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Photocatalytic Decarboxylative Hydroxylation of Carboxylic Acids Driven by Visible Light and Using Molecular Oxygen

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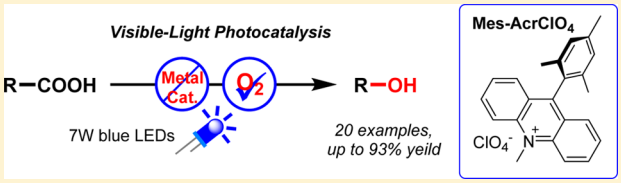
Supporting Information

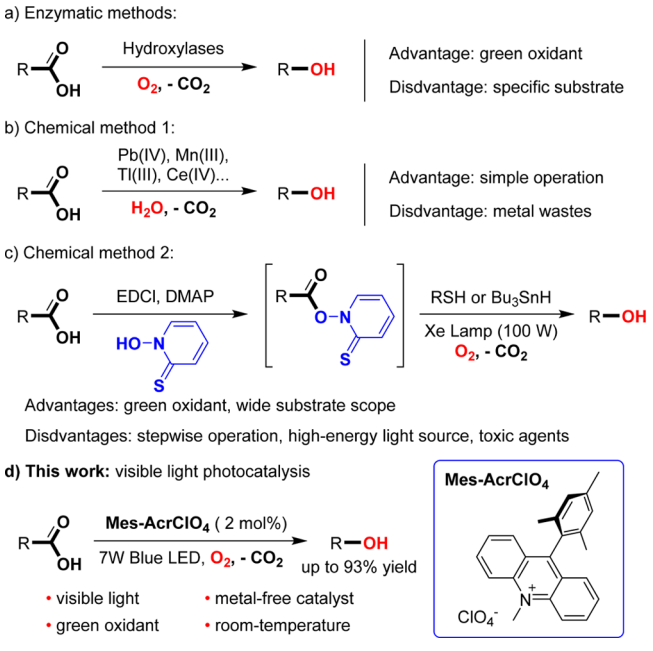
ABSTRACT: This paper discloses the first example of photocatalytic direct decarboxylative hydroxylation of carboxylic acids. It enables the conversion of a variety of readily available carboxylic acids to alcohols in moderate to high yields. This unprecedented protocol is accomplished under extremely mild reaction conditions using molecular oxygen (O_2) as a green oxidant and using visible light as a driving force.



INTRODUCTION

Decarboxylative hydroxylation is an important transformation in organisms and synthetic chemistry. In nature, this process is catalyzed by various hydroxylases in a highly efficient and specific way (Scheme 1a).[1] For example, salicylate hydroxylase (SALH) which was isolated from *Pseudomonas putida S-1* can selectively break the C–CO_2H bond of a carboxylic acid and forge a new C–O bond in the conversion of salicylate to catechol, accompanied by the release of CO_2.[1d] In contrast to enzymatic methods using molecular oxygen (O_2) as green oxidant, many chemical methods for decarboxylative hydroxylations require the use of stoichiometric high-valent metal reagents as oxidants, such as Pb(IV), Mn(III), Tl(III), and Ce(IV), which result in much metal waste (Scheme 1b).[2,3] In addition, Barton and co-workers developed an indirect method for the decarboxylative hydroxylation of carboxylic acids, in which corresponding thiohydroxamate esters need to be preformed (Scheme 1c).[4,5] Though being favorable due to its mild reaction condition, green oxidant, and wide substrate scope, this protocol suffers from the two-step operation, the stability of thiohydroxamate esters and the utilization of toxic agents (e.g., Bu_3SnH or *t*-BuSH).[6] Thus, the search of new, direct, and green decarboxylative hydroxylation reactions of carboxylic acids is still a significant task for synthetic chemists. Herein, we describe a visible-light photocatalytic decarboxylative hydroxylation of carboxylic acids, which can be conducted under metal catalyst-free conditions at room temperature and by using O_2 as a favorable oxidant (Scheme 1d).

Scheme 1. Decarboxylative Hydroxylation of Carboxylic Acids



In the past years, visible-light-induced decarboxylative transformations of carboxylic acids have received increasing research interests for its prominent advantages.[7,8] First, carboxylic acids are readily available, highly stable and inexpensive feedstocks. Second, the cleavage of C–CO_2H bonds allows the subsequent functionalizations in a site-specific way. Third, the application of visible light photocatalysis[9] in decarboxylative transformations of carboxylic acids enables the reaction to proceed under extremely mild condition. Last year, our group[10] developed a decarboxylative carbonylative alkynylation of carboxylic acids through visible light photoredox catalysis (Figure 1, left).[8c] Critical to this success is the capture of a radical by the small molecule CO. Therefore, we expect that the same radical might react with the small molecule O_2 and the resulting intermediate could be further converted into an alcohol product (Figure 1, right).

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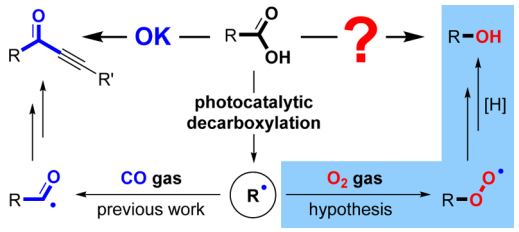
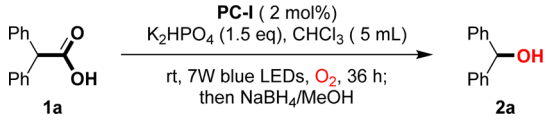


Figure 1. Hypothesis: O_2-capture of radicals for photocatalytic decarboxylative hydroxylation.

RESULTS AND DISCUSSION

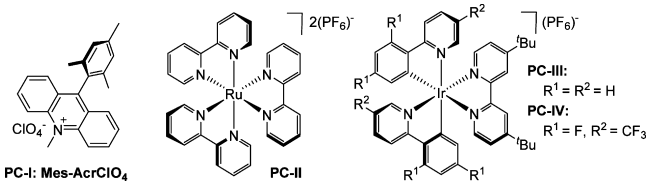
To test the above hypothesis, we initially examined the feasibility of this photocatalytic decarboxylative hydroxylation reaction using 2,2-diphenylacetic acid **1a** as the model substrate. After examining a wide array of reaction conditions,[11] we determined that the alcohol **2a** can be produced in a good yield (80%) in the presence of photocatalyst PC-I (Mes-AcrClO$_4$, 2 mol%), K_2HPO_4 (1.5 equiv), and O_2 in $CHCl_3$ under irradiation of 7W blue LEDs at room temperature (r.t.), followed by a reduction operation (Table 1, entry 1).[11]

Table 1. Effect of Reaction Parameters on the Photocatalytic Decarboxylative Hydroxylation[a]



entry	variation from the standard conditions	yield/%[b]
1	none	78 (80[c])
2	no PC-I	0
3	no visible light	0
4	no K_2HPO_4	0
5	Ar, instead of O_2	0
6	PC-II, instead of PC-I	0
7	PC-III, instead of PC-I	0
8	PC-IV, instead of PC-I	0
9	Na_2CO_3, instead of K_2HPO_4	75
10	2,6-lutidine, instead of K_2HPO_4	76
11	DCE, instead of $CHCl_3$	53
12	CH_3CN, instead of $CHCl_3$	43

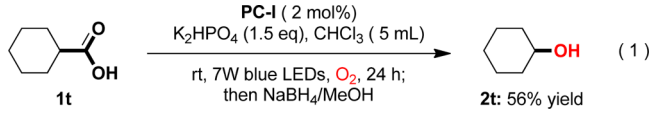
[a]Standard conditions: **1a** (0.5 mmol), PC-I (0.01 mmol, 2 mol %), K_2HPO_4 (0.75 mmol, 1.5 equiv), O_2 balloon, and $CHCl_3$ (5.0 mL) at r.t. under the irradiation of 7 W blue LEDs for 36 h; then $NaBH_4$ (1.0 mmol, 2.0 equiv) and MeOH (2 mL) were added and stirred for 0.5 h. [b]Determined by ^{1}H NMR analysis using 1,3,5-trimethoxybenzene as an internal standard. [c]Isolated yield. Mes-AcrClO$_4$: 9-mesityl-10-methylacridinium perchlorate. DCE: 1,2-dichloroethane.



The data in Table 1 illuminated the effect of a variety of parameters on the reaction efficiency. For example, results of control experiments showed that photocatalyst, visible light, base, and molecular oxygen are essential for this reaction (entries 2–5). Replacing of PC-I with other commercially available ruthenium and iridium photocatalysts (i.e., PC-II ~ IV), which have been previously proved to be efficient photocatalysts for the visible-light-induced decarboxylative functionalization of carboxylic acids, did not give alcohol **2a** (entries 6–8). Photocatalysts PC-II, PC-III, and PC-IV possess lower oxidation potential [e.g., $E_{1/2}(PC^*/PC^-)$ = +0.66 V for PC-II; $E_{1/2}(PC^*/PC^-)$ = +0.77 V for PC-III; $E_{1/2}(PC^*/PC^-)$ = +1.27 for PC-IV][9c] than the Fukuzumi catalyst PC-I [$E_{1/2}(PC^*/PC^-)$ = +2.06].[9g] Obviously, PC-II and PC-III are difficult to oxidize the carboxylic ion **1a** ($E_{1/2}^{ox}$ = +1.07 for **1a**)[8j] in this reaction. However, the reason why PC-IV [$E_{1/2}(PC^*/PC^-)$ = +1.27] is not an efficient photocatalyst for this transformation is not clear at current stage. In addition to K_2HPO_4, other inorganic and organic bases (e.g., Na_2CO_3 and 2,6-lutidine) were also suitable for this transformation with comparable reaction efficiency (Table 1 entries 9 and 10). When DCE or CH_3CN was employed as the reaction media to replace $CHCl_3$, a notable decrease of yield was observed (Table 1 entries 11 and 12).

With the optimum conditions in hand, we started to probe the generality of this photocatalytic decarboxylative hydroxylation. As highlighted in Table 2, a wide range of substituted benzylic carboxylic acids were suitable for the current reaction, producing corresponding benzyl alcohols in moderate to good yields. In addition to phenyl group, carboxylic acids bearing alkyl groups (i.e., methyl, ethyl, cyclohexyl, benzyl, and allyl) at the benzylic position were proven feasible, providing the structurally varied alcohol products **2b–2f** in 17–93% yields. However, the reaction with the ester-substituted substrate **2g** only gave a complex mixture, presumably due to its instability under this condition. Moreover, phenyl acetic acids bearing electron-donating groups were also efficient substrates for this transformation (**2j**, 64% yield and **2k**, 42% yield). Subquently, the electronic effect on this photocatalytic decarboxylative hydroxylation was investigated with 2-aryl propanoic acids as examples. We found that, incorporation of either electron-donating groups (Me and MeO) or electron-withdrawing groups (Br and Cl) on the benzene ring had no obvious impact on the reaction efficiency and the corresponding products **2l–2o** were obtained in 69–75% yields. Notably, heteroaryl-substituted carboxylic acids, such as thiophene, can readily undergo this reaction to provide the alcohol product **2p** in a moderate yield. Interestingly, drug molecules Ibuprofen, Naproxen, and Carprofen which belong to the family of nonsteroidal anti-inflammatory (NSAI) agents,[12] can also undergo this decarboxylative hydroxylation process smoothly, affording the corresponding hydroxylation products in moderate yields (**2q–2s**).

Beyond these benzylic carboxylic acids, other substrates were tested for this photocatalytic reaction. For example, when cyclohexanecarboxylic acid **1t** and adamantane-1-carboxylic acid **1u** were subjected to the standard conditions, to our delight, these reactions proceeded well, delivering the corresponding alcohols in moderate yields (eq 1: **2t**, 56% yield; eq 2: **2u**, 40% yield).



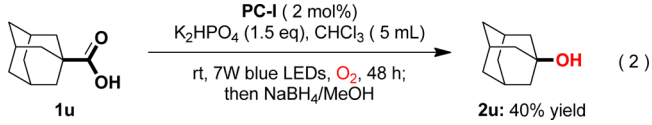


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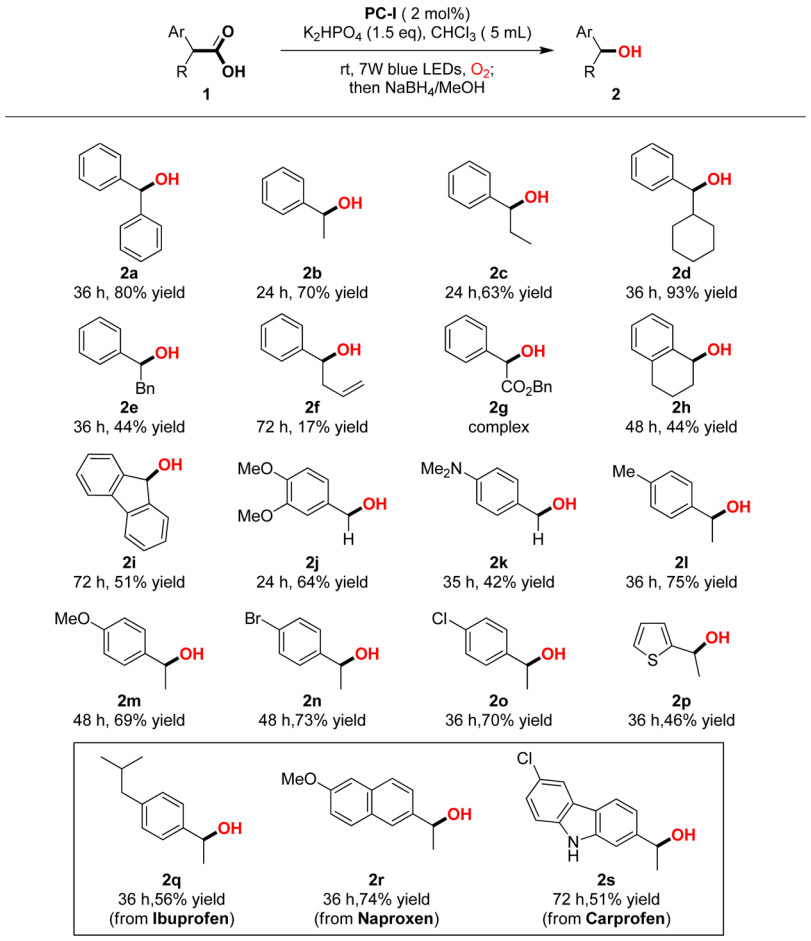
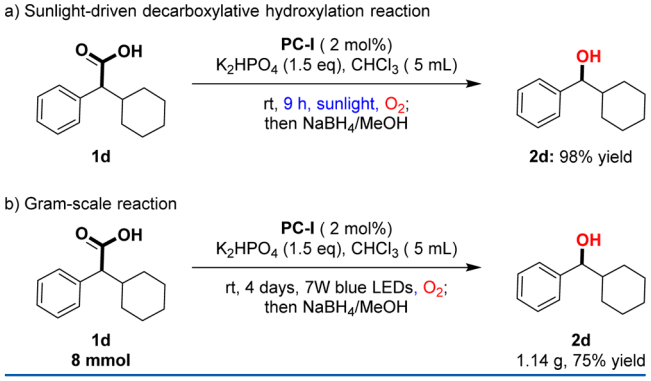
Table 2. Generality of the Photocatalytic Decarboxylative Hydroxylation[a]



[a]Reaction conditions: **1** (0.5 mmol), PC-I (0.01 mmol, 2 mol%), K_2HPO_4 (0.75 mmol, 1.5 equiv), O_2 balloon, and $CHCl_3$ (5.0 mL) at r.t. under the irradiation of 7 W blue LEDs; then $NaBH_4$ (1.0 mmol, 2.0 equiv) and MeOH (2 mL) were added and stirred for 0.5 h. Yields of isolated products.

Following, we performed more decarboxylative hydroxylation reactions to demonstrate the utility of this method. Replacing the blue LEDs with the ambient sunlight, the reaction of carboxylic acid **1d** still proceeded very well under the photocatalytic condition, providing cyclohexyl(phenyl)methanol product **2d** in a shortened reaction time and excellent yield (Scheme 2a, 9 h, 98% yield). Additionally, a gram-scale

Scheme 2. Demonstration of Synthetic Utility



decarboxylative hydroxylation reaction of substrate **1d** was carried out under the standard condition, we were pleased to find that the desired product **2d** can be afforded in good yield, albeit at a prolonged time (Scheme 2b, 1.14g, 75% yield).

Despite the success of this photocatalytic system, there are some patterns of carboxylic acids that fail to proceed with the decarboxylic hydroxylation reaction. As exemplified in Figure 2,

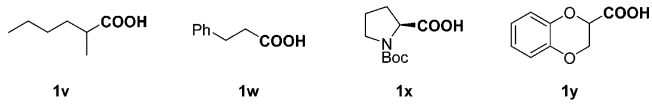


Figure 2. Unsuccessful substrates for this photocatalytic decarboxylative hydroxylation reaction.

when branched acyclic fatty acid **1v**, heteroatom-containing carboxylic acids **1x** and **1y** were used as substrates, only complex reaction mixtures were observed instead of the corresponding alcohol products. In the case of primary aliphatic acid **1w**, no reaction occurs under the standard conditions. Presumably, the active radicals are not easy to form or apt to decompose before its capture by molecular oxygen.

Furthermore, two control experiments were carried out to shed light on the reaction mechanism. As indicated in the literature,[2] the oxygen atom comes from H_2O or the anion of metal salts (i.e., AcO^-) in the decarboxylative hydroxylations of carboxylic acids mediated by high valent metals. That is because the radicals generated from carboxylic acids through these oxidative decarboxylation processes are prone to be over oxidized; the resulting carbon cation intermediates facilely react with nucleophilic species H_2O or AcO^- to deliver the final

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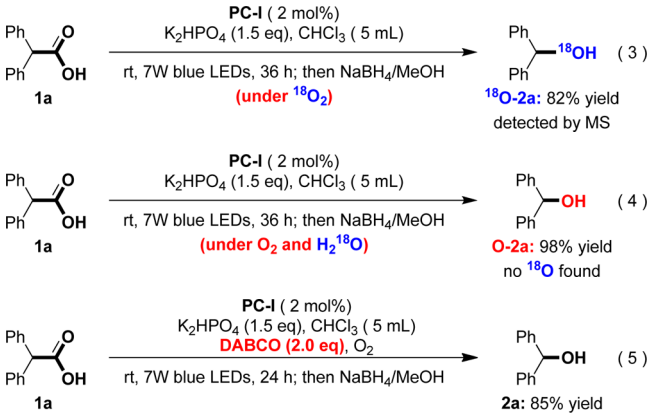
hydroxylation products. To rule out this possibility in our transformation, the ^{18}O-labeling experiments were performed using carboxylic acid **1a** as the substrate. When ^{18}O-labeling oxygen was used, corresponding ^{18}O-labeling alcohol **2a** was isolated in 82% yield and definitively confirmed by MS (eq 3); when ^{18}O-labeling H_2O (10 equiv) was added to the standard conditions, no ^{18}O-labeled alcohol **2a** was observed (eq 4). According to these results, the pathway in which the radicals generated from carboxylic acids were captured by O_2 was believed to be more favorable. Meanwhile, it is well-known that DABCO can be used to quench the singlet oxygen.[13] The model reaction, however, worked very well even with the addition of two equivalents of DABCO and affords product **2a** in 85% yield (eq 5). Therefore, the singlet oxygen pathway could be ruled out from the current reaction.



Thus, a possible mechanism was proposed to illustrate this photocatalytic decarboxylative hydroxylation according to the experimental evidence and published literatures (Scheme 3).[8d,14−16] First, the carboxylate **A** [$E_{1/2}(\mathbf{1a}^{-}/\mathbf{1a}^{\cdot})$ = +1.07 V vs SCE] which is generated in situ from carboxylic acid **1** under the basic conditions is oxidized to afford carboxyl radical **B** by the excited state of photocatalyst ($Acr^{\cdot}$-Mes^{+}) [$E_{1/2}$(PC-I*/ PC-I^{-}) = +2.06 V vs SCE].[14,15] Then, radical **C** which comes from the photooxidized product **B** through release of CO_2 is captured by soluble O_2 to deliver peroxyl radical **D**.[16] Finally, the mixture of intermediates **E** and **F** (confirmed by MS), which is generated from **D**[16b] is reduced in situ by sodium borohydride and the alcohol **2** is produced. In addition to the capture of the carbon radical **C**, O_2 [$E_{1/2}(O_2/O_2^{-\cdot})$ = +0.99 V vs SCE] is also believed to function as a oxidant to regenerate the ground state of photocatalyst (Acr^{+}-Mes) from the reduced state of photocatalyst ($Acr^{\cdot}$-Mes) [$E_{1/2}$(PC-I^{-}/PC-I) = −0.57 V vs SCE].[15d]

CONCLUSIONS

In summary, we have developed a novel and direct decarboxylative hydroxylation reaction of carboxylic acids through visible-light-induced photocatalysis. This protocol enables the conversion of a variety of readily available carboxylic acids to alcohols in moderate to high yields. It is also favorable for its green and mild reaction conditions, such as the use of metal-free catalyst, green oxidants (O_2), and sustainable energy (visible light or sunlight).

EXPERIMENTAL SECTION

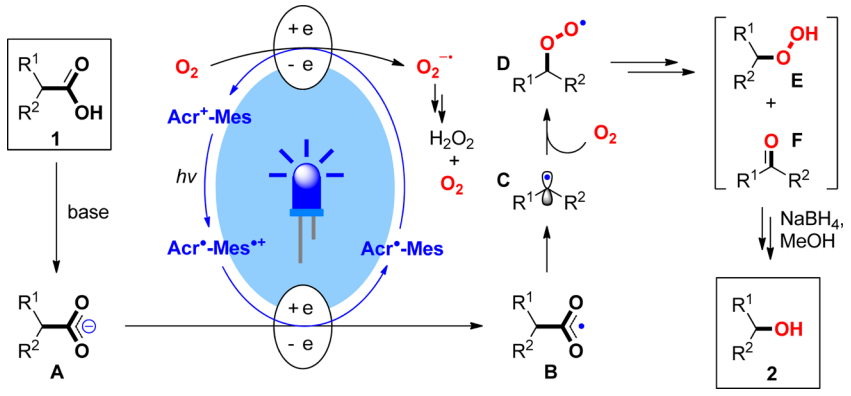
General Information. All reagents and catalysts were purchased from commercial suppliers and used without further purification. All the solvents were treated according to general methods before use. NMR spectra were recorded on NMR spectrometers (400/600 MHz) in $CDCl_3$ or DMSO-*d6*. Data are reported as follows: chemical shift, multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, dd = doublet of doublets, m = multiplet, br = broad signal), coupling constants (Hz), and integration. Mass spectra were measured on a MS spectrometer. IR spectra were recorded on an IR spectrophotometer. All characterized data of products coordinate with reported literatures.[17]

General Procedure for Photocatalytic Decarboxylative Hydroxylations. Carboxylic acid **1** (0.5 mmol), Mes-AcrClO$_4$ (2 mol%), K_2HPO_4 (0.75 mmol, 1.5 equiv), and $CHCl_3$ (5 mL) were added to 10 mL Schlenk tube. After charged with O_2 using a balloon, the reaction mixture was stirred under irradiation of 7W blue LEDs (400−500 nm; max. absorption: 432 nm) (distance approx 5 cm) at room temperature. When the reaction finished (monitored by TLC), $NaBH_4$ (1.0 mmol, 2.0 equiv) and MeOH (2 mL) were added to the mixture and stirred for 30 min. Then, the reaction mixture was quenched with saturated aq. NH_4Cl, and extracted with DCM for three time (3 × 10 mL). The combined organic layers were washed with brine and dried over anhydrous Na_2SO_4. Finally, the solvent was removed in vacuo and the crude reaction mixture was purified by flash chromatography on silica gel [silica: 200−300; eluent: petroleum ether/ethyl acetate (30:1−20:1)] to afford the pure product.

*Diphenylmethanol (**2a**).* 36 h, white solid: 73.7 mg, yield: 80%, mp. 70 °C. ^1H NMR (600 MHz, $CDCl_3$) δ 7.38 (d, J = 6.6 Hz, 4H), 7.34 (t, J = 7.8 Hz, 4H), 7.30 (m, 2H), 5.85 (s, 1H), 2.22 (br, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 143.7, 128.3, 127.4, 126.5, 76.0. IR (in KBr): 3588, 3332, 1591, 1395, 1181, 1113 cm^{-1}. MS m/z (EI): calcd for $[C_{13}H_{12}O]^+$: 184.2, found: 184.3.

*1-Phenylethanol (**2b**).* 24 h, colorless oil: 42.8 mg, yield: 70%. ^1H NMR (600 MHz, $CDCl_3$) δ 7.42−7.32 (m, 4H), 7.29−7.26 (m, 1H), 4.91 (dd, J = 6.6, 2.5 Hz, 1H), 1.72 (br, 3H), 1.50 (d, J = 6.4 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 145.7, 128.4, 127.4, 125.3, 70.3, 25.1.

Scheme 3. Proposed Mechanism



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IR (in KBr): 3620, 3339, 1593, 1400, 1115 cm^{-1}. MS *m*/*z* (EI): calcd for $[C_8H_{10}O]^+$: 122.1, found: 122.2.

1-Phenylpropan-1-ol (**2c**). 24 h, colorless oil: 42.9 mg, yield: 63%. ^1H NMR (600 MHz, CDCl3) δ 7.40−7.25 (m, 5H), 4.61 (t, *J* = 6.7 Hz, 1H), 1.86−1.73 (m, 2H), 1.69 (br, 1H), 0.93 (q, *J* = 6.0 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 144.5, 128.3, 127.4, 125.9, 76.0, 31.8, 10.1. IR (in KBr): 3646, 3444, 3326, 1590, 1397, 1113 cm^{-1}. MS *m*/*z* (EI): calcd for $[C_9H_{12}O]^+$: 136.1, found: 136.0.

Cyclohexyl(phenyl)methanol (**2d**). 36 h, white solid: 88.5 mg, yield: 93%, mp. 53 °C. ^1H NMR (600 MHz, $CDCl_3$) δ 7.49−7.09 (m, 4H), 4.36 (d, *J* = 7.2 Hz, 1H), 1.98 (d, *J* = 13.0 Hz, 1H), 1.78−1.72 (m, 2H), 1.70−1.57 (m, 3H), 1.37 (d, *J* = 13.2 Hz, 1H), 1.24−1.21 (m, 1H), 1.14−1.10 (m, 2H), 1.09−1.01 (m, 1H), 0.97−0.90 (m, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 143.5, 128.1, 127.3, 126.6, 79.3, 44.8, 29.2, 28.8, 26.4, 26.0, 25.9. IR (in KBr): 3524, 3338, 2926, 1593, 1449, 1080 cm^{-1}. MS *m*/*z* (EI): calcd for $[C_{13}H_{18}O]^+$: 190.2, found: 190.2.

1,2-Diphenylethanol (**2e**). 36 h, white solid: 43.6 mg, yield: 44%. ^1H NMR (600 MHz, $CDCl_3$) δ 7.36 (d, *J* = 6.5 Hz, 4H), 7.30 (q, *J* = 5.9, 4.3 Hz, 3H), 7.24 (d, *J* = 7.2 Hz, 1H), 7.21 (d, *J* = 7.4 Hz, 2H), 4.91 (dd, *J* = 8.7, 4.7 Hz, 1H), 3.07−2.97 (m, 2H), 1.91 (br, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 143.7, 138.0, 129.5, 128.5, 128.4, 127.6, 126.6, 125.9, 75.3, 46.0. IR (in KBr): 3658, 3316, 1707, 1495, 1369, 1197 cm^{-1}. MS *m*/*z* (EI): calcd for $[C_{14}H_{15}O]^+$: 199.2, found: 199.6.

1-Phenylbut-3-en-1-ol (**2f**). 72 h, pale yellow oil: 12.6 mg, yield: 17%. ^1H NMR (600 MHz, $CDCl_3$) δ 7.39−7.27 (m, 4H), 7.27−7.23 (m, 1H), 5.87−5.71 (m, 1H), 5.13 (m, *J* = 3.5, 1.4 Hz, 1H), 4.78−4.67 (m, 1H), 2.51 (m, *J* = 8.8, 7.5, 6.2, 1.2 Hz, 2H), 2.03 (br, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 143.5, 134.1, 128.0, 127.1, 125.5, 117.8, 73.2, 43.6. IR (in KBr): 3666, 3311, 1707, 1494, 1368, 1201, 1045 cm^{-1}. MS *m*/*z* (EI): calcd for $[C_{10}H_{13}O]^+$:149.2, found: 149.2.

1,2,3,4-Tetrahydronaphthalen-1-ol (**2h**). 48 h, colorless oil: 32.6 mg, yield: 44%. ^1H NMR (600 MHz, $CDCl_3$) δ 7.47−7.39 (m, 1H), 7.24−7.16 (m, 2H), 7.11 (d, *J* = 5.1 Hz, 1H), 4.79 (t, *J* = 4.7 Hz, 1H), 2.83 (m, *J* = 16.5, 5.5 Hz, 1H), 2.76−2.70 (m, 1H), 1.99 (m, *J* = 11.2, 4.0 Hz, 2H), 1.94−1.90 (m, 1H), 1.78 (m, *J* = 9.7, 6.8, 3.4 Hz, 1H), 1.70 (br, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 138.7, 137.1, 129.0, 128.6, 127.5, 126.1, 68.1, 32.2, 29.2, 18.7. IR (in KBr): 3662, 2938, 1695, 1486, 1372, 1036 cm^{-1}. MS *m*/*z* (EI): calcd for $[C_{10}H_{12}O]^+$: 148.2, found: 148.4.

9H-Fluoren-9-ol (**2i**). 72 h, white solid: 46.5 mg, yield: 51%, mp. 158 °C. ^1H NMR (600 MHz, $CDCl_3$) δ 7.66 (dd, *J* = 7.4, 4.4 Hz, 4H), 7.40 (t, *J* = 7.5 Hz, 2H), 7.33 (t, *J* = 7.5 Hz, 2H), 5.59 (s, 1H), 1.93−1.45 (br, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 145.5, 139.9, 129.0, 127.7, 125.0, 119.9, 75.1. IR (in KBr): 3662, 3310, 1711, 1500, 1291, 1190 cm^{-1}. MS *m*/*z* (EI): calcd for $[C_{13}H_{10}O]^+$: 182.2, found: 182.5.

(3,4-Dimethoxyphenyl)methanol (**2j**). 24 h, pale yellow oil: 53.8 mg, yield: 64%. ^1H NMR (600 MHz, $CDCl_3$) δ 6.94 (s, 1H), 6.90 (d, *J* = 8.1 Hz, 1H), 6.87−6.84 (m, 1H), 4.63 (s, 2H), 3.90 (s, 3H), 3.88 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 148.8, 148.3, 133.5, 119.2, 110.8, 110.2, 64.9, 55.7, 55.6. IR (in KBr): 3523, 3442, 3338, 1596, 1514, 1458, 1328, 1142 cm^{-1}. MS *m*/*z* (EI): calcd for $[C_9H_{12}O_3]^+$: 168.2, found: 168.5.

(4-(Dimethylamino)phenyl)methanol (**2k**). 35 h, pale yellow oil: 31.8 mg, yield: 42%. ^1H NMR (600 MHz, $CDCl_3$) δ 7.24 (d, *J* = 8.7 Hz, 2H), 6.73 (d, *J* = 8.3 Hz, 2H), 4.56 (s, 2H), 2.94 (s, 6H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 150.2, 128.9, 128.5, 112.6, 65.2, 40.6. IR (in KBr): 3645, 2878, 1678, 1523, 1348, 1163 cm^{-1}. MS *m*/*z* (EI): calcd for $[C_9H_{13}NO]^+$: 151.2, found: 151.5.

1-(p-Tolyl)ethanol (**2l**). 36 h, colorless oil: 51.1 mg, yield: 75%. ^1H NMR (400 MHz, $CDCl_3$) δ 7.30−7.25 (m, 2H), 7.17 (s, 2H), 4.89−4.84 (m, 1H), 2.34 (s, 3H), 1.71 (br, 1H), 1.48 (d, *J* = 6.3 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 142.9, 137.0, 129.1, 125.4, 70.1, 25.1, 21.1. IR (in KBr): 3622, 3330, 1592, 1392, 1115 cm^{-1}. MS *m*/*z* (EI): calcd for $[C_9H_{12}O]^+$: 136.2, found: 136.1.

1-(4-Methoxyphenyl)ethanol (**2m**). 48 h, colorless oil: 52.5 mg, yield: 69%. ^1H NMR (600 MHz, $CDCl_3$) δ 7.30 (d, *J* = 8.2 Hz, 2H), 6.88 (d, *J* = 8.1 Hz, 2H), 4.85 (q, *J* = 6.5 Hz, 1H), 3.80 (s, 3H), 1.80 (br, 1H), 1.48 (d, *J* = 6.4 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 159.0, 137.9, 126.6, 113.8, 70.0, 55.3, 25.0. IR (in KBr): 3652, 3328, 1598, 1512, 1244, 1173 cm^{-1}. MS *m*/*z* (EI): calcd for $[C_9H_{12}O_2]^+$: 152.2, found: 152.2.

1-(4-Bromophenyl)ethanol (**2n**). 48 h, white solid: 73.4 mg, yield: 73%, mp. 40 °C. ^1H NMR (600 MHz, $CDCl_3$) δ 7.47 (d, *J* = 8.1 Hz, 2H), 7.25 (s, 2H), 4.88 (q, *J* = 6.5 Hz, 1H), 1.80 (br, 1H), 1.48 (d, *J* = 6.5 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 144.70, 131.50, 127.10, 121.10, 69.73, 25.21. IR (in KBr): 3663, 3310, 1711, 1489, 1201, 1066 cm^{-1}. MS *m*/*z* (EI): calcd for $[C_8H_9BrO]^+$: 201.1, found: 201.4.

1-(4-Chlorophenyl)ethanol (**2o**). 36 h, colorless oil: 54.8 mg, yield: 70%. ^1H NMR (400 MHz, $CDCl_3$) δ 7.37−7.28 (m, 4H), 5.05−4.69 (m, 1H), 1.76 (br, 2H), 1.48 (d, *J* = 6.0 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 143.9, 132.5, 128.1, 126.5, 69.3, 25.1. IR (in KBr): 3594, 3336, 1593, 1491, 1402, 1086 cm^{-1}. MS *m*/*z* (EI): calcd for $[C_8H_9ClO]^+$: 156.6, found: 156.2.

1-(Thiophen-2-yl)ethanol (**2p**). 36 h, colorless oil: 29.5 mg, yield: 46%. ^1H NMR (600 MHz, $CDCl_3$) δ 7.24 (d, *J* = 4.7 Hz, 1H), 7.01−6.95 (m, 2H), 5.14 (d, *J* = 6.9 Hz, 1H), 1.79 (br, 2H), 1.61 (d, *J* = 6.8 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 149.8, 126.6, 124.4, 123.1, 66.2, 25.2. IR (in KBr): 3647, 3329, 1592, 1389, 1119 cm^{-1}. MS *m*/*z* (EI): calcd for $[C_6H_8OS]^+$: 128.2, found: 128.0.

1-(4-Isobutylphenyl)ethanol (**2q**). 36 h, colorless oil: 49.9 mg, yield: 56%. ^1H NMR (400 MHz, $CDCl_3$) δ 7.25 (d, *J* = 8.0 Hz, 2H), 7.10 (d, *J* = 8.0 Hz, 2H), 4.86 (q, *J* = 6.5 Hz, 1H), 2.46 (d, *J* = 7.2 Hz, 2H), 1.85 (m, *J* = 13.5, 6.8 Hz, 1H), 1.49 (d, *J* = 6.5 Hz, 3H), 0.90 (d, *J* = 6.6 Hz, 6H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 143.0, 141.0, 129.2, 125.2, 70.3, 45.1, 30.2, 25.0, 22.4. IR (in KBr): 3646, 3313, 3018, 1672, 1513, 1366, 1008 cm^{-1}. MS *m*/*z* (EI): calcd for $[C_{12}H_{18}O]^+$: 178.3, found: 178.2.

1-(6-Methoxynaphthalen-2-yl)ethanol (**2r**). 36 h, white solid: 74.8 mg, yield: 74%, mp. 115 °C. ^1H NMR (400 MHz, $CDCl_3$) δ 7.73 (t, *J* = 7.0 Hz, 3H), 7.48 (d, *J* = 8.6 Hz, 1H), 7.18−7.10 (m, 2H), 5.04 (q, *J* = 6.6 Hz, 1H), 3.92 (s, 3H), 1.69 (br, 2H), 1.57 (d, *J* = 6.4 Hz, 3H). ^{13}C NMR (100 MHz, CDCl3) δ 157.5, 140.9, 133.9, 129.3, 128.6, 127.1, 124.3, 123.7, 118.9, 105.6, 70.4, 55.2, 25.0. IR (in KBr): 3627, 3523, 3334, 1594, 1392, 1116, 1025 cm^{-1}. MS *m*/*z* (EI): calcd for $[C_{13}H_{14}O_2]^+$: 202.3, found: 202.5.

1-(6-Chloro-9H-carbazol-2-yl)ethanol (**2s**). 72 h, white solid: 62.7 mg, yield: 51%. ^1H NMR (600 MHz, DMSO-d^6) δ 11.28 (s, 1H), 8.10 (d, *J* = 2.1 Hz, 1H), 8.00 (d, *J* = 8.1 Hz, 1H), 7.41 (d, *J* = 8.6 Hz, 2H), 7.28 (m, *J* = 8.6, 2.1 Hz, 1H), 7.08 (d, *J* = 8.1 Hz, 1H), 5.18 (s, 1H), 4.85−4.77 (m, 1H), 1.33 (d, *J* = 6.4 Hz, 3H). ^{13}C NMR (100 MHz, DMSO-d^6) δ 146.8, 141.1, 138.9, 125.4, 124.3, 123.3, 120.8, 120.7, 120.1, 117.5, 112.8, 108.2, 69.2, 26.9. IR (in KBr): 3405, 2971, 1719, 1503, 1155 cm^{-1}. MS *m*/*z* (EI): calcd for $[C_{14}H_{13}ClNO]^+$: 246.7, found: 246.7.

Cyclohexanol (**2t**). 24 h, colorless oil: 28.1 mg, yield: 56%. ^1H NMR (600 MHz, $CDCl_3$) δ 3.61 (d, *J* = 9.0 Hz, 1H), 1.89 (d, *J* = 10.1 Hz, 2H), 1.76−1.71 (m, 2H), 1.55 (br, *J* = 13.3 Hz, 1H), 1.28 (m, *J* = 10.8, 9.6 Hz, 5H), 1.17 (d, *J* = 11.5 Hz, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 70.2, 35.4, 25.4, 24.1. IR (in KBr): 3614, 3443, 1591, 1392, 1113 cm^{-1}. MS *m*/*z* (EI): calcd for $[C_6H_{12}O]^+$: 100.2, found: 100.3

1-Adamantanol (**2u**). 48 h, colorless solid: 30.4 mg, yield: 40%, mp. 245 °C. ^1H NMR (400 MHz, $CDCl_3$) δ 2.14 (s, 3H), 1.71 (d, J = 2.8 Hz, 6H), 1.62 (q, J = 12.7 Hz, 6H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 68.2, 45.3, 36.0, 30.7. IR (in KBr): 3666, 3310, 2911, 1504, 1349, 1113 cm^{-1}. MS *m*/*z* (EI): calcd for $[C_{10}H_{16}O]^+$: 152.1, found: 152.2.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.joc.6b01360.

Details for condition optimizations, copies of ^1H NMR and ^{13}C NMR spectra of product **2**, references for known compounds, and the mechanism study (PDF)

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Notes

The authors declare no competing financial interest.

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