicating the crucial role of $Na_2HPO_4{\cdot}7H_2O$. The subsequent thorough survey of other hydrates and inorganic bases didn't improve the reactivity. Notably, $Na_2HPO_4{\cdot}12H_2O$ afforded a similar efficiency to that of $Na_2HPO_4{\cdot}7H_2O$ (Table 1, entry 10). To verify the role of water, replacement of Na_2HPO_4 $7H_2O$ with a combination of Na_2HPO_4 and water sharply reduced the reactivity, implying that water in the crystalline hydrate prompted the reaction (Table 1, entry 11). Increasing the reaction temperature or introducing the inert gas didn't enhance the reaction yields (Table S1,† entries 23 and 24). Extension of the reaction time resulted in the formation of by-products (Table S1,† entry 25).

To examine the substrate scope of this diene synthesis, various nitrodienes were explored under the optimal reaction conditions (Scheme 2A). Both electron-donating and electron-withdrawing groups were tolerated in good yields. The nitro group, which would be susceptible to reduction under reported conditions,[3] was also tolerated, affording **2b** in 69% yield. γ-Alkyl nitrodienes were also viable substrates with good yields (**2d**). Further investigation on diverse styrene derivatives was carried out under the optimal reaction conditions (Scheme 2B).

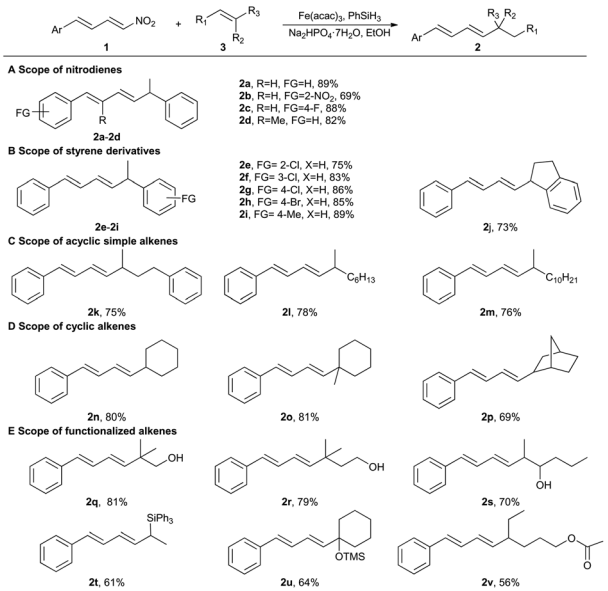
Table 1 Optimization experiments[a]



1a 2a

Entry	Catalyst	Reductant	Additive	Yield[b] (%)
1	$Fe(acac)_3$	$PhSiH_3$	Na_2HPO_4	48
2	$Fe(dibm)_3$	$PhSiH_3$	Na_2HPO_4	39
3	$Fe(acac)_3$	$(EtO)_3SiH$	Na_2HPO_4	34
4	$Fe(acac)_3$	Et_3SiH	Na_2HPO_4	N.R.
5	$Fe(acac)_3$	Ph_3SiH	Na_2HPO_4	N.R.
6	$Fe(acac)_3$	PMHS	Na_2HPO_4	43
7	$Fe(acac)_3$	$PhSiH_3$	—	29
8	$Fe(acac)_3$	$PhSiH_3$	$Na_2HPO_4{\cdot}2H_2O$	62
9	$Fe(acac)_3$	$PhSiH_3$	$Na_2HPO_4{\cdot}7H_2O$	89
10	$Fe(acac)_3$	$PhSiH_3$	$Na_2HPO_4{\cdot}12H_2O$	83
11	$Fe(acac)_3$	$PhSiH_3$	$Na_2HPO_4{\cdot}7H_2O$	12

[a] Reaction conditions: **1** (0.2 mmol, 1 equiv.), styrene (2 equiv.), catalyst (30 mol%), reductant (2 equiv.) and additive (2 equiv.) were added to 2 mL of EtOH under air at 40 °C for 2 h. [b] Isolated yields are given. N.R. = No reaction.



Scheme 2 Scope of reductive cross-coupling reactions.

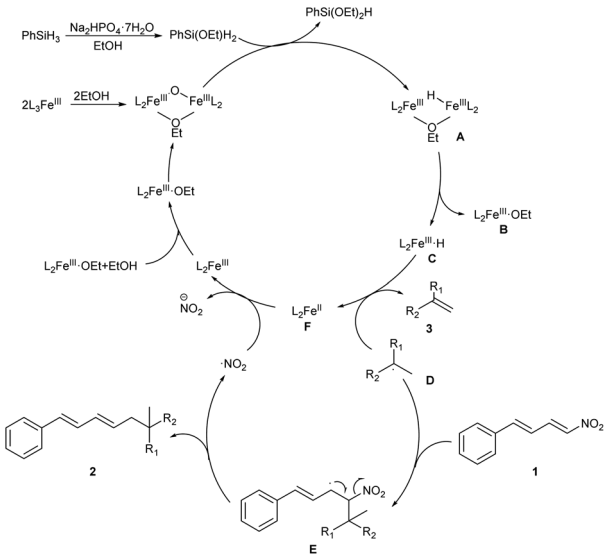
The steric effect of styrene had a crucial impact on the reaction yield, *e.g.* the yield of **2e** was lower than those of **2f** and **2g**. The cyclic styrene derivative indene also gave the product **2j** under the reaction conditions in a satisfactory yield.

Encouraged by these results, the styrene derivative was extended to other alkenes (Scheme 2C and D). Both acyclic and cyclic alkenes can undergo the reaction smoothly with reasonable yields (**2k–2p**). Notably, the quaternary carbon center can be readily assembled with good yield of **2o** (81%). The bicyclic alkenes borbornenes could be also converted to **2p**, which is difficult to achieve with conventional methods. In addition to the above simple alkenes, functionalized alkenes were also employed as substrates for the reductive coupling reactions (Scheme 2E). The hydroxyl group, silane and silyl ether were tolerated under the optimal conditions (**2q–2u**). Surprisingly, a substrate with a carbonyl group, a potential reductive site, also successfully affords the desired product in a satisfactory yield (**2v**). However, cinnamic acid didn't undergo this reductive cross-coupling reaction with nitrodiene **1a**.

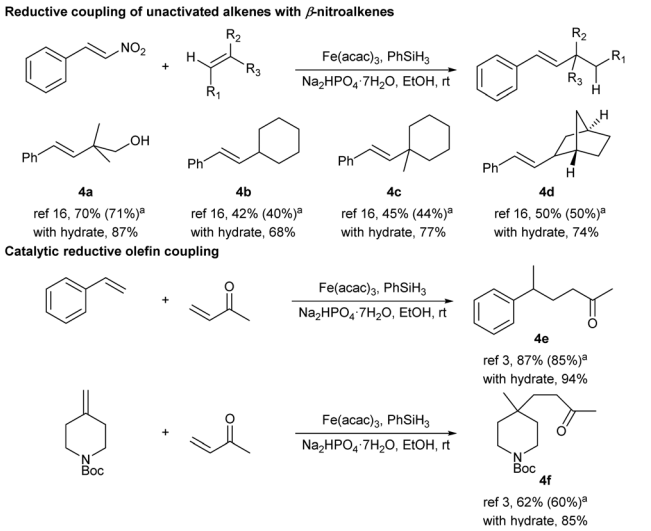
To better understand the protocol, a series of investigations was conducted for the proposal of a mechanism. The addition of a radical scavenger, TEMPO, effectively inhibits the reaction, indicating a radical-mediated reaction pathway. In comparison with additive-free conditions, the reaction released hydrogen immediately upon the addition of $Na_2HPO_4{\cdot}7H_2O$. According to the previous report[12] and our results, we rationalized that $Na_2HPO_4{\cdot}7H_2O$ accelerates the *in situ* generation of the active silane $PhSi(OEt)H_2$ and acts as a buffering agent to promote the stability of silane and prevent the deactivation of catalyst. Further investigation on generating $PhSi(OEt)H_2$ during the reaction revealed that the addition of $Na_2HPO_4{\cdot}7H_2O$ significantly accelerated the rate of active silane generation compared with the Na_2HPO_4 and additive free situation (Scheme S1d†).

Moreover, the TG-DSC investigation of the solid additive before and after the reaction revealed that the release of 6 water molecules per $Na_2HPO_4{\cdot}7H_2O$ formula occurs during the reaction, which might promote the formation of $PhSi(OEt)H_2$ (Scheme S1a–c†). Therefore, a mechanism was proposed as shown in Scheme 3. $Na_2HPO_4{\cdot}7H_2O$ mediated the rapid conversion of $PhSiH_3$ into $PhSi(OEt)H_2$, which will undergo hydrogen atom transfer (HAT), affording Fe^{III} complex (**A**). The resulting intermediate **A** undergoes dissociation to afford active catalyst species $L_2Fe^{III}{\cdot}H$ (**C**), which adds hydrogen to alkene (**3**), generating radical **D**. **D** is trapped by nitroalkene (**1**) to generate the β-nitro radical **E**. The sequential fragmentation of **E** would furnish the alkylated dienes (**2**) and a nitro radical, which would reoxidize **F** to form Fe^{III} species, completing the catalytic cycle.

Intrigued by the results, we envisioned that our protocol might be a general improvement of various types of reductive cross-coupling reactions and could be extended to the Fe-catalyzed reductive coupling of unactivated alkenes with β-nitroalkenes and even catalytic reductive olefin coupling. Disubstituted and trisubstituted alkenes served as viable donor substrates with β-nitrostyrenes in an open flask manner providing tertiary alkylated styrenes in good to excellent yields (Scheme 4, **4a–4d**). For example, cyclohexene and 1-methylcyclohexene exhibit prompt reactivity under optimal conditions compared with the literature[16] (**4b** and **4c**). When the more hindered norbornene was applied in this protocol, the reaction furnished the endocyclic tethered styrene **4d** in a better yield (of 74%) than 50%.[16] Additionally, unactivated olefins reacted with α,β-unsaturated alkenes readily under the optimal conditions, providing increased outcome of the reaction[3] (Scheme 4, **4e–4f**). Furthermore, to rule out the possibility of using different sources of catalyst or other reagents, we carried out the literature experiments and obtained a similar efficiency to Baran and Cui's report.[3,16]



Scheme 3 The proposed mechanism.



Scheme 4 Literature comparison. [a] Repeated results under the conditions of ref. 16 and 3.

Conclusions

In summary, a crystalline hydrate promoted mild $Fe(acac)_3$-catalyzed reductive coupling reaction of nitrodienes with unactivated alkenes has been developed. The mechanism analysis revealed that $Na_2HPO_4{\cdot}7H_2O$ plays an essential role in accelerating the *in situ* generation of the active silane $PhSi(OEt)H_2$and preventing the deactivation of catalyst. Such a protocol can realize the reductive coupling of nitrodienes with unactivated alkenes for the first time. Remarkably, it can be applied not only to reductive coupling of unactivated alkenes to nitrodienes and nitroalkenes but also to olefin coupling reactions in an open flask other than under air and moisture free conditions. Further extension of this protocol to other reductive cross coupling reactions is under investigation.

Experimental

Materials and methods

Unless otherwise noted, all reagents were obtained from commercial suppliers and used without further purification. The reaction product was isolated by column chromatography on a silica gel (236–400 mesh) column using petroleum ether (PE) with a boiling range from 60 to 90 °C and EtOAc. ^1H and ^{13}C NMR spectra were recorded on 400 and 101 MHz NMR spectrometers using DMSO-d_6 or $CDCl_3$ as solvent. In addition, ^1H and ^{13}C NMR spectra were recorded using tetramethylsilane as the internal standard. Chemical shifts are reported in ppm relative to the solvent signal. Multiplicity is indicated as follows: s (singlet); d (doublet); t (triplet); q (quartet); m (multiplet); dd (doublet of doublets). HRMS were conducted using an Agilent 6540 Q-TOF LC/MS equipped with an electrospray ionization (ESI) probe operating in positive ion mode. Thermogravimetric analyses (TG-DSC) were performed at

30–800 °C at heating rate of 10 °C min^{-1} using a PerkinElmer STA 6000 instrument. GC-MS were performed using an Agilent 6890/5973 N GC. Unless otherwise noted, all reagents were weighed and handled in air, and all reactions were carried out in air.

General procedure for the synthesis of compounds 2a–2v

A Schlenk tube containing nitrodiene (0.2 mmol, 1 equiv.), alkene (0.4 mmol, 2 equiv.), $Fe(acac)_3$ (30 mol%), and $PhSiH_3$ (2 equiv.) in EtOH (2 mL) was taken. Then, $Na_2HPO_4{\cdot}7H_2O$ (2 equiv.) was added as an additive. The solution was kept at 40 °C for 2 h. Then the solution was diluted and filtered through Celite. The solvent was evaporated under vacuum. The purification was performed by flash column chromatography on silica gel using petroleum ether (for **2a–2p**, **2t** and **4b–4e**) or petroleum ether/EtOAc (9 : 1 to 2 : 1) (for **2q–2s**, **2v–2u**, **4a** and **4f**) as eluent to give the pure products.

General procedure for the synthesis of compounds 4a–4d

A Schlenk tube containing β-nitrostyrene (0.2 mmol, 1 equiv.), alkene (0.4 mmol, 2 equiv.), $Fe(acac)_3$ (30 mol%), and $PhSiH_3$ (2 equiv.) in EtOH (2 mL) was taken. Then, $Na_2HPO_4{\cdot}7H_2O$ (2 equiv.) was added as an additive. The solution was kept at 40 °C for 2 h. Then the solution was diluted and filtered through Celite. The solvent was evaporated under vacuum. The purification was performed by flash column chromatography on silica gel using petroleum ether (for **4b–4d**) or petroleum ether/EtOAc (9 : 1 to 2 : 1) (for **4a**) as eluent to give the pure products.

General procedure for the synthesis of compound 4e

A Schlenk tube containing styrene (0.2 mmol, 1 equiv.), methyl vinyl ketone (0.6 mmol, 3 equiv.), $Fe(acac)_3$ (30 mol%), and $PhSiH_3$ (2 equiv.) in EtOH (1 mL) was taken. Then, $Na_2HPO_4{\cdot}7H_2O$ (2 equiv.) was added as an additive. The solution was kept at 40 °C for 2 h. Then the solution was diluted and filtered through Celite. The solvent was evaporated under vacuum. The purification was performed by flash column chromatography on silica gel using petroleum ether as eluent to give the pure product.

General procedure for the synthesis of compound 4f

A Schlenk tube containing *tert*-butyl 4-methylenepiperidine-1-carboxylate (0.2 mmol, 1 equiv.), methyl vinyl ketone (0.6 mmol, 3 equiv.), $Fe(acac)_3$ (30 mol%), and $PhSiH_3$ (2 equiv.) in EtOH (1 mL) was taken. Then, $Na_2HPO_4{\cdot}7H_2O$ (2 equiv.) was added as an additive. The solution was kept at 40 °C for 2 h. Then the solution was diluted and filtered through Celite. The solvent was evaporated under vacuum. The purification was performed by flash column chromatography on silica gel using petroleum ether/EtOAc (9 : 1 to 2 : 1) as eluent to give the pure product.

((1*E*,3*E*)-Hexa-1,3-diene-1,5-diyl)dibenzene (2a). Colorless oil; 41.7 mg, 89% yield; R_f = 0.69 (petroleum ether); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.40–7.34 (m, 2H), 7.34–7.25 (m, 4H), 7.27–7.15 (m, 4H), 6.77 (dd, J = 15.7, 10.3 Hz, 1H), 6.48 (d, J = 15.6 Hz, 1H), 6.23 (ddd, J = 15.2, 10.3, 1.4 Hz, 1H), 6.00 (dd, J = 15.2, 6.8 Hz, 1H), 3.58 (p, J = 7.0 Hz, 1H), 1.43 (d, J = 7.0 Hz, 3H). ^{13}C NMR (101 MHz, DMSO-d_6) δ 145.9, 140.5, 137.6, 131.2, 129.6, 129.4, 129.1, 128.9, 127.7, 127.5, 126.6, 126.5, 42.3, 21.6. HRMS (ESI) m/z: 235.1478 $[M + H]^+$; Calcd for $C_{18}H_{19}^+$: 235.1481.

1-Nitro-2-((1*E*,3*E*)-5-phenylhexa-1,3-dien-1-yl)benzene (2b). Colorless oil; 38.5 mg, 69% yield; R_f = 0.39 (petroleum ether); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.48 (dd, J = 7.7, 1.5 Hz, 1H), 7.38–7.32 (m, 2H), 7.31–7.19 (m, 4H), 6.95 (td, J = 7.5, 1.1 Hz, 1H), 6.91–6.83 (m, 3H), 6.31 (dd, J = 15.2, 8.4 Hz, 1H), 6.02 (dd, J = 15.2, 6.8 Hz, 1H), 3.62 (p, J = 6.8 Hz, 1H), 1.46 (d, J = 7.0 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 156.7, 145.8, 139.3, 130.0, 129.9, 128.5, 128.3, 127.4, 126.6, 126.3, 126.2, 125.8, 120.7, 110.9, 42.5, 21.2. HRMS (ESI) m/z: 280.1328 $[M + H]^+$; Calcd for $C_{18}H_{18}NO_2^+$: 280.1332.

1-Fluoro-4-((1*E*,3*E*)-5-phenylhexa-1,3-dien-1-yl)benzene (2c). Colorless oil; 46.8 mg, 88% yield; R_f = 0.41 (petroleum ether); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.35–7.29 (m, 4H), 7.27–7.19 (m, 3H), 6.99 (t, J = 8.7 Hz, 2H), 6.68 (dd, J = 15.7, 10.3 Hz, 1H), 6.45 (d, J = 15.7 Hz, 1H), 6.21 (dd, J = 15.3, 10.3 Hz, 1H), 6.00 (dd, J = 15.2, 6.8 Hz, 1H), 3.58 (p, J = 7.0 Hz, 1H), 1.43 (d, J = 7.0 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 162.1 (d, J = 246.8 Hz), 145.6, 139.9, 133.7 (d, J = 3.4 Hz), 129.7, 128.9 (d, J = 2.5 Hz), 128.5, 127.6 (d, J = 7.8 Hz), 127.3, 126.3, 115.6, 115.4, 42.5, 21.2. HRMS (ESI) m/z: 253.1389 $[M + H]^+$; Calcd for $C_{18}H^{18}F^+$: 253.1387.

((1*E*,3*E*)-2-Methylhexa-1,3-diene-1,5-diyl)dibenzene (2d). Colorless oil; 40.7 mg, 82% yield; R_f = 0.52 (petroleum ether); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.36–7.27 (m, 6H), 7.25–7.14 (m, 4H), 6.43 (d, J = 32.1 Hz, 1H), 6.28 (d, J = 15.6 Hz, 1H), 5.98 (ddd, J = 20.6, 15.6, 7.1 Hz, 1H), 3.58 (dp, J = 20.8, 7.0 Hz, 1H), 1.99 (t, J = 2.1 Hz, 3H), 1.42 (dd, J = 23.2, 7.0 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 146.0, 135.8, 134.7, 133.9, 130.2, 129.4, 129.2, 128.5, 128.1, 127.3, 126.4, 126.2, 42.7, 21.5, 14.1. HRMS (ESI) m/z: 249.1634 $[M + H]^+$; Calcd for $C_{19}H_{21}^+$: 249.1638.

1-Chloro-2-((3*E*,5*E*)-6-phenylhexa-3,5-dien-2-yl)benzene (2e). Colorless oil; 40.0 mg, 75% yield; R_f = 0.70 (petroleum ether); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.40–7.33 (m, 3H), 7.34–7.25 (m, 3H), 7.26–7.10 (m, 3H), 6.78 (dd, J = 15.7, 10.4 Hz, 1H), 6.50 (d, J = 15.6 Hz, 1H), 6.26 (dd, J = 15.3, 10.3 Hz, 1H), 5.98 (dd, J = 15.3, 6.3 Hz, 1H), 4.12 (p, J = 6.8 Hz, 1H), 1.41 (d, J = 6.9 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 142.9, 138.0, 137.5, 133.5, 131.2, 129.8, 129.6, 129.0, 128.6, 128.2, 127.4, 127.3, 127.0, 126.2, 38.3, 19.9. HRMS (ESI) m/z: 269.1088 $[M + H]^+$; Calcd for $C_{18}H_{18}Cl^+$: 269.1092.

1-Chloro-3-((3*E*,5*E*)-6-phenylhexa-3,5-dien-2-yl)benzene (2f). Colorless oil; 42.2 mg, 83% yield; R_f = 0.40 (petroleum ether); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.37 (d, J = 7.1 Hz, 2H), 7.30 (t, J = 7.6 Hz, 2H), 7.26–7.16 (m, 4H), 7.12 (dd, J = 7.5, 1.6 Hz, 1H), 6.77 (dd, J = 15.7, 10.4 Hz, 1H), 6.50 (d, J = 15.7 Hz, 1H), 6.23 (dd, J = 15.3, 10.4 Hz, 1H), 5.94 (dd, J = 15.2, 6.9 Hz, 1H), 3.56 (p, J = 6.9 Hz, 1H), 1.41 (d, J = 7.0 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 147.7, 138.7, 137.4, 134.3, 131.5, 129.8, 129.7, 128.9, 128.6, 127.5, 127.4, 126.4, 126.3, 125.6, 42.2, 21.1. HRMS (ESI) m/z: 269.1088 $[M + H]^+$; Calcd for $C_{18}H_{18}Cl^+$: 269.1092.

1-Chloro-4-((3*E*,5*E*)-6-phenylhexa-3,5-dien-2-yl)benzene (2g). Colorless oil; 43.7 mg, 86% yield; R_f = 0.40 (petroleum ether); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.40–7.33 (m, 2H), 7.34–7.24 (m, 4H), 7.25–7.13 (m, 3H), 6.76 (dd, J = 15.7, 10.3 Hz, 1H), 6.49 (d, J = 15.7 Hz, 1H), 6.25–6.15 (m, 1H), 5.94 (dd, J = 15.2, 6.7 Hz, 1H), 3.56 (p, J = 6.9 Hz, 1H), 1.40 (d, J = 7.0 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 144.1, 139.1, 137.4, 131.9, 131.3, 129.6, 128.9, 128.7, 128.6, 128.6, 127.4, 126.2, 41.9, 21.1. HRMS (ESI) m/z: 269.1088 $[M + H]^+$; Calcd for $C_{18}H_{18}Cl^+$: 269.1092.

1-Bromo-4-((3*E*,5*E*)-6-phenylhexa-3,5-dien-2-yl)benzene (2h). Colorless oil; 50.7 mg, 85% yield; R_f = 0.39 (petroleum ether); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.44–7.41 (m, 2H), 7.39–7.34 (m, 2H), 7.30 (t, J = 7.7 Hz, 2H), 7.22–7.17 (m, 1H), 7.14–7.08 (m, 2H), 6.75 (dd, J = 15.7, 10.4 Hz, 1H), 6.49 (d, J = 15.7 Hz, 1H), 6.20 (dd, J = 15.2, 10.4 Hz, 1H), 5.93 (dd, J = 15.2, 6.7 Hz, 1H), 3.54 (p, J = 6.9 Hz, 1H), 1.39 (d, J = 7.0 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 144.6, 139.0, 137.4, 131.6, 131.4, 129.6, 129.1, 128.9, 128.6, 127.4, 126.2, 120.0, 41.9, 21.1. HRMS (ESI) m/z: 313.0582 $[M + H]^+$; Calcd for $C_{18}H_{18}Br^+$: 313.0586.

1-Methyl-4-((3*E*,5*E*)-6-phenylhexa-3,5-dien-2-yl)benzene (2i). Colorless oil; 41.7 mg, 89% yield; R_f = 0.57 (petroleum ether); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.38 (d, J = 7.3 Hz, 2H), 7.31 (t, J = 7.6 Hz, 2H), 7.22 (d, J = 7.2 Hz, 1H), 7.15 (s, 4H), 6.79 (dd, J = 15.6, 10.3 Hz, 1H), 6.50 (d, J = 15.7 Hz, 1H), 6.24 (dd, J = 15.2, 10.4 Hz, 1H), 6.00 (dd, J = 15.2, 6.8 Hz, 1H), 3.62–3.52 (m, 1H), 2.35 (s, 3H), 1.43 (d, J = 7.0 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 142.6, 140.2, 137.6, 135.7, 130.8, 129.3, 129.2, 129.0, 128.6, 127.2, 127.2, 126.2, 42.0, 21.2, 21.0. HRMS (ESI) m/z: 249.1634 $[M + H]^+$; Calcd for $C_{19}H_{21}^+$: 249.1638.

1-((1*E*,3*E*)-4-Phenylbuta-1,3-dien-1-yl)-2,3-dihydro-1H-indene (2j). Colorless oil; 35.9 mg, 73% yield; R_f = 0.50 (petroleum ether); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.40 (d, J = 7.3 Hz, 2H), 7.32 (t, J = 7.6 Hz, 2H), 7.26–7.14 (m, 5H), 6.82 (dd, J = 15.7, 10.4 Hz, 1H), 6.53 (d, J = 15.7 Hz, 1H), 6.36 (dd, J = 15.0, 10.4 Hz, 1H), 5.88 (dd, J = 15.1, 8.6 Hz, 1H), 3.87 (q, J = 8.2 Hz, 1H), 2.99–2.85 (m, 2H), 2.44–2.34 (m, 1H), 1.90 (dq, J = 12.5, 8.7 Hz, 1H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 145.8, 143.9, 137.7, 137.5, 131.0, 130.9, 129.0, 128.6, 127.3, 126.7, 126.3, 126.2, 124.5, 124.5, 49.0, 33.6, 31.7. HRMS (ESI) m/z: 247.1479 $[M + H]^+$; Calcd for $C_{19}H_{19}^+$: 247.1481.

((1*E*,3*E*)-5-Methylhepta-1,3-diene-1,7-diyl)dibenzene (2k). Colorless oil; 39.3 mg, 75% yield; R_f = 0.70 (petroleum ether); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.40–7.37 (m, 2H), 7.33–7.27 (m, 4H), 7.19 (qd, J = 7.4, 3.4 Hz, 5H), 6.77 (dd, J = 15.6, 10.4 Hz, 1H), 6.47 (d, J = 15.6 Hz, 1H), 6.21 (dd, J = 15.2, 10.4 Hz, 1H), 5.75 (dd, J = 15.2, 8.0 Hz, 1H), 2.68–2.56 (m, 2H), 2.28 (p, J = 7.1 Hz, 1H), 1.71–1.63 (m, 2H), 1.08 (d, J = 6.7 Hz, 3H). ^{13}C NMR (101 MHz, DMSO-d_6) δ 142.7, 141.5, 137.7, 130.6, 129.9, 129.6, 129.1, 128.8, 128.7, 127.7, 126.5, 126.1, 38.8, 36.4, 33.5, 20.8. HRMS (ESI) m/z: 263.1792 $[M + H]^+$; Calcd for $C_{20}H_{23}^+$: 263.1794.

((1*E*,3*E*)-5-Methylundeca-1,3-dien-1-yl)benzene (2l). Colorless oil; 37.8 mg, 78% yield; R_f = 0.73 (petroleum ether); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.40–7.34 (m, 2H), 7.32–7.27 (m, 2H), 7.21–7.15 (m, 1H), 6.75 (dd, J = 15.6, 10.4 Hz, 1H), 6.45 (d, J = 15.7 Hz, 1H), 6.16 (dd, J = 15.2, 10.4 Hz, 1H), 5.71 (dd, J = 15.2, 7.8 Hz, 1H), 2.20 (q, J = 6.8 Hz, 1H), 1.26 (d, J = 6.5 Hz, 10H), 1.03 (d, J = 6.7 Hz, 3H), 0.91–0.85 (m, 3H). ^{13}C NMR (101 MHz, DMSO-d_6) δ 141.9, 137.7, 130.4, 129.9, 129.2, 129.1, 127.6, 126.5, 29.3, 27.3, 22.6, 20.9, 14.4. HRMS (ESI) m/z: 243.2109 $[M + H]^+$; Calcd for $C_{18}H_{27}^+$: 243.2107.

((1*E*,3*E*)-5-Methylpentadeca-1,3-dien-1-yl)benzene (2m). Colorless oil; 45.3 mg, 76% yield; R_f = 0.77 (petroleum ether); ^{1}H NMR (400 MHz, DMSO-d_6) δ 7.41 (d, J = 7.3 Hz, 2H), 7.30 (m, J = 9.5, 5.7 Hz, 2H), 7.19 (t, J = 7.3 Hz, 1H), 6.88–6.78 (m, 1H), 6.51–6.45 (m, 1H), 6.17 (dd, J = 15.2, 10.4 Hz, 1H), 5.74 (dd, J = 15.3, 7.8 Hz, 1H), 2.19 (m, J = 13.7, 6.8 Hz, 1H), 1.22 (s, 16H), 1.00–0.94 (m, 3H), 0.89 (m, J = 14.9, 7.4 Hz, 2H), 0.83 (t, J = 6.7 Hz, 3H). ^{13}C NMR (101 MHz, DMSO-d_6) δ 142.0, 137.7, 132.0, 130.4, 129.9, 129.1, 127.6, 126.5, 37.0, 36.8, 31.8, 30.5, 29.6, 29.5, 29.2, 27.3, 22.6, 20.9, 19.1, 14.4. HRMS (ESI) m/z: 299.2730 $[M + H]^+$; Calcd for $C_{22}H_{35}^+$: 299.2733.

((1*E*,3*E*)-4-Cyclohexylbuta-1,3-dien-1-yl)benzene (2n). Colorless oil; 34.0 mg, 80% yield; R_f = 0.77 (petroleum ether); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.40–7.34 (m, 2H), 7.32–7.27 (m, 2H), 7.22–7.16 (m, 1H), 6.74 (dd, J = 15.6, 10.4 Hz, 1H), 6.45 (d, J = 15.7 Hz, 1H), 6.17 (dd, J = 15.3, 10.4 Hz, 1H), 5.78 (dd, J = 15.3, 6.9 Hz, 1H), 2.06 (dd, J = 12.0, 4.0 Hz, 1H), 1.74 (d, J = 9.4 Hz, 4H), 1.66 (d, J = 12.7 Hz, 1H), 1.35–1.21 (m, 3H), 1.15 (ddd, J = 20.7, 10.3, 4.4 Hz, 2H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 141.7, 137.8, 130.0, 129.9, 128.5, 127.9, 127.0, 126.1, 40.9, 32.9, 26.2, 26.0. HRMS (ESI) m/z: 213.1635 $[M + H]^+$; Calcd for $C_{16}H_{21}^+$: 213.1638.

((1*E*,3*E*)-4-(1-Methylcyclohexyl)buta-1,3-dien-1-yl)benzene (2o). Colorless oil; 36.7 mg, 81% yield; R_f = 0.65 (petroleum ether); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.38 (d, J = 7.4 Hz, 2H), 7.30 (t, J = 7.6 Hz, 2H), 7.20 (t, J = 7.3 Hz, 1H), 6.79 (dd, J = 15.6, 10.3 Hz, 1H), 6.48 (d, J = 15.7 Hz, 1H), 6.18 (dd, J = 15.6, 10.3 Hz, 1H), 5.83 (d, J = 15.6 Hz, 1H), 1.56–1.33 (m, 10H), 1.04 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 146.1, 137.8, 130.2, 129.9, 128.5, 127.0, 126.8, 126.1, 38.0, 36.3, 27.6, 26.3, 22.5. HRMS (ESI) m/z: 227.1792 $[M + H]^+$; Calcd for $C_{17}H_{23}^+$: 227.1794.

2-((1*E*,3*E*)-4-Phenylbuta-1,3-dien-1-yl)bicyclo[2.2.1]heptane (2p). Colorless oil; 30.9 mg, 69% yield; R_f = 0.57 (petroleum ether); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.42–7.35 (m, 2H), 7.30 (d, J = 7.6 Hz, 2H), 7.18 (t, J = 7.4 Hz, 1H), 6.73 (dd, J = 15.7, 10.3 Hz, 1H), 6.43 (d, J = 15.7 Hz, 1H), 6.13 (dd, J = 15.1, 10.3 Hz, 1H), 5.74 (dd, J = 15.1, 8.1 Hz, 1H), 2.26 (s, 1H), 2.19 (q, J = 7.9 Hz, 1H), 2.11–2.04 (m, 1H), 1.50 (s, 2H), 1.39 (d, J = 9.9 Hz, 1H), 1.35–1.21 (m, 3H), 1.19 (d, J = 7.5 Hz, 1H), 1.14 (d, J = 10.3 Hz, 1H). ^{13}C NMR (101 MHz, DMSO-d_6) δ 141.5, 137.7, 130.4, 129.9, 129.1, 128.6, 127.6, 126.4, 45.1, 42.7, 37.8, 36.5, 35.9, 29.7, 29.0. HRMS (ESI) m/z: 225.1634 $[M + H]^+$; Calcd for $C_{17}H_{21}^+$: 225.1638.

(3*E*,5*E*)-2,2-Dimethyl-6-phenylhexa-3,5-dien-1-ol (2q). Yellow oil; 32.7 mg, 81% yield; R_f = 0.28 (EtOAc/petroleum ether 1 : 5); ^{1}H NMR (400 MHz, DMSO-d_6) δ 7.41 (d, J = 7.3 Hz, 2H), 7.29 (t, J = 7.6 Hz, 2H), 7.21–7.15 (m, 1H), 6.83 (dd, J = 15.7, 10.3 Hz, 1H), 6.50 (d, J = 15.7 Hz, 1H), 6.16 (dd, J = 15.6, 10.3 Hz, 1H), 5.87 (d, J = 15.6 Hz, 1H), 4.60 (t, J = 5.5 Hz, 1H), 3.17 (d, J = 5.6 Hz, 2H), 0.95 (d, J = 11.4 Hz, 6H). ^{13}C NMR (101 MHz, DMSO-d_6) δ 144.0, 137.8, 130.6, 130.3, 129.1, 127.7, 127.6, 126.5, 70.6, 38.9, 24.5. HRMS (ESI) m/z: 203.1428 $[M + H]^+$; Calcd for $C_{14}H_{19}O^+$: 203.1430.

(4*E*,6*E*)-3,3-Dimethyl-7-phenylhepta-4,6-dien-1-ol (2r). Yellow oil; 34.2 mg, 79% yield; R_f = 0.20 (EtOAc/petroleum ether 1 : 5); ^{1}H NMR (400 MHz, DMSO-d_6) δ 7.43–7.38 (m, 2H), 7.32–7.27 (m, 2H), 7.21–7.16 (m, 1H), 6.84 (dd, J = 15.7, 10.2 Hz, 1H), 6.50 (d, J = 15.7 Hz, 1H), 6.11 (dd, J = 15.5, 10.3 Hz, 1H), 5.84 (d, J = 15.5 Hz, 1H), 4.26 (t, J = 5.0 Hz, 1H), 3.38 (td, J = 7.6, 4.9 Hz, 2H), 1.51 (dd, J = 8.2, 7.0 Hz, 2H), 1.01 (s, 6H). ^{13}C NMR (101 MHz, DMSO-d_6) δ 145.7, 137.7, 130.6, 130.1, 129.0, 127.6, 126.8, 126.5, 58.3, 45.6, 35.6, 27.9. HRMS (ESI) m/z: 217.1586 $[M + H]^+$; Calcd for $C_{15}H_{21}O^+$: 217.1587.

(6*E*,8*E*)-5-Methyl-9-phenylnona-6,8-dien-4-ol (2s). Yellow oil; 32.3 mg, 70% yield; R_f = 0.44 (EtOAc/petroleum ether 1 : 5); ^{1}H NMR (400 MHz, DMSO-d_6) δ 7.44–7.39 (m, 2H), 7.29 (td, J = 7.9, 3.1 Hz, 2H), 7.21–7.16 (m, 1H), 6.84 (ddt, J = 15.5, 10.5, 2.4 Hz, 1H), 6.47 (dd, J = 15.8, 2.8 Hz, 1H), 6.22–6.12 (m, 1H), 5.85 (tdd, J = 14.5, 9.5, 3.0 Hz, 1H), 4.38 (tt, J = 4.9, 2.2 Hz, 1H), 3.37–3.25 (m, 1H), 2.28–2.15 (m, 1H), 1.45–1.19 (m, 4H), 0.99 (tt, J = 4.9, 2.5 Hz, 3H), 0.87–0.81 (m, 3H). ^{13}C NMR (101 MHz, DMSO-d_6) δ 139.8, 138.8, 137.8, 130.4, 130.3, 129.1, 127.6, 126.5, 73.7, 43.0, 36.9, 19.3, 17.1, 14.6. HRMS (ESI) m/z: 231.1745 $[M + H]^+$; Calcd for $C_{16}H_{23}O^+$: 231.1743.

Triphenyl((3*E*,5*E*)-6-phenylhexa-3,5-dien-2-yl)silane (2t). Yellow oil; 50.8 mg, 61% yield; R_f = 0.20 (petroleum ether); ^{1}H NMR (400 MHz, DMSO-d_6) δ 7.50–7.42 (m, 10H), 7.41 (d, J = 1.7 Hz, 1H), 7.42–7.34 (m, 10H), 6.80–6.69 (m, 1H), 6.30 (dd, J = 14.6, 3.7 Hz, 1H), 5.70 (dd, J = 20.3, 3.7 Hz, 1H), 1.35 (d, J = 7.8 Hz, 1H), 1.19–0.84 (m, 3H). ^{13}C NMR (101 MHz, DMSO-d_6) δ 137.4, 135.9, 135.6, 135.1, 134.2, 134.1, 130.2, 130.0, 128.5, 128.5, 8.1, 4.6. HRMS (ESI) m/z: 417.2035 $[M + H]^+$; Calcd for $C_{30}H_{29}Si^+$: 417.2033.

Trimethyl((1-((1*E*,3*E*)-4-phenylbuta-1,3-dien-1-yl)cyclohexyl)oxy)silane (2u). Yellow oil; 38.4 mg, 64% yield; R_f = 0.50 (EtOAc/petroleum ether 1 : 4); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.40 (d, J = 7.4 Hz, 2H), 7.31 (t, J = 7.7 Hz, 2H), 7.20 (t, J = 7.3 Hz, 1H), 6.84 (dd, J = 15.5, 9.0 Hz, 1H), 6.53 (d, J = 15.6 Hz, 1H), 6.34 (d, J = 2.9 Hz, 1H), 5.84 (s, 1H), 2.20 (dd, J = 10.0, 6.0 Hz, 4H), 1.66–1.52 (m, 6H), 0.18 (s, 7H), 0.15 (s, 2H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 137.0, 131.0, 130.8, 129.9, 128.6, 127.1, 126.1, 125.6, 26.2, 24.5, 22.5, 1.3, 1.0. HRMS (ESI) m/z: 301.1980 $[M + H]^+$; Calcd for $C_{19}H_{29}OSi^+$: 301.1982.

(5*E*,7*E*)-4-Ethyl-8-phenylocta-5,7-dien-1-yl acetate (2v). Yellow oil; 30.5 mg, 56% yield; R_f = 0.64 (EtOAc/petroleum ether 1 : 5); ^{1}H NMR (400 MHz, DMSO-d_6) δ 7.43–7.40 (m, 2H), 7.29 (t, J = 7.6 Hz, 2H), 7.19 (t, J = 7.3 Hz, 1H), 6.85 (ddd, J = 15.8, 10.4, 3.4 Hz, 1H), 6.49 (d, J = 15.7 Hz, 1H), 6.18 (ddd, J = 15.2, 10.4, 1.7 Hz, 1H), 5.60 (ddd, J = 14.8, 9.0, 5.3 Hz, 1H), 4.00–3.89 (m, 2H), 1.97 (s, 4H), 1.56–1.37 (m, 2H), 1.25 (dtd, J = 15.8, 9.1, 8.3, 3.2 Hz, 2H), 1.06–0.91 (m, 2H), 0.83 (dt, J = 11.8, 7.1 Hz, 3H). ^{13}C NMR (101 MHz, DMSO-d_6) δ 170.8, 139.8, 137.7, 131.3, 130.5, 129.7, 129.6, 129.1, 126.5, 64.4, 44.3, 31.1, 28.0, 26.6, 21.2, 12.1. HRMS (ESI) m/z: 273.1850 $[M + H]^+$; Calcd for $C_{18}H_{25}O_2^+$: 273.1849.

(*E*)-2,2-Dimethyl-4-phenylbut-3-en-1-ol (4a). Yellow oil; 30.6 mg, 87% yield; R_f = 0.15 (EtOAc/petroleum ether 1 : 10); ^{1}H NMR (400 MHz, DMSO-d_6) δ 7.45–7.33 (m, 2H), 7.33–7.25 (m, 2H), 7.18 (m, J = 7.3, 3.9, 1.1 Hz, 1H), 6.38–6.23 (m, 2H), 4.58 (t, J = 31.2, 5.4 Hz, 1H), 3.35–3.16 (s, 2H), 1.08–0.83 (m, 6H). ^{13}C NMR (101 MHz, DMSO-d_6) δ 138.95, 138.01, 128.94, 127.29, 126.67, 126.37, 70.75, 38.87, 24.48. HRMS (ESI) m/z: 177.1272 $[M + H]^+$; Calcd for $C_{12}H_{17}O^+$: 177.1274.

(*E*)-(2-Cyclohexylvinyl)benzene (4b). White oil; 25.3 mg, 68% yield; R_f = 0.7 (petroleum ether); ^{1}H NMR (400 MHz, DMSO-d_6) δ 7.36 (d, J = 7.6 Hz, 2H), 7.28 (t, J = 7.5 Hz, 2H), 7.18 (t, J = 7.2 Hz, 1H), 6.34 (d, J = 16.1 Hz, 1H), 6.23 (dd, J = 16.1, 6.7 Hz, 1H), 2.10 (dd, J = 7.1, 3.6 Hz, 1H), 1.73 (t, J = 12.8 Hz, 4H), 1.66–1.61 (m, 1H), 1.31–1.23 (m, 2H), 1.15 (d, J = 14.1 Hz, 2H), 0.90 (t, J = 7.4 Hz, 1H). ^{13}C NMR (101 MHz, DMSO-d_6) δ 137.9, 136.8, 129.0, 127.5, 127.3, 126.3, 40.9, 32.9, 26.1, 26.0. HRMS (ESI) m/z: 187.1481 $[M + H]^+$; Calcd for $C_{14}H_{19}^+$: 187.1481.

(*E*)-(2-(1-Methylcyclohexyl)vinyl)benzene (4c). White oil; 30.8 mg, 77% yield; R_f = 0.72 (petroleum ether); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.29 (s, 2H), 7.26 (s, 3H), 6.29 (d, J = 16.3 Hz, 1H), 6.18 (d, J = 16.4 Hz, 1H), 1.60 (dt, J = 12.1, 5.2 Hz, 2H), 1.50 (d, J = 5.7 Hz, 4H), 1.38 (dq, J = 19.0, 5.8 Hz, 4H), 1.06 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 139.2, 138.9, 129.4, 128.9, 127.2, 127.0, 56.1, 37.1, 30.2, 24.6, 11.7. HRMS (ESI) m/z: 201.1634 $[M + H]^+$; Calcd for $C_{15}H_{21}^+$: 201.1638.

2-((*E*)-Styryl)bicyclo[2.2.1]heptane (4d). White oil; 29.3 mg, 74% yield; R_f = 0.42 (petroleum ether); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.37 (d, J = 7.2 Hz, 2H), 7.34–7.26 (m, 2H), 7.25–7.18 (m, 1H), 6.34 (d, J = 15.8 Hz, 1H), 6.16 (dd, J = 15.8, 8.0 Hz, 1H), 2.31 (d, J = 10.2 Hz, 2H), 2.18 (s, 1H), 1.64–1.54 (m, 3H), 1.48 (dt, J = 9.7, 2.0 Hz, 1H), 1.42 (ddd, J = 10.6, 6.0, 2.7 Hz, 1H), 1.26 (dq, J = 29.8, 10.5, 9.7 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 138.1, 136.5, 128.5, 127.3, 126.7, 126.0, 45.5, 42.7, 38.0, 36.7, 35.9, 29.8, 29.0. HRMS (ESI) m/z: 199.1480 $[M + H]^+$; Calcd for $C_{15}H_{19}^+$: 199.1481.

5-Phenylhexan-2-one (4e). Yellow oil; 33.1 mg, 94% yield; R_f = 0.40 (petroleum ether); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.33–7.26 (m, 2H), 7.20 (m, J = 14.0, 5.5, 4.1 Hz, 3H), 2.69 (m, J = 15.8, 10.1, 4.5 Hz, 1H), 2.39–2.22 (m, 2H), 2.06 (s, 3H), 1.95–1.79 (m, 2H), 1.27 (d, J = 6.9 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 208.9, 146.5, 128.5, 127.0, 126.2, 77.4, 77.1, 76.7, 41.8, 39.4, 31.9, 29.9, 22.5. HRMS (ESI) m/z: 176.1272 $[M + H]^+$; Calcd for $C_{12}H_{17}O^+$: 177.1274.

***tert*-Butyl 4-methyl-4-(3-oxobutyl)piperidine-1-carboxylate (4f).** Colorless oil; 45.8 mg, 85% yield; R_f = 0.47 (EtOAc/petroleum ether 1 : 2); ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.63–3.50 (m, 4H), 3.16 (m, J = 13.3, 9.0, 4.0 Hz, 2H), 2.42–2.30 (m, 3H), 2.14 (s, 4H), 1.44 (s, 9H), 1.28 (m, J = 9.1, 4.6 Hz, 2H), 0.89 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 209.0, 155.0, 79.3, 39.7, 37.9, 36.5, 35.0, 30.9, 30.0, 28.5, 23.0. HRMS (ESI) m/z: 270.2060 $[M + H]^+$; Calcd for $C_{15}H_{28}NO_3^+$: 270.2064.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

The authors gratefully acknowledge support from the National Natural Science Foundation of China (21502046), the Natural

Science Foundation of Heilongjiang Province (B2016008) and the University Nursing Program for Young Scholars with Creative Talents in Heilongjiang Province (UNPYSCT-2017124). The Fundamental Research Funds for the Central Universities from Harbin Engineering University (HEUCFD1412, HEUCFJ161002, HEUCFJ171006, and HEUCFJ181008) is also acknowledged. Dr Guijie Mao is acknowledged for her help in NMR spectra recording.

Notes and references

1 R. W. Hoffmann, *Chem. Soc. Rev.*, 2016, **45**, 577583.
2 (*a*) H. T. Dao, C. Li, Q. Michaudel, B. D. Maxwell and P. S. Baran, *J. Am. Chem. Soc.*, 2015, **137**, 8046–8049; (*b*) J. Gui, C. M. Pan, Y. Jin, T. Qin, J. C. Lo, B. J. Lee, S. H. Spergel, M. E. Mertzman, W. J. Pitts, T. E. La Cruz, M. A. Schmidt, N. Darvatkar, S. R. Natarajan and P. S. Baran, *Science*, 2015, **348**, 886–891; (*c*) J. C. Lo, J. Gui, Y. Yabe, C. M. Pan and P. S. Baran, *Nature*, 2014, **516**, 343–348; (*d*) M. Yan, J. C. Lo, J. T. Edwards and P. S. Baran, *J. Am. Chem. Soc.*, 2016, **138**, 12692–12714.
3 J. C. Lo, D. Kim, C. M. Pan, J. T. Edwards, Y. Yabe, J. Gui, T. Qin, S. Gutierrez, J. Giacoboni, M. W. Smith, P. L. Holland and P. S. Baran, *J. Am. Chem. Soc.*, 2017, **139**, 2484–2503.
4 (*a*) S. W. Crossley, F. Barabe and R. A. Shenvi, *J. Am. Chem. Soc.*, 2014, **136**, 16788–16791; (*b*) S. W. Crossley, C. Obradors, R. M. Martinez and R. A. Shenvi, *Chem. Rev.*, 2016, **116**, 8912–9000; (*c*) S. A. Green, J. L. Matos, A. Yagi and R. A. Shenvi, *J. Am. Chem. Soc.*, 2016, **138**, 12779–12782.
5 C. Obradors, R. M. Martinez and R. A. Shenvi, *J. Am. Chem. Soc.*, 2016, **138**, 4962–4971.
6 (*a*) S. Bordi and J. T. Starr, *Org. Lett.*, 2017, **19**, 2290–2293; (*b*) W. Cao, H. Deng, Y. Sun, B. Liu and S. Qin, *Chem. – Eur. J.*, 2018, **24**, 9120–9129; (*c*) S. W. Crossley, R. M. Martinez, S. Guevara-Zuluaga and R. A. Shenvi, *Org. Lett.*, 2016, **18**, 2620–2623; (*d*) H. Deng, W. Cao, R. Liu, Y. Zhang and B. Liu, *Angew. Chem., Int. Ed.*, 2017, **56**, 5849–5852; (*e*) Z. Deng, C. Chen and S. Cui, *RSC Adv.*, 2016, **6**, 93753–93755.
7 (*a*) D. T. George, E. J. Kuenstner and S. V. Pronin, *J. Am. Chem. Soc.*, 2015, **137**, 15410–15413; (*b*) M. D. Greenhalgh, A. S. Jones and S. P. Thomas, *ChemCatChem*, 2015, **7**, 190–222; (*c*) K. Hung, X. Hu and T. J. Maimone, *Nat. Prod. Rep.*, 2018, **35**, 174–202; (*d*) S. M. King, X. Ma and S. B. Herzon, *J. Am. Chem. Soc.*, 2014, **136**, 6884–6887; (*e*) G. Li, J. L. Kuo, A. Han, J. M. Abuyuan, L. C. Young, J. R. Norton and J. H. Palmer, *J. Am. Chem. Soc.*, 2016, **138**, 7698–7704.
8 (*a*) X. Lu, B. Xiao, Z. Zhang, T. Gong, W. Su, J. Yi, Y. Fu and L. Liu, *Nat. Commun.*, 2016, **7**, 11129; (*b*) X. Ma and S. B. Herzon, *Chem. Sci.*, 2015, **6**, 6250–6255; (*c*) X. Ma and S. B. Herzon, *J. Am. Chem. Soc.*, 2016, **138**, 8718–8721; (*d*) X. Ma and S. B. Herzon, *J. Org. Chem.*, 2016, **81**, 8673–8695; (*e*) J. Qi, J. Zheng and S. Cui, *Org. Lett.*, 2018, **20**, 1355–1358.
9 (*a*) J. Qi, J. Zheng and S. Cui, *Org. Chem. Front.*, 2018, **5**, 222–225; (*b*) S. A. Ruider, T. Sandmeier and E. M. Carreira, *Angew. Chem., Int. Ed.*, 2015, **54**, 2378–2382; (*c*) M. Saladrigas, C. Bosch, G. V. Saborit, J. Bonjoch and B. Bradshaw, *Angew. Chem., Int. Ed.*, 2018, **57**, 182–186; (*d*) Y. Shen, B. Huang, J. Zheng, C. Lin, Y. Liu and S. Cui, *Org. Lett.*, 2017, **19**, 1744–1747; (*e*) Y. Shen, J. Qi, Z. Mao and S. Cui, *Org. Lett.*, 2016, **18**, 2722–2725.
10 (*a*) H. Shigehisa, T. Ano, H. Honma, K. Ebisawa and K. Hiroya, *Org. Lett.*, 2016, **18**, 3622–3625; (*b*) H. Shigehisa, M. Hayashi, H. Ohkawa, T. Suzuki, H. Okayasu, M. Mukai, A. Yamazaki, R. Kawai, H. Kikuchi, Y. Satoh, A. Fukuyama and K. Hiroya, *J. Am. Chem. Soc.*, 2016, **138**, 10597–10604; (*c*) H. Shigehisa, N. Koseki, N. Shimizu, M. Fujisawa, M. Niitsu and K. Hiroya, *J. Am. Chem. Soc.*, 2014, **136**, 13534–13537; (*d*) A. Simonneau and M. Oestreich, *Angew. Chem., Int. Ed.*, 2015, **54**, 3556–3558; (*e*) L. Yang, W. W. Ji, E. Lin, J. L. Li, W. X. Fan, Q. Li and H. Wang, *Org. Lett.*, 2018, **20**, 1924–1927.
11 (*a*) H. Zhang, H. Li, H. Yang and H. Fu, *Org. Lett.*, 2016, **18**, 3362–3365; (*b*) N. Zhang, Z. J. Quan and X. C. Wang, *Adv. Synth. Catal.*, 2016, **358**, 3179–3183; (*c*) J. Zheng, J. Qi and S. Cui, *Org. Lett.*, 2016, **18**, 128–131; (*d*) K. Zhu, M. P. Shaver and S. P. Thomas, *Chem. – Asian J.*, 2016, **11**, 977–980.
12 B. Marciniec, *Z. Phys. Chem.*, 1974, **91**, 25–35.
13 R. Mannhold, H. Kubinyi, G. Folkers and S. Hanessian, *Natural Products in Medicinal Chemistry*, Wiley-VCH Weinheim, Germany, 2014.
14 (*a*) S. R. Sardini and M. K. Brown, *J. Am. Chem. Soc.*, 2017, **139**, 9823–9826; (*b*) A. Tortajada, R. Ninokata and R. Martin, *J. Am. Chem. Soc.*, 2018, **140**, 2050–2053; (*c*) X. H. Yang and V. M. Dong, *J. Am. Chem. Soc.*, 2017, **139**, 1774–1777.
15 V. T. Nguyen, H. T. Dang, H. H. Pham, V. D. Nguyen, C. Flores-Hansen, H. D. Arman and O. V. Larionov, *J. Am. Chem. Soc.*, 2018, **140**, 8434–8438.
16 J. Zheng, D. Wang and S. Cui, *Org. Lett.*, 2015, **17**, 4572–4575.

