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Efficient synthesis of β-substituted α-haloenones by rhodium(II)-catalyzed and thermal reactions of iodonium ylides

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Rhodium(II)-catalyzed and thermal reaction of iodonium ylides are described. Rhodium(II)-catalyzed reactions of iodonium ylides with benzyl halides and acid halides afforded α-chloro-α,β-enones and α-bromo-α,β-enones in good yields, whereas thermal reactions of iodonium ylides in a solvent such as benzene afforded α-iodo-α,β-enones in good yields.

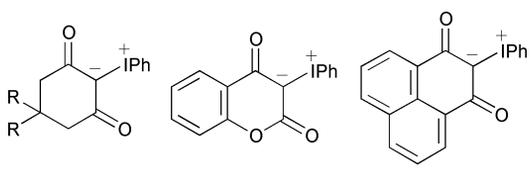
Introduction

α-Haloenones are valuable and versatile intermediates in the synthesis of α-carbon substituted enones[1] and biologically active natural products.[2] α-Haloenones are typically prepared by a halogenation–dehydrohalogenation reaction,[3] an addition–elimination reaction,[4] and a halohydrin–dehydration reaction.[5] Although many methods for the preparation of these compounds have been developed, their synthetic exploitation has been limited due to difficulty in handling and controlling the regioselectivity, the strong acidic conditions, and the side reactions involving over-oxidation.[6] The necessity to overcome these serious problems has prompted further research into new methods for the preparation of α-haloenones. We have discovered a facile method for the preparation of β-substituted α-chloroenones starting from diazodicarbonyl compounds.[7] We found that these reactions sometimes afforded β-substituted α-chloroenones in low yields. Therefore, we have tried developing a more useful and efficient method for the preparation of β-substituted α-haloenones.

Iodonium ylides are attractive and important reagents in organic synthesis.[8] Photochemical and metal-mediated reactions of iodonium ylides with several substrates have been widely studied by many groups.[9] However, the rhodium-catalyzed reaction of iodonium ylides with halides to prepare β-substituted α-haloenones has not been investigated. We report herein a new and efficient synthesis of β-substituted α-haloenones starting from the corresponding iodonium ylides with a variety of halides.

Results and discussion

Iodonium ylides **1**–**4** were prepared by reaction of the corresponding 1,3-dicarbonyl compounds with iodobenzene diacetate according to Koser's method in 81, 86, 80, and 91% yields.[10] Iodonium ylides **1**–**4** are fairly stable and can be stored in a refrigerator for a long time without any decomposition.

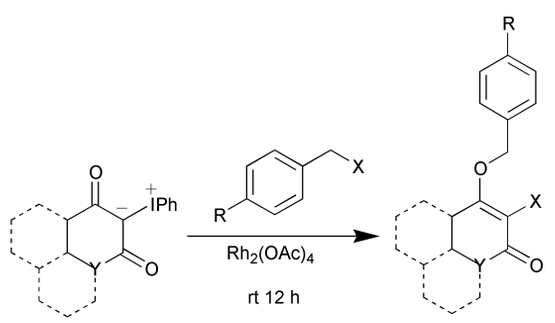


1 R=H
2 R=CH_3

3

4

The strategy that we have developed begins with the reaction of iodonium ylides and halides (10-fold excess), which serve as a solvent and a reactant, in the presence of 1 mol% of $Rh_2(OAc)_4$. Reaction of iodonium ylides with benzyl halides was examined first (Chart 1). When iodonium ylide **1** was



X=Cl, Br
Y=H, O
R=H, CH_3, OCH_3

Chart 1

treated with benzyl chloride at room temperature for 12 h, 3-benzyloxy-2-chlorocyclohex-2-enone (**5**) was obtained as a single compound in 81% yield. Support for the structural assignment was obtained from spectroscopic analysis. α-Chloroenone **5** is identified by the IR carbonyl absorption of the enone at 1657 cm^{-1} and the ^1H NMR peak of the methylene group of benzyl ether as a singlet at δ 5.24. Similarly, reaction of iodonium ylides **2**–**4** with benzyl chloride afforded α-chloroenones **6**–**8** in 92, 55, and 59% yields, respectively. Under the same conditions, 4-methylbenzyl chloride afforded α-chloroenone **9** in 50% yield, whereas 4-methoxybenzyl chloride gave **10** and **11** in 85 and 75% yields, respectively. When benzyl bromide was used, the expected 3-benzyloxy-2-bromocyclohex-2-enones (**12** and **13**) were produced in 51 and 52% yields, respectively. The results are summarized in Fig. 1.

The formation of **8** can be explained in terms of a nucleophilic attack by the chloride of benzyl chloride. A plausible mechanism is shown in Scheme 1. The iodonium ylide **4** first gives a carbenoid **14** (or a carbene) by displacement of iodobenzene by $Rh_2(OAc)_4$.The intermediate **14** is attacked by the chloride of benzyl chloride to give **15**, which subsequently undergoes intramolecular substitution to give product **8**.

Reactions with acid halides were also examined (Chart 2). Treatment of iodonium ylide **1** with AcCl at room temperature

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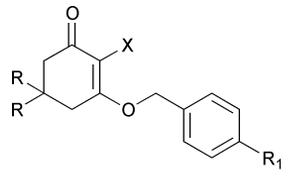
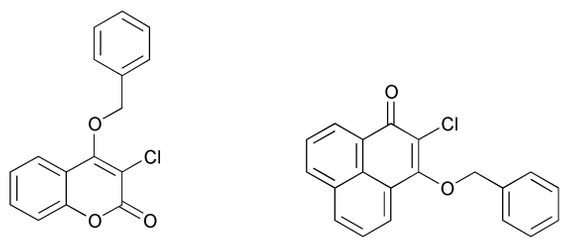
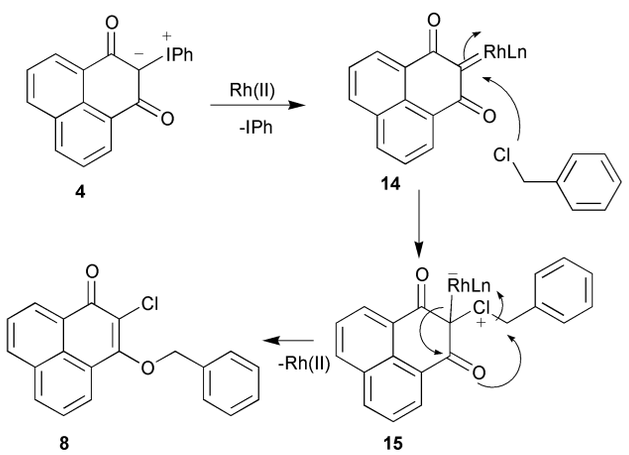


5 R=H, R_1=H, X=Cl 81%
6 R=CH_3, R_1=H, X=Cl 92%
9 R=CH_3, R_1=CH_3, X=Cl 50%
10 R=H, R_1=OCH_3, X=Cl 85%
11 R=CH_3, R_1=OCH_3, X=Cl 75%
12 R=H, R_1=H, X=Br 51%
13 R=CH_3, R_1=H, X=Br 52%



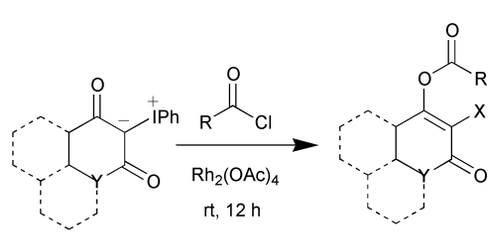
7 55% **8** 59%

Fig. 1



4 **14** **15** **8**

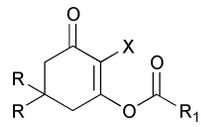
Scheme 1



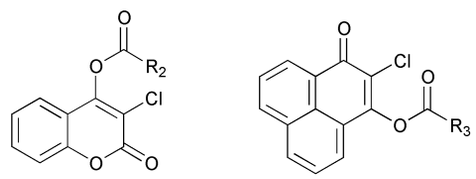
X=Cl, Br
Y=H, O
R=CH_3, CH_2CH_3

Chart 2

for 12 h in the presence of 1 mol% of $Rh_2(OAc)_4$ gave 3-acetoxy-2-chlorocyclohex-2-enone (**16**) in 94% yield. The structure of **16** is easily identified by the two IR carbonyl absorptions at 1777 and 1693 cm^{-1} associated with a vinyl ester and a ketone. The ^1H NMR spectrum shows the peak of the methyl group of the vinyl acetate at 2.26 ppm as a singlet. Similarly, reaction of iodonium ylides **2**–**4** with AcCl afforded the expected α-chloroenones **17**–**19** in 90, 91, and 92% yields, respectively. In these cases, only a single product was seen and no other products were found. When propionyl chloride was used, α-chloroenones **20**–**23** were produced in 91–97% yields. Extension of the reaction with AcBr was also successful. Treatment of **2** with acetyl bromide at room temperature



16 R=H, R_1=CH_3, X=Cl 94%
17 R=CH_3, R_1=CH_3, X=Cl 90%
20 R=H, R_1=CH_2CH_3, X=Cl 97%
21 R=CH_3, R_1=CH_2CH_3, X=Cl 97%
24 R=CH_3, R_1=CH_3, X=Br 40%



18 R_2=CH_3, X=Cl 91%
22 R_2=CH_2CH_3, X=Cl 96%

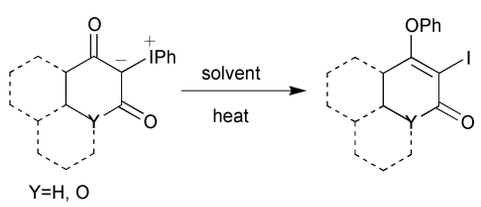
19 R_3=CH_3, X=Cl 92%
23 R_3=CH_2CH_3, X=Cl 91%

Fig. 2

for 12 h afforded 3-acetoxy-2-bromo-5,5-dimethylcyclohex-2-enone (**24**) in 40% yield. The results are summarized in Fig. 2.

Although the exact mechanism for the formation of **19** is still not clear, it is best described as shown in Scheme 2. Two possible intermediates **25** (chloronium ylide) and **27** (carbonyl ylide) can be formed by the competitive nucleophilic attack of chloride (path a) or oxygen (path b) on the electrophilic metal carbenoid **14**. However, only compound **19** has been observed experimentally, with no formation of the other possible product **28** being observed. A mechanism involving formation of a chloronium ylide (path a) explains the formation of **19** from metal carbenoid **14**. Nucleophilic attack of the chloride on the electrophilic carbenoid **14** yields intermediate **25**, which undergoes fast intramolecular nucleophilic addition of oxygen to the carbonyl group with the cleavage of the C–Cl bond to give product **19**.

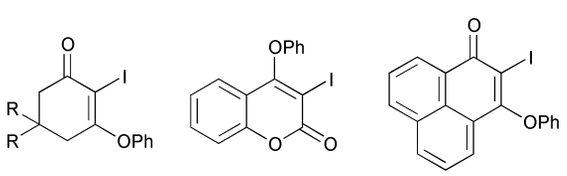
Finally, thermal reactions of iodonium ylides in the absence of $Rh_2(OAc)_4$, were investigated (Chart 3). Some evidence of



Y=H, O

Chart 3

this thermal rearrangement to give α-iodoenone is available in the literature.[11] We surveyed these reactions by using several solvents such as THF, acetonitrile, and benzene for the production of α-iodoenones. Tetrahydrofuran (reflux, 3 h) gave only a low yield (20%) of 2-iodo-3-phenoxycyclohex-2-enone (**29**), whereas acetonitrile (reflux, 3 h) and benzene (reflux, 3 h) afforded **29** in 72 and 89% yields, respectively. We found that benzene as a nonpolar solvent was more efficient than polar solvents such as acetonitrile or THF for the preparation of α-iodoenones. Other results from reactions in refluxing benzene are summarized in Fig. 3.



29 R=H 89%
30 R=CH_3 90%

31 92%

32 88%

Fig. 3

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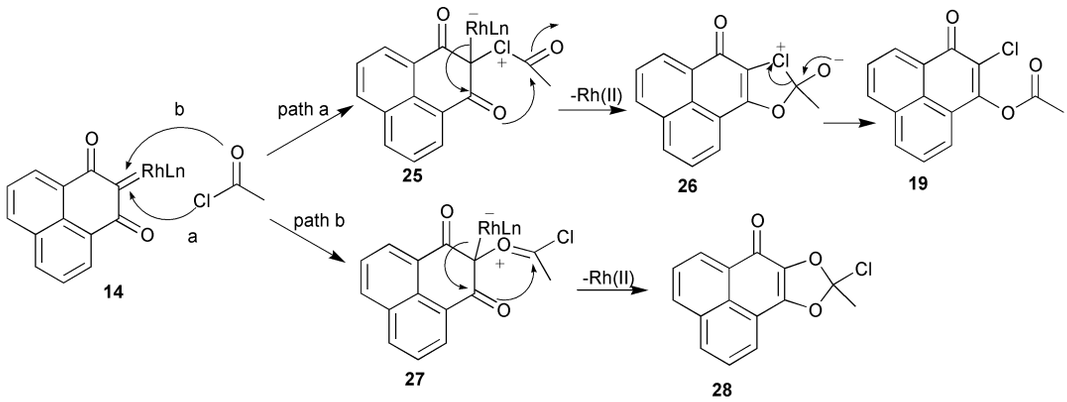

Scheme 2

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In conclusion, rhodium-catalyzed reactions and thermal reactions of iodonium ylides offer a simple and facile method for the synthesis of α-halo-α,β-unsaturated enones in good yields. Further applications of these reactions are currently being investigated in our laboratory.

Experimental

All experiments were carried out under a nitrogen atmosphere. Merck precoated silica gel plates (Art. 5554) with fluorescent indicator were used for analytical TLC. Flash column chromatography was performed using silica gel 9385 (Merck). Melting points were determined with microcover glasses on a Fisher–Johns apparatus and are uncorrected. ^{1}H NMR spectra were recorded on a Bruker Model ARX (300 MHz) spectrometer. ^{13}C NMR spectra were recorded on a Bruker Model ARX (75 MHz) spectrometer in $CDCl_3$ using 77.0 ppm as the solvent chemical shift. IR spectra were recorded on a JASCO FTIR 5300 spectrophotometer. Elemental analyses and mass spectra were carried out by Korea Basic Science Institute.

General procedure for the synthesis of α-chloro- and α-bromoenones

To a solution of iodonium ylide (1.0 mmol) and alkyl or acyl halide (10.0 mmol) was added rhodium acetate (4.4 mg, 0.01 mmol) at room temperature under a N_2 atmosphere. The reaction mixture was stirred at room temperature for 12 h. The excess alkyl or acyl halide was evaporated under reduced pressure to give a residue. The residue was purified by flash column chromatography on silica gel to give the product.

3-Benzyloxy-2-chlorocyclohex-2-enone (5). Reaction of **1** (314 mg, 1.0 mmol) and benzyl chloride (1.26 g, 10.0 mmol) afforded **5** (192 mg, 81%) as a solid, mp 98–99 °C (from hexane–ethyl acetate) (Found: C, 65.58; H, 5.20. $C_{13}H_{13}ClO_2$ requires C, 65.97; H, 5.54%); ν_{max} (KBr)/cm^{-1} 3036, 2945, 2889, 1657 (C=O, enone), 1589, 1458, 1368, 1294, 1262, 1192, 1154, 1080, 1026, 1007, 922, 905, 817; δ_H (300 MHz, $CDCl_3$) 7.41–7.33 (5H, m, ArH), 5.24 (2H, s, CH_2Ph), 2.67 (2H, dd, *J* 6.2, 6.1, CH_2), 2.48 (2H, dd, *J* 7.0, 6.2, CH_2), 1.98 (2H, m, CH_2); δ_C (75 MHz, $CDCl_3$) 191.88 (C=O), 171.14, 135.86, 129.33, 128.98, 128.05, 127.41, 127.13, 112.99, 71.03 (CH_2Ph), 37.09 (CH_2), 29.07 (CH_2). 20.66 (CH_2); *m*/*z* (EI) 236 (M^+, 10%), 146 (53), 120 (31), 118 (92), 91 (100), 89 (16), 65 (59).

3-Benzyloxy-2-chloro-5,5-dimethylcyclohex-2-enone (6). Reaction of **2** (342 mg, 1.0 mmol) and benzyl chloride (1.26 g, 10.0 mmol) afforded **6** (244 mg, 92%) as a solid, mp 92–93 °C (from hexane–ethyl acetate) (Found: C, 67.94; H, 6.72. $C_{15}H_{17}ClO_2$ requires C, 68.05; H, 6.47%); ν_{max} (KBr)/cm^{-1} 3038, 2963, 2934, 2880, 1649 (C=O, enone), 1586, 1460, 1400, 1358, 1302, 1252, 1171, 1152, 1053, 1011, 943, 918, 900, 842; δ_H (300 MHz, $CDCl_3$) 7.40–7.32 (5H, m, ArH), 5.23 (2H, s, CH_2Ph), 2.51 (2H, s, CH_2), 2.34 (2H, s, CH_2), 1.02 (6H, s, 2 × CH_3).

4-Benzyloxy-3-chlorochromen-2-one (7). Reaction of **3** (364 mg, 1.0 mmol) and benzyl chloride (1.26 g, 10.0 mmol) afforded **7** (158 mg, 55%) as a liquid (Found: C, 66.70; H, 3.92. $C_{16}H_{11}ClO_3$ requires C, 67.03; H, 3.87%); ν_{max} (neat)/cm^{-1} 3067, 3036, 1732 (C=O, ester), 1609, 1557, 1487, 1454, 1389, 1333, 1275, 1206, 1161, 1098, 1036, 1003, 914, 860; δ_H (300 MHz, $CDCl_3$) 7.71–7.24 (9H, m, ArH), 5.54 (2H, s, CH_2Ph).

3-Benzyloxy-2-chlorophenalen-1-one (8). Reaction of **4** (398 mg, 1.0 mmol) and benzyl chloride (1.26 g, 10.0 mmol) afforded **8** (189 mg, 59%) as a solid, mp 95–96 °C (from hexane–ethyl acetate) (Found: C, 74.52; H, 4.39.$C_{20}H_{13}ClO_2$ requires C, 74.89; H, 4.08%); ν_{max} (KBr)/cm^{-1} 3030, 1647 (C=O, enone), 1561, 1453, 1406, 1372, 1310, 1221, 1204, 1144, 1094, 1026, 965, 937, 903, 864, 839; δ_H (300 MHz, $CDCl_3$) 8.69 (1H, d, *J* 7.3, ArH), 8.20 (1H, d, *J* 8.1, ArH), 8.06 (2H, dd, *J* 8.1, 7.3, ArH), 7.76 (1H, dd, *J* 7.8, 7.6, ArH), 7.60–7.52 (3H, m, ArH), 7.44–7.34 (3H, m, ArH), 5.40 (2H, s, CH_2Ph); *m*/*z* (EI) 320 (M^+, 9%), 285 (20), 284 (10), 230 (8), 201 (7), 173 (11), 164 (11), 146 (30), 129 (15), 91 (100), 71 (7), 65 (11).

2-Chloro-5,5-dimethyl-3-(4-methylbenzyloxy)cyclohex-2-enone (9). Reaction of **2** (342 mg, 1.0 mmol) and 4-methylbenzyl chloride (1.41g, 10.0 mmol) afforded **9** (139 mg, 50%) as a solid, mp 101–102 °C (from hexane–ethyl acetate) (Found: C, 69.15; H, 6.99. $C_{16}H_{19}ClO_2$ requires C, 68.93; H, 6.87%); ν_{max} (KBr)/cm^{-1} 3032, 2959, 2932, 2890, 1649 (C=O, enone), 1586, 1460, 1408, 1362, 1306, 1248, 1221, 1173, 1049, 1015, 947, 918; δ_H (300 MHz, $CDCl_3$) 7.23 (2H, d, *J* 8.1, ArH), 7.18 (2H, d, *J* 8.1, ArH), 5.19 (2H, s, CH_2Ph), 2.51 (2H, s, CH_2), 2.34 (5H, s, CH_2 and CH_3), 1.03 (6H, s, 2 × CH_3); *m*/*z* (EI) 278 (M^+, 1%), 244 (2), 174 (3), 149 (5), 129 (8), 118 (8), 105 (100), 103 (16), 77 (22).

2-Chloro-3-(4-methoxybenzyloxy)cyclohex-2-enone (10). Reaction of **1** (314 mg, 1.0 mmol) and 4-methoxybenzyl chloride (1.57 g, 10.0 mmol) afforded **10** (227 mg, 85%) as a solid, mp 139–140 °C (from hexane–ethyl acetate) (Found: C, 62.72; H, 5.91. $C_{14}H_{15}ClO_3$ requires C, 63.04; H, 5.67%); ν_{max} (KBr)/cm^{-1} 2957, 1649 (C=O, enone), 1582, 1514, 1453, 1416, 1368, 1327, 1294, 1260, 1173, 1071, 1011, 897; δ_H (300 MHz, $CDCl_3$) 7.27 (2H, d, *J* 8.6, ArH), 6.91 (2H, d, *J* 8.6, ArH), 5.16 (2H, s, CH_2Ph), 3.80 (3H, s, OCH_3), 2.68 (2H, m, CH_2), 2.47 (2H, m, CH_2), 2.00 (2H, m, CH_2).

2-Chloro-3-(4-methoxybenzyloxy)-5,5-dimethylcyclohex-2-enone (11). Reaction of **2** (342 mg, 1.0 mmol) and 4-methoxybenzyl chloride (1.57 g, 10.0 mmol) afforded **11** (221

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mg, 75%) as a solid, mp 142–143 °C (from hexane–ethyl acetate) (Found: C, 65.36; H, 6.82. $C_{16}H_{19}ClO_3$ requires C, 65.19; H, 6.50%); ν_{max} (KBr)/cm^{-1} 2957, 1649 (C=O, enone), 1586, 1514, 1462, 1304, 1246, 1175, 1032, 945; δ_H (300 MHz, $CDCl_3$) 7.27 (2H, d, *J* 8.6, ArH), 6.89 (2H, d, *J* 8.6, ArH), 5.16 (2H, s, CH_2Ph), 3.79 (3H, s, OCH_3), 2.52 (2H, s, CH_2), 2.35 (2H, s, CH_2), 1.03 (6H, s, 2 × CH_3).

3-Benzyloxy-2-bromocyclohex-2-enone (12). Reaction of **1** (314 mg, 1.0 mmol) and benzyl bromide (1.71 g, 10.0 mmol) afforded **12** (143 mg, 51%) as a solid, mp 104–105 °C (from hexane–ethyl acetate) (Found: C, 55.48; H, 4.85. $C_{13}H_{13}BrO_2$ requires C, 55.54; H, 4.66%); ν_{max} (KBr)/cm^{-1} 3063, 3036, 2949, 2887, 1655 (C=O, enone), 1585, 1499, 1458, 1368, 1287, 1260, 1192, 1154, 1080, 1026, 987, 920, 904; δ_H (300 MHz, $CDCl_3$) 7.38–7.33 (5H, m, ArH), 5.25 (2H, s, CH_2Ph), 2.66 (2H, dd, *J* 6.3, 6.1, CH_2), 2.51 (2H, dd, *J* 6.8, 6.3, CH_2), 1.99 (2H, m, CH_2).

3-Benzyloxy-2-bromo-5,5-dimethylcyclohex-2-enone (13). Reaction of **2** (342 mg, 1.0 mmol) and benzyl bromide (1.71 g, 10.0 mmol) afforded **13** (161 mg, 52%) as a solid, mp 102–103 °C (from hexane–ethyl acetate) (Found: C, 58.57; H, 5.91. $C_{15}H_{17}BrO_2$ requires C, 58.24; H, 5.54%); ν_{max} (KBr)/cm^{-1} 3063, 2957, 2872, 1667 (C=O, enone), 1589, 1462, 1352, 1292, 1244, 1171, 1038, 1001, 910; δ_H (300 MHz, $CDCl_3$) 9.38–7.35 (5H, m, ArH), 5.24 (2H, s, CH_2Ph), 2.50 (2H, s, CH_2), 2.38 (2H, s, CH_2), 1.02 (6H, s, 2 × CH_3).

3-Acetoxy-2-chlorocyclohex-2-enone (16). Reaction of **1** (314 mg, 1.0 mmol) and acetyl chloride (785 mg, 10.0 mmol) afforded **16** (177 mg, 94%) as a liquid (Found: C, 50.82; H, 5.14. $C_8H_9ClO_3$ requires C, 50.94; H, 4.81%); ν_{max} (neat)/cm^{-1} 2959, 1777 (C=O, vinylic ester), 1693 (C=O, enone), 1630, 1427, 1371, 1352, 1281, 1169, 1065, 1007, 968, 912, 873, 845; δ_H (300 MHz, $CDCl_3$) 2.67 (2H, dd, *J* 6.2, 6.1, CH_2), 2.59 (2H, dd, *J* 6.1, 5.1, CH_2), 2.26 (3H, s, CH_3), 2.06 (2H, m, CH_2); δ_C (75 MHz, $CDCl_3$) 191.31 (C=O, enone), 166.15 (C=O, vinylic ester), 164.31, 121.97, 37.21, 29.84, 20.58, 20.13.

3-Acetoxy-2-chloro-5,5-dimethylcyclohex-2-enone (17). Reaction of **2** (342 mg, 1.0 mmol) and acetyl chloride (785 mg, 10.0 mmol) afforded **17** (195 mg, 90%) as a liquid (Found: C, 55.43; H, 6.24. $C_{10}H_{13}ClO_3$ requires C, 55.54; H, 6.05%); ν_{max} (neat)/cm^{-1} 2963, 2876, 1777 (C=O, vinylic ester), 1694 (C=O, enone), 1634, 1470, 1416, 1372, 1348, 1294, 1181, 1026, 947, 920, 856; δ_H (300 MHz, $CDCl_3$) 2.54 (2H, s, CH_2), 2.44 (2H, s, CH_2), 2.25 (3H, s, CH_3), 1.10 (6H, s, 2 × CH_3); *m*/*z* (EI) 216 (M$^+$, 5%), 174 (96), 159 (21), 149 (15), 129 (6), 118 (100), 103 (12), 83 (22), 55 (16).

4-Acetoxy-3-chlorochromen-2-one (18).[7] Reaction of **3** (364 mg, 1.0 mmol) and acetyl chloride (785 mg, 10.0 mmol) afforded **18** (217 mg, 91%) as a solid, mp 167–168 °C (from hexane–ethyl acetate); ν_{max} (KBr)/cm^{-1} 3109, 3071, 3045, 1784 (C=O, vinylic ester), 1730 (C=O, ester), 1620, 1566, 1493, 1453, 1356, 1281, 1200, 1173, 1138, 1090, 1038, 1015, 1001, 903, 777, 734; δ_H (300 MHz, $CDCl_3$) 7.59 (1H, dd, *J* 8.2, 7.5, ArH), 7.49 (1H, d, *J* 7.8, ArH), 7.39 (1H, d, *J* 8.2, ArH), 7.34 (1H, dd, *J* 7.8, 7.5, ArH), 2.49 (3H, s, CH_3); *m*/*z* (EI) 238 (M$^+$, 17%), 196 (100), 162 (9), 121 (71), 92 (13), 63 (6).

3-Acetoxy-2-chlorophenalen-1-one (19). Reaction of **4** (398 mg, 1.0 mmol) and acetyl chloride (785 mg, 10.0 mmol) afforded **19** (251 mg, 92%) as a solid, mp 195–198 °C (from hexane–ethyl acetate) (Found: C, 65.95; H, 3.39. $C_{15}H_9ClO_3$ requires C, 66.07; H, 3.33%); ν_{max} (KBr)/cm^{-1} 2926, 1775 (C=O, vinylic ester), 1640 (C=O, enone), 1574, 1404, 1368, 1323, 1225, 1215, 1182, 1157, 1088, 1028, 1001, 960; δ_H (300 MHz, $CDCl_3$) 8.73 (1H, dd, *J* 7.4, 1.2, ArH), 8. 25 (1H, dd, *J* 8.0, 1.1, ArH), 8.10 (1H, dd, *J* 8.2, 1.2, ArH), 7. 89 (1H, dd, *J* 7.4, 1.1, ArH), 7.80 (1H, dd, *J* 8.0, 7.4, ArH), 7.64 (1H, dd, *J* 8.2, 7.4, ArH), 2.52 (3H, s, CH_3); δ_C (75 MHz, $CDCl_3$) 179.20 (C=O, enone), 167.05 (C=O, ester), 154.93, 136.37, 133.69, 132.48, 132.37, 128.61, 127.86, 127.58, 126.99, 125.63, 125.48, 124.40, 21.04 (CH_3); *m*/*z* (EI) 272 (M$^+$, 10%), 230 (100), 292 (15), 196 (15), 173 (22), 155 (30), 138 (34), 129 (22), 105 (9), 87 (5), 71 (6), 57 (7).

2-Chloro-3-propanoyloxycyclohex-2-enone (20). Reaction of **1** (314 mg, 1.0 mmol) and propionyl chloride (925 mg, 10.0 mmol) afforded **20** (197 mg, 97%) as a liquid (Found: C, 53.22; H, 5.54. $C_9H_{11}ClO_3$ requires C, 53.35; H, 5.47%); ν_{max} (neat)/cm^{-1} 2946, 2888, 1770 (C=O, vinylic ester), 1694 (C=O, enone), 1628, 1460, 1424, 1345, 1277, 1167, 1115, 1076, 1017, 986, 841; δ_H (300 MHz, $CDCl_3$) 2.64 (2H, t, *J* 5.9, CH_2), 2.57–2.48 (4H, m, 2 × CH_2), 2.03 (2H, m, CH_2), 1.19 (3H, t, *J* 6.0, CH_3); δ_C (75 MHz, $CDCl_3$) 191.33 (C=O, enone), 169.78 (C=O, ester), 164.49, 121.85, 37.23, 29.91, 27.42, 20.15, 8.75.

2-Chloro-5,5-dimethyl-3-propanoyloxycyclohex-2-enone (21). Reaction of **2** (342 mg, 1.0 mmol) and propionyl chloride (925 mg, 10.0 mmol) afforded **21** (224 mg, 97%) as a liquid (Found: C, 57.54; H, 6.44. $C_{11}H_{15}ClO_3$ requires C, 57.27; H, 6.55%); ν_{max} (neat)/cm^{-1} 2962, 2878, 1771 (C=O, vinylic ester), 1694 (C=O, enone), 1634, 1464, 1372, 1345, 1290, 1267, 1155, 1113, 1074, 1026, 947, 918, 850; δ_H (300 MHz, $CDCl_3$) 2.55 (2H, q, *J* 6.0, CH_2), 2.54 (2H, s, CH_2), 2.45 (2H, s, CH_2), 1.22 (3H, t, *J* 6.0, CH_3), 1.11 (6H, s, 2 × CH_3).

3-Chloro-4-propanoyloxychromen-2-one (22). Reaction of **3** (364 mg, 1.0 mmol) and propionyl chloride (925 mg, 10.0 mmol) afforded **22** (243 mg, 96%) as a solid, mp 112 °C (from hexane–ethyl acetate) (Found: C, 57.18; H, 3.69. $C_{12}H_9ClO_4$ requires C, 57.05; H, 3.59%); ν_{max} (KBr)/cm^{-1} 3046, 2948, 1780 (C=O, vinylic ester), 1730 (C=O, ester), 1618, 1566, 1451, 1348, 1283, 1262, 1105, 1065, 1015, 997, 877; δ_H (300 MHz, $CDCl_3$) 7.58 (1H, dd, *J* 7.9, 7.7, ArH), 7.47 (1H, d, *J* 7.7, ArH), 7.39–7.28 (2H, m, ArH), 2.78 (2H, q, *J* 7.5, CH_2), 1.35 (3H, t, *J* 7.5, CH_3); *m*/*z* (EI) 252 (M$^+$, 16%), 196 (31), 167 (5), 121 (37), 120 (21), 92 (13), 75 (6), 57 (100).

2-Chloro-3-propanoyloxyphenalen-1-one (23).[7] Reaction of **4** (398 mg, 1.0 mmol) and propionyl chloride (925 mg, 10.0 mmol) afforded **23** (261 mg, 91%) as a solid, mp 146–147 °C (from hexane–ethyl acetate); ν_{max} (KBr)/cm^{-1} 2963, 2932, 2874, 1765 (C=O, vinylic ester), 1647 (C=O, enone), 1577, 1404, 1377, 1323, 1300, 1211, 1182, 1148, 1122, 1063, 965, 842, 820, 777; δ_H (300 MHz, $CDCl_3$) 8.69 (1H, d, *J* 7.5, ArH), 8.21 (1H, d, *J* 8.0, ArH), 8.31 (1H, d, *J* 8.3, ArH), 7.84 (1H, d, *J* 7.4, ArH), 7.76 (1H, dd, *J* 8.0, 7.6, ArH), 7.61 (1H, dd, *J* 8.3, 7.4, ArH), 2.83 (2H, q, *J* 7.5, CH_2), 1.38 (3H, t, *J* 7.5, CH_3); *m*/*z* (EI) 286 (M$^+$, 12%), 230 (100), 196 (22), 173 (14), 155 (14), 129 (32), 112 (9), 71 (8), 57 (32).

3-Acetoxy-2-bromo-5,5-dimethylcyclohex-2-enone (24). Reaction of **2** (342 mg, 1.0 mmol) and acetyl bromide (1.23 g, 10.0 mmol) afforded **24** (104 mg, 40%) as a liquid (Found: C, 45.79; H, 5.21. $C_{10}H_{13}BrO_3$ requires C, 46.00; H, 5.02%); ν_{max} (neat)/cm^{-1} 2965, 2874, 1777 (C=O, vinylic ester), 1690 (C=O, enone), 1626, 1470, 1416, 1370, 1290, 1179, 1123, 1013, 934, 912, 856; δ_H (300 MHz, $CDCl_3$) 2.51 (2H, s, CH_2), 2.45 (2H, s, CH_2), 2.24 (3H, s, CH_2), 1.07 (6H, s, CH_3).

General procedure for the synthesis of α-iodoenones

The iodonium ylide (1.0 mmol) was refluxed in benzene (10 mL) for 3 h. After evaporation of the solvent, the residue

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was purified by flash column chromatography on silica gel to give the product.

2-Iodo-3-phenoxycyclohex-2-enone (29).[11] Reaction of **1** (314 mg, 1.0 mmol) in benzene afforded **29** (280 mg, 89%) as a solid, mp 107–109 °C (from hexane–ethyl acetate); ν_{max} (KBr)/cm^{-1} 2953, 1655 (C=O, enone), 1568, 1487, 1418, 1316, 1233, 1186, 1142, 1069, 1022, 982, 966, 916; δ_H (300 MHz, $CDCl_3$) 7.36 (2H, dd, *J* 8.2, 7.4, ArH), 7.23 (1H, t, *J* 7.4, ArH), 7.04 (2H, d, *J* 8.2, ArH), 2.58 (2H, dd, *J* 6.2, 6.1, CH_2), 2.40 (2H, dd, *J* 6.1, 5.1, CH_2), 1.94 (2H, m, CH_2); *m*/*z* (EI) 314 (M^+, 76%), 254 (13), 238 (100), 210 (82), 187 (25), 159 (22), 149 (6), 131 (25), 112 (42), 94 (34), 84 (53), 83 (51), 55 (77).

2-Iodo-5,5-dimethyl-3-phenoxycyclohex-2-enone (30).[12] Reaction of **2** (342 mg, 1.0 mmol) in benzene afforded **30** (308 mg, 90%) as a solid, mp 158–162 °C (from hexane–ethyl acetate); ν_{max} (KBr)/cm^{-1} 2963, 2932, 1661 (C=O, enone), 1580, 1487, 1454, 1372, 1343, 1294, 1229, 1192, 1138, 1073, 1024, 1001, 897; δ_H (300 MHz, $CDCl_3$) 7.39 (2H, dd, *J* 8.2, 7.4, ArH), 7.25 (1H, t, *J* 7.4, ArH), 7.02 (2H, d, *J* 8.2, ArH), 2.47 (2H, s, CH_2), 2.28 (2H, s, CH_2), 1.03 (6H, s, 2 × CH_3); *m*/*z* (EI) 342 (M^+, 100%), 286 (8), 215 (29), 193 (38), 159 (33), 131 (19), 122 (6), 103 (5), 94 (20), 77 (21), 67 (8), 51 (6).

3-Iodo-4-phenoxychromen-2-one (31). Reaction of **3** (364 mg, 1.0 mmol) in benzene afforded **31** (333 mg, 92%) as a solid, mp 124–126 °C (from hexane–ethyl acetate) (Found: C, 49.21; H, 2.56. $C_{15}H_9IO_3$ requires C, 49.48; H, 2.49%); ν_{max} (KBr)/cm^{-1} 3074, 1736 (C=O, ester), 1591, 1555, 1483, 1447, 1337, 1246, 1209, 1161, 1082, 1034, 970, 889; δ_H (300 MHz, $CDCl_3$) 7.58 (1H, dd, *J* 8.3, 7.2, ArH), 7.52 (1H, d, *J* 7.2, ArH), 7.42 (1H, d, *J* 8.3, ArH), 7.34 (2H, dd, *J* 8.1, 7.8, ArH), 7.18 (1H, dd, *J* 7.8, 7.5, ArH), 7.12 (1H, t, *J* 7.5, ArH), 6.94 (2H, d, *J* 8.1, ArH).

2-Iodo-3-phenoxyphenalen-1-one (32). Reaction of **4** (398 mg, 1.0 mmol) in benzene afforded **32** (350 mg, 88%) as a solid, mp 183–184 °C (from hexane–ethyl acetate) (Found: C, 57.42; H, 2.66. $C_{19}H_{11}IO_2$ requires C, 57.31; H, 2.78%); ν_{max} (KBr)/cm^{-1} 3065, 1638, 1572, 1553, 1489, 1402, 1312, 1225, 1209, 1165, 1152, 1074, 1024, 947; δ_H (300 MHz, $CDCl_3$) 8.76 (1H, d, *J* 7.3 ArH), 8.25 (1H, d, *J* 8.1, ArH), 8.10 (1H, d, *J* 8.1, ArH), 7.99 (1H, d, *J* 7.3, ArH), 7.80 (1H, dd, *J* 8.0, 7.5, ArH), 7.53 (1H, dd, *J* 8.0, 7.5, ArH), 7.31 (2H, dd, *J* 8.6, 7.5, ArH), 7.07 (1H, t, *J* 7.5, ArH), 6.99 (2H, d, *J* 8.6, ArH); *m*/*z* (EI) 398 (M^+, 41%), 271 (100), 243 (15), 215 (17), 213 (12), 150 (34), 129 (63), 112 (18), 105 (14), 71 (17), 57 (22).

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