HETEROCYCLES, Vol. 81, No. 4, 2010, pp. 965 - 976. © The Japan Institute of Heterocyclic Chemistry
Received, 12th January, 2010, Accepted, 9th February, 2010, Published online, 10th February, 2010
DOI: 10.3987/COM-10-11906

DDQ-MEDIATED TANDEM SYNTHESIS OF FUNCTIONALIZED PYRANOCOUMARINS FROM 4-HYDROXYCOUMARINS AND 1,3-DIARYLALLYLIC COMPOUNDS

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Abstract - A simple and efficient DDQ-mediated oxidative cross-coupling between 4-hydroxycoumarin and 1,3-diarylallylic compounds was developed. The reaction furnished functionalized pyranocoumarins in a single step without using any metal catalyst. The tandem process involves an intermolecular C–C bond formation and an intramolecular C–O bond formation through double oxidative C–H activation.

There has been great development of various transition-metal-catalyzed coupling reactions in organic synthesis and related disciplines.[1] On the other hand, with the prevalence of "atom economy"[2] and "green chemistry",[3] the direct formations of carbon-carbon bonds[4] or carbon-heteroatom bonds[5] from C-H bonds by cross-coupling reactions have attracted great attention recently.

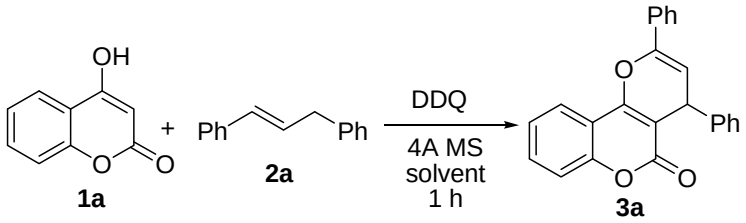
2,3-Dichloro-5,6-dicyano-1,4-benzoquinone (DDQ) is a well-known powerful oxidant in organic chemistry,[6] particularly useful for dehydrogenation to form aromatic compounds,[6a] oxidizes activated methylene[6b,6c] and hydroxy groups[6d] to carbonyl compounds. In recent years, there has been enormous interest in developing DDQ-mediated direct oxidative cross-coupling by C-H activation without using any metal catalyst.[7] Typical examples include the DDQ-mediated cross-dehydrogenative-coupling reaction between benzyl ethers and simple ketones,[7a] the DDQ-mediated cyclization reaction of benzylic and allylic ethers,[7b] and the oxidative cross-coupling reactions between benzylic substrates and active methylenic compounds or alcohols.[7c-7e] To the best of our knowledge, however, there has been no report on DDQ-mediated tandem double oxidative C-H activation.

Coumarin and its derivatives are one of the important classes of heterocyclic compounds and are known to possess a wide range of biological activities such as anti-HIV, antimalarial, antibacterial, and cytotoxic.[8] Among the various coumarin derivatives, functionalized pyranocoumarin represents a significant class of compounds as biologically active compounds.[9] As a part of our continuing program on development of

tandem synthesis of heterocycles,[10] we herein reported a tandem approach to functionalized pyranocoumarins from 1,3-diarylallylic compounds and 4-hydroxycoumarin via the DDQ-mediated double oxidative C-H activation.

We initially examined the reaction of 4-hydroxycoumarin (**1a**) with 1,3-diphenyl-1-propene (**2a**) in the presence of DDQ (2.0 equiv) using CH_2Cl_2 as a solvent (Table 1, entry 1). After reacting under ambient conditions for 1 h, the resulting mixture was filtered to separate a black solid, consisting mainly of hydroquinone ($DDQH_2$). The filtrate was concentrated and purified by chromatography on a silica gel column to give pyranocoumarin **3a** with 52% yield. The structure of compound **3a** was unambiguously confirmed by single-crystal X-ray analysis (Figure 1).[11] Furthermore, we found that the desired product **3a** could be obtained in 68% yield with 4 Å MS as an additive (Table 1, entry 2). In order to slow the reaction, we then set the reaction temperature to 0 ^oC and this reaction was completed for 3 h. However, the yield reduced obviously (Table 1, entry 3). When the reaction temperate was increased to reflux, the yield resulted in a slight decrease (Table 1, entry 4). Then various solvents were screened. The reaction could proceed in $ClCH_2CH_2Cl$ with good efficiency (Table 1, entry 5). When MeCN and PhMe were used as solvents, the yield was remarkably diminished (Table 1, entries 6 and 7). No desired product was detected when $CHCl_3$, $MeNO_2$ or THF were used as solvents (Table 1, entries 8, 9 and 10). Switching the ratio of substrates **1a**/**2a** decreased the yield (Table 1, entry 11). The influence of the amount of DDQ was also evaluated and both increase and decrease the amount of DDQ reduced the yield (Table 1, entries 13 and 14). No product was detected in the absence of DDQ (Table 1, entry 15). Thus, the most suitable reaction conditions for the formation of **3a** were established (Table 1, entry 2).

Table 1. Screening for the Reaction Conditions[a]



Entry	Solvent	Temp.	Yield (%)[b]
1	CH_2Cl_2	rt	52[c]
2	CH_2Cl_2	rt	68
3	CH_2Cl_2	0 ^oC	48
4	CH_2Cl_2	reflux	65
5	$ClCH_2CH_2Cl$	rt	66
6	MeCN	rt	35
7	PhMe	rt	24
8	$CHCl_3$	rt	nd
9	$MeNO_2$	rt	nd
10	THF	rt	nd

11	CH_2Cl_2	rt	47[d]
12	CH_2Cl_2	rt	58[e]
13	CH_2Cl_2	rt	55[f]
14	CH_2Cl_2	rt	41[g]
15	CH_2Cl_2	rt	0[h]

[a] Conditions: **2a** (0.25 mmol), **1a** (1.2 equiv.), DDQ (2.0 equiv.), 4 Å MS (0.25 g), solvent (3 mL), 1 h.
[b] Isolated yield.
[c] None of 4 Å MS.
[d] 0.25 mmol of **1a**, 1.2 equiv. of **2a**, 2.0 equiv. of DDQ.
[e] 0.25 mmol of **1a**, 1.0 equiv. of **2a**, 2.0 equiv. of DDQ.
[f] 3.0 equiv. of DDQ.
[g] 1.6 equiv. of DDQ.
[h] In the absence of DDQ.

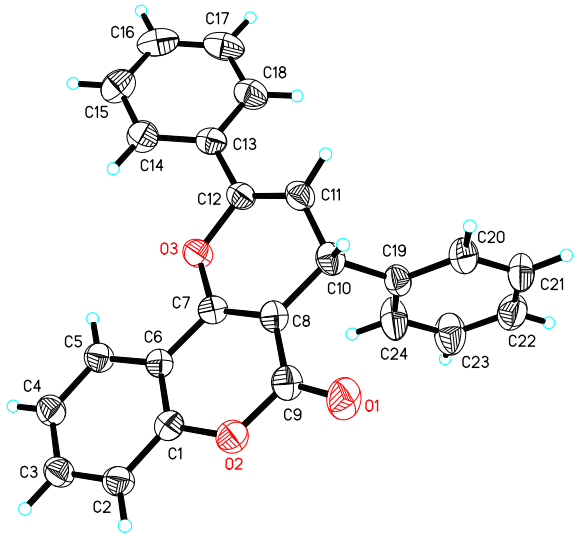
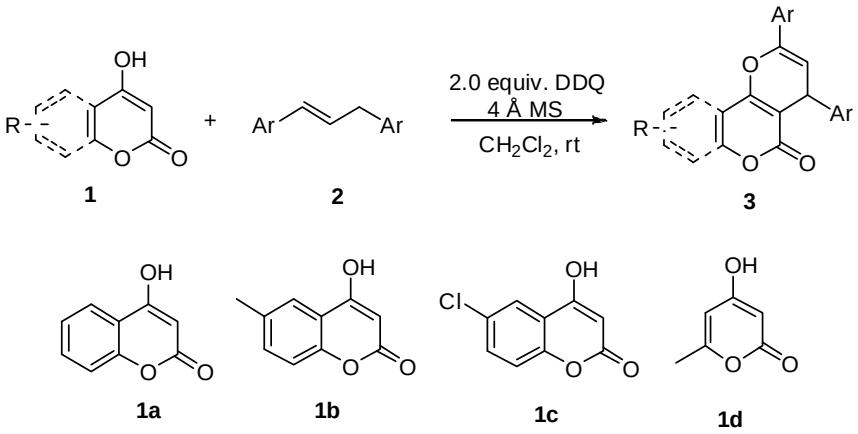


Figure 1. X-Ray crystal structure of **3a**

The scope of the reaction was investigated with a variety of reactants under the optimized reaction conditions, and the results were presented in Table 2. 4-Hydroxycoumarins **1a-1d** and 1,3-diarylallylic compounds **2a-2e** underwent the oxidative cross-coupling process to generate **3a-3l** in modest to good yields (48-72%). The electronic effect of the substituents on aromatic ring of substrates **1** was observed (Table 2, entries 1-3 and 5-7). The electron-donating group substituted 4-hydroxycoumarin **1b** (Table 2, entries 2 and 6) gave higher yields than the electron-withdrawing group substituted substrates **1c** (Table 2, entries 3 and 7). Similarly, reaction of 1,3-diarylallylic compounds **2a** and **2b** with 4-hydroxy-6-methyl-2-pyrone **1d** allows the efficient synthesis of product **3d** and **3h** in moderate yields under the optimized conditions, respectively (Table 2, entries 4 and 8). The electronic effect of the substituents on the aromatic ring of **2** was examined. When the substrates **2** are bearing a halogen group, the reaction gave good yields in a rapid rate (Table 2, entries 5-8). However, the result was the opposite when an electron-donating group was introduced (Table 2, entry 9).

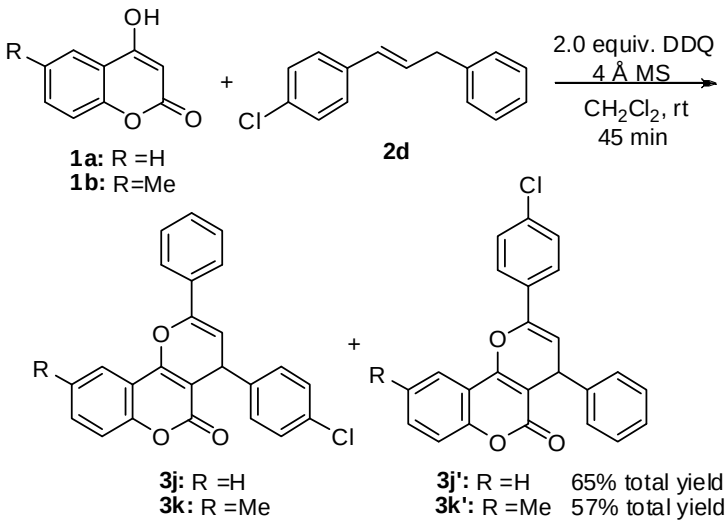
Table 2. Formation of functionalized pyranocoumarins[a]



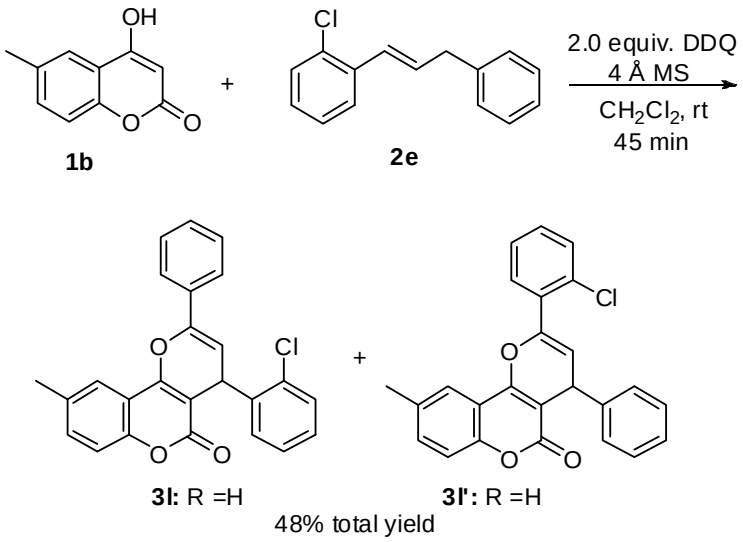
entry	1	2 (Ar)	reaction time (h)	product	yield (%)[b]
1	**1a**	**2a(C_6H_5)**	1	**3a**	68
2	**1b**	**2a**	1	**3b**	70
3	**1c**	**2a**	1	**3c**	55
4	**1d**	**2a**	1	**3d**	63
5	**1a**	**2b(4-BrC_6H_4)**	0.75	**3e**	70
6	**1b**	**2b**	0.75	**3f**	72
7	**1c**	**2b**	0.75	**3g**	64
8	**1d**	**2b**	0.75	**3h**	66
9	**1a**	**2c(4-$CH_3C_6H_4$)**	1.5	**3i**	48

[a] Reaction conditions: 2 (0.25 mmol), 1 (1.2 equiv.), DDQ (2.0 equiv.), 4 Å MS (0.25 g), CH_2Cl_2 (3 mL), rt
[b] Isolated yield

To expand the scope of the substrates, we further examined the mono-substituted 1,3-diarylpropenes **2d** (Scheme 1) and **2e** (Scheme 2). In these cases, we obtained a mixture of two isomers **3j**+**3j′** (in 65% total yield), **3k**+**3k′** (in 57% total yield) or **3l**+**3l′** (in 48% total yield), respectively. The ratios of two isomers **3j**+**3j′**, **3k**+**3k′** and **3l**+**3l′** were 4:1, 7:3, and 3:1, respectively, which were determined by ^{1}H NMR analysis.

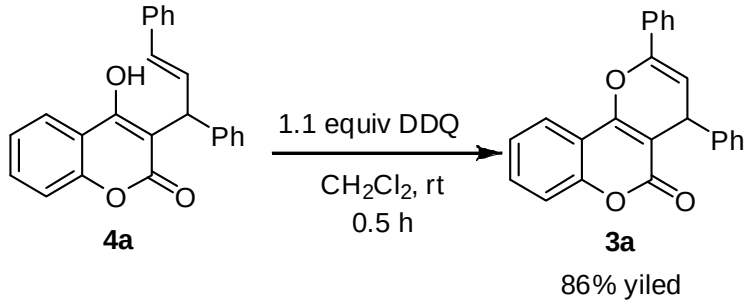


Scheme 1. Synthesis of **3j**+**3j′** and **3k**+**3k′**



Scheme 2. Synthesis of **3l**+**3l′**

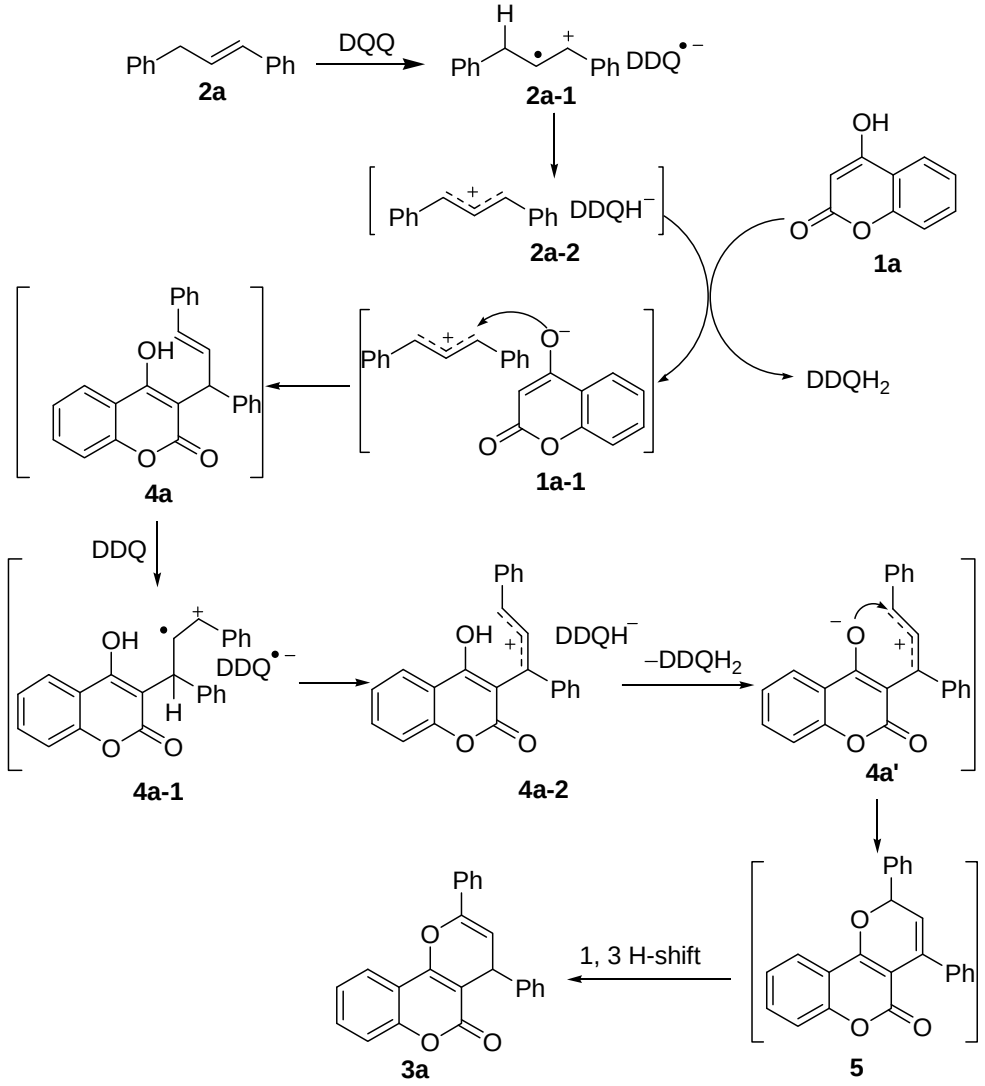
To provide further insight into the mechanism, (*E*)-3-(1,3-diphenylallyl)-4-hydroxy-2*H*-chromen-2-one **4a** was conducted the oxidative coupling reaction in the presence of 1.1 equiv. DDQ under ambient conditions in CH_2Cl_2 (Scheme 3). The expected product **3a** was obtained in 86% yield by an intramolecular oxidation coupling reaction promoted by DDQ. Furthermore, we found that the reaction did not proceed in the absence of DDQ (Table 1, entry 15).



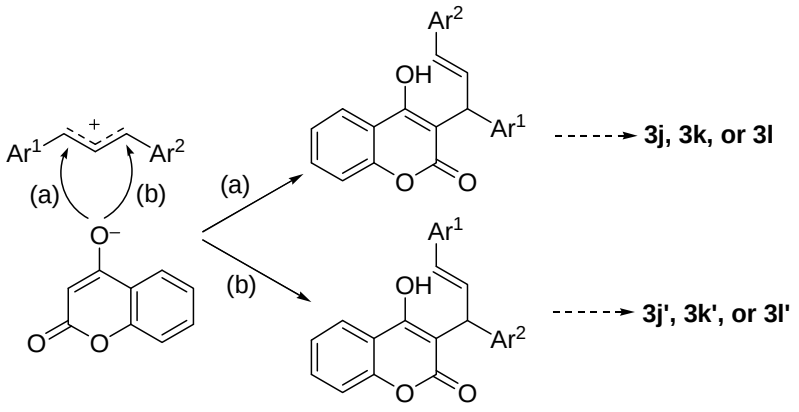
Scheme 3. Intramolecular oxidation coupling reaction of **4a**

According to the literatures[7] and on the basis of our experiments, a tentative mechanism for the coupling reaction is proposed in Scheme 4. A single electron transfer from alkene **2a** to DDQ generates a radical ion pair **2a-1**, which further converts to the ion pair **2a-2** through hydrogen transfer from the allylic radical cation to DDQ radical anion. Then, a proton transfer from **1a** to DDQH anion forms the ion pair **1a-1** and $DDQH_2$. The attack of the enolate anion to the allylic cation in the ion pair **1a-1** generates the intermediate **4a**. A single electron transfer from **4a** to DDQ generates another radical ion pair **4a-1**, which is immediately converted to the ion pair **4a-2** through a hydrogen transfer. Further proton transfer from hydroxyl group to DDQH anion in the ion pair **4a-2** generates the Zwitterion **4a′** and $DDQH_2$. The ring closing of **4a′** and the subsequent 1,3 H-shift afford the desired product **3a**. For the mono-substituted

1,3-diarylallylic compounds **2d** and **2e**, they could generate two different allylic carbocations, which led to the formation of two isomer products **3j**+**3j′**, **3k**+**3k′** and **3l**+**3l′** (Scheme 5).



Scheme 4. Tentative mechanism for the tandem reaction



Scheme 5. Formation of two isomer products **3j**+**3j′**, **3k**+**3k′** and **3l**+**3l′**

In conclusion, we have demonstrated a DDQ-mediated oxidative cross-coupling reaction between 4-hydroxycoumarin and 1,3-diarylallylic compounds, which furnished biologically interesting pyranocoumarins under ambient conditions without using any metal catalyst. The process involves a direct intermolecular C-C bond formation and an intramolecular C-O bond formation. It is the first example for the DDQ-mediated tandem double oxidative C-H activation and further application of this method is under investigation.

EXPERIMENTAL

Column chromatography was carried out on silica gel (300-400 mesh) with mixed solvents (petroleum-EtOAc). CH_2Cl_2 was distilled from CaH_2. Infrared spectra was obtained on a FTIR spectrometer. NMR spectra was recorded for ^{1}H NMR at 400 MHz, for ^{13}C NMR at 100 MHz at 293 K unless otherwise noted. Chemical shifts are reported relative to residue peaks of the solvents either $CDCl_3$ (7.26 ppm for ^{1}H and 77.27 ppm for ^{13}C) or DMSO-d_6 (2.50 ppm for ^{1}H and 40.00 ppm for ^{13}C). Data are presented as follows: chemical shift (ppm), multiplicity (s = singlet, d = doublet, t = triplet, m = multiplet), coupling constant, J (Hz) and integration. Low-resolution MS and HRMS were obtained using ESI ionization.

Starting Materials. 1b and **1c** were prepared according to the literature.[12] The diarylallylic compounds were prepared according to the literature.[13] **4a** was prepared according to the literature.[14]

General Procedure for the Synthesis of 3

A 10 mL round-bottom flask was charged with 4-hydroxycoumarin (**1**) (1.2 equiv.), 1,3-diphenyl-1-propene (**2**) (0.25 mmol) and 4 Å MS (0.25 g) in 3 mL of CH_2Cl_2. Then DDQ (2.0 equiv.) was added in portions during 15 min. The reaction mixture was stirred for the corresponding time, and then filtered through a Celite plug. Purification was done by column chromatography on silica gel with petroleum and EtOAc (10:1) as the eluent to give the pure product **3**.

2,4-Diphenylpyrano[3,2-*c*]chromen-5(4*H*)-one (3a)[9a]: A white solid; mp 168-169 ºC; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.02 (dd, J_1 = 1.6 Hz, J_2 = 8.0 Hz, 1 H), 7.73 (d, J = 7.2 Hz, 2 H), 7.56 (m, 1 H), 7.47~7.30 (m, 9 H), 7.23 (m, 1 H), 5.84 (d, J = 4.8 Hz, 1 H), 4.70 (d, J = 4.8 Hz, 1 H), ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 161.42, 155.69, 152.69, 146.82, 143.49, 132.56, 131.96, 129.21, 128.63, 128.59, 128.43, 127.19, 124.61, 124.12, 122.63, 116.78, 114.50, 103.69, 103.62, 36.57 ppm; IR (KBr) ν 3026, 2918, 1720, 1632, 1610, 1492, 1387, 1270, 1169, 1012, 765, 692 cm^{-1}; MS (ESI) m/z 374.8 ([M+Na]$^+$); HRMS (ESI) calcd for $C_{24}H_{16}O_3$ ([M+Na]$^+$), 375.0992; found, 375.0986.

9-Methyl-2,4-diphenylpyrano[3,2-*c*]chromen-5(4*H*)-one (3b): A white solid; mp 212-213 ºC; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.67 (s, 1 H), 7.60 (d, J = 6.4 Hz, 2 H), 7.48~7.36 (m, 9 H), 7.23 (d, J = 8.4 Hz, 1 H), 6.15 (d, J = 3.6 Hz 1 H), 5.77 (d, J = 4.4 Hz, 1 H), 2.43 (s, 3 H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ

161.36, 158.85, 151.79, 138.29, 137.94, 135.32, 133.68, 133.66, 129.23, 128.88, 127.87, 127.79, 127.52, 127.38, 122.82, 120.11, 116.36, 114.80, 102.69, 78.77, 20.86 ppm; IR (KBr) *v* 3055, 3025, 1717, 1625, 1550, 1493, 1397, 1363, 1280, 1111, 1001, 765, 755, 702, 533 cm^{-1}; MS (ESI) m/z 389.02 ($[M+Na]^+$); HRMS (ESI) calcd for $C_{25}H_{18}O_3$ ($[M+Na]^+$), 389.1148; found, 389.1141.

9-Chloro-2,4-diphenylpyrano[3,2-*c*]chromen-5(4*H*)-one (3c): A light yellow solid; mp 177-178 ºC; ^1H NMR (400 MHz, $CDCl_3$) δ 7.84 (d, *J* = 2.0 Hz 1 H), 7.60 (d, *J* = 6.8 Hz, 2 H), 7.53~7.46 (m, 4 H), 7.42~7.36 (m, 5 H), 7.29 (m, 1 H), 6.20 (d, *J* = 4.4 Hz, 1 H), 5.82 (d, *J* =4.4 Hz, 1 H), ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 160.06, 158.12, 151.89, 137.83, 137.58, 134.93, 132.52, 129.50, 129.47, 129.00, 127.97, 127.94, 127.59, 127.40, 122.70, 120.74, 118.07, 116.07, 116.33, 79.05 ppm; IR (KBr) *v* 3059, 2925, 1721, 1625, 1544, 1480, 1391, 1156, 1114, 993, 760, 699 cm^{-1}; MS (ESI) m/z 409.2 ($[M+Na]^+$); HRMS (ESI) calcd for $C_{24}H_{15}ClO_3$ ($[M+Na]^+$), 409.0602; found, 409.0594.

7-Methyl-2,4-diphenylpyrano[4,3-*b*]pyran-5(4*H*)-one (3d): A yellow oil; ^1H NMR (400 MHz, CD_3SOCD_3) δ 7.45 (d, *J* = 8.0 Hz 2 H), 7.30~7.34 (m, 3 H), 7.25~7.18 (m, 5 H), 6.19 (s, 1 H), 6.10 (d, *J* = 4.4 Hz, 1 H), 5.67 (d, *J* = 4.4 Hz, 1 H), 2.14 (s, 3 H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 166.64, 164.86, 159.51, 138.86, 138.08, 133.75, 129.36, 129.19, 127.96, 127.75, 127.71, 120.11, 100.16, 99.35, 77.72, 20.01 ppm; IR (film) *v* 3061, 2925, 1723, 1644, 1542, 1493, 1446, 1409, 1206, 1121, 998, 155, 699 cm^{-1}; MS (ESI) m/z 338.9 ($[M+Na]^+$); HRMS (ESI) calcd for $C_{21}H_{16}O_3$ ($[M+Na]^+$), 339.0992; found, 339.0996.

2,4-Bis(4-bromophenyl)pyrano[3,2-*c*]chromen-5(4*H*)-one (3e): A white solid; mp 158-159 ºC; ^1H NMR (400 MHz, $CDCl_3$) δ 7.84 (d, *J* = 8 Hz, 1 H), 7.59~7.56 (m, 3 H), 7.50 (d, *J* = 7.6 Hz, 2 H), 7.43 (d, *J* = 8.0 Hz, 2 H), 7.33 (d, *J* = 8.4 Hz, 1 H), 7.28 (d, *J* = 7.6 Hz, 1 H), 7.21 (d, *J* = 7.6 Hz, 2 H), 6.11 (d, *J* = 4.0 Hz, 1 H), 5.73 (d, *J* = 4.0 Hz, 1 H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 161.33, 158.53, 153.56, 136.86, 136.58, 134.66, 132.98, 132.16, 131.10, 129.12, 129.06, 124.13, 123.60, 123.23, 122.07, 119.79, 116.71, 114.90, 102.34, 77.88 ppm; IR (KBr) *v* 3053, 1724, 1632, 1608, 1553, 1488, 1404, 1385, 1329, 1265, 1211, 1072, 1023, 999. 812, 756 cm^{-1}; MS (ESI) m/z 530.2 ($[M+Na]^+$); HRMS (ESI) calcd for $C_{24}H_{14}Br_2O_3$ ($[M+Na]^+$), 530.9202; found, 530.9205.

2,4-Bis(4-bromophenyl)-9-methylpyrano[3,2-*c*]chromen-5(4*H*)-one (3f): A light yellow solid; mp 187-188 ºC; ^1H NMR (400 MHz, $CDCl_3$) δ 7.59 (s, 1 H), 7.57 (d, *J* = 8.4 Hz, 2 H), 7.48 (d, *J* = 8.4 Hz, 2 H), 7.42 (d, *J* = 8.4 Hz, 2 H), 7.36 (dd, J_1 = 2.0 Hz, J_2 = 8.8 Hz, 1 H), 7.21~7.18 (m, 3 H), 6.07 (d, *J* = 4.4 Hz, 1 H), 5.69 (d, *J* = 4.4 Hz, 1 H), 2.40 (s, 3 H), ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 161.38, 158.72, 151.78, 136.96, 136.67, 134.76, 134.09, 133.92, 132.16, 131.06, 129.16, 129.05, 123.57, 122.76, 122.02, 119.68, 116.48, 114.52, 102.24, 77.91, 20.90 ppm; IR (KBr) *v* 3064, 2922, 1724, 1630, 1556, 1489, 1402, 1200, 1118, 1072, 1010, 814, 532 cm^{-1}; MS (ESI) m/z 544.8 ($[M+Na]^+$); HRMS (ESI) calcd for $C_{25}H_{16}Br_2O_3$ ($[M+Na]^+$), 544.9358; found, 544.9345.

2,4-Bis(4-bromophenyl)-9-chloropyrano[3,2-*c*]chromen-5(4*H*)-one (3g): A light yellow solid; mp 185-186 ºC; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.77 (d, *J* = 2.4 Hz, 1 H), 7.57 (d, *J* = 8.4 Hz, 2 H), 7.50 (m, 3 H), 7.41 (d, *J* = 8.4 Hz, 2 H), 7.27 (s, 1 H), 7.17 (d, *J* = 8.4 Hz, 2 H), 6.11 (d, *J* = 3.6 Hz, 1 H), 5.73 (d, *J* = 4.4 Hz, 1 H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 160.06, 157.96, 151.87, 136.48, 136.30, 134.37, 132.88, 132.27, 131.14, 129.72, 129.20, 129.04, 123.82, 122.63, 122.20, 120.32, 118.18, 116.03, 102.88, 77.18 ppm; IR (KBr) *v* 3064, 2922, 1724, 1630, 1556, 1489, 1402, 1267, 1200, 1117, 1072, 1009, 814, 772 cm^{-1}; MS (ESI) m/z 565.2 ([M+Na]$^+$); HRMS (ESI) calcd for $C_{24}H_{13}Br_2ClO_3$ ([M+Na]$^+$), 564.9032; found, 564.9065.

2,4-Bis(4-bromophenyl)-7-methylpyrano[4,3-*b*]pyran-5(4*H*)-one (3h): A white solid; mp 186-187 ºC; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.55 (d, *J* = 8.0 Hz, 2 H), 7.47 (d, *J* = 8.4 Hz, 2 H), 7.36 (d, *J* = 8.0 Hz, 2 H), 7.18 (d, *J* = 8.4 Hz, 2 H), 5.91 (m, 2 H), 5.55 (d, *J* = 4.4 Hz, 1 H), 2.25(s, 3 H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 166.40, 164.37, 159.96, 137.06, 136.39, 134.13, 132.07, 130.96, 129.21, 129.11, 123.47, 121.97, 118.55, 100.00, 99.34, 77.70, 20.29 ppm; IR (KBr) *v* 3097, 2924, 1718, 1641, 1541, 1487, 1406, 1205, 1007, 997, 827, 540cm^{-1}; MS (ESI) m/z 494.9 ([M+Na]$^+$); HRMS (ESI) calcd for $C_{21}H_{14}Br_2O_3$ ([M+Na]$^+$), 494.9202; found, 494.9199.

2,4-Dip-tolylpyrano[3,2-*c*]chromen-5(4*H*)-one (3i): A yellow oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.83 (d, *J* = 8.0 Hz, 1 H), 7.65 (t, *J* = 8.0 Hz, 1 H), 7.46 (d, *J* = 7.6 Hz, 2 H), 7.36 (m, 2 H), 7.22 (m,4 H), 7.13 (d, *J* = 7.6 Hz, 2 H), 6.31 (d, *J* = 5.2 Hz, 1 H), 5.88 (d, *J* = 4.8 Hz, 1 H), 2.31 (s, 3 H), 2.28 (s, 3 H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 160.94, 158.03, 153.29, 138.99, 137.08, 135.54, 135.37, 134.09, 133.48, 129.75. 128.65, 127.68, 124.81, 123.35, 121.11, 116.72, 115.14, 102.99, 77.81, 21.19, 21.16 ppm; IR (film) *v* 3028, 2924, 1731, 1614, 1573, 1493, 1398, 1327, 1266, 1177, 759 cm^{-1}; MS (ESI) m/z 403.1 ([M+Na]$^+$); HRMS (ESI) calcd for $C_{26}H_{20}O_3$ ([M+Na]$^+$), 403.1305; found, 403.1320.

2-(4-Chlorophenyl)-4-phenylpyrano[3,2-*c*]chromen-5(4*H*)-one (3j+3j′): A white solid; mp 185-186 ºC; ^{1}H NMR (400 MHz, $CDCl_3$) (**3j**/**3j′** = 4:1) δ 7.86-7.81 (m, 1 H), 7.58-7.49 (m, 3 H), 7.44-7.24 (m, 9 H), 6.14 (d, *J* = 4.0 Hz, 0.8 H), 6.11 (d, *J* = 4.8 Hz, 0.2 H), 5.74-5.72 (m, 1 H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 161.45, 158.61, 153.57, 137.99, 137.64, 136.34, 135.26, 134.16, 133.69, 132.74, 132.70, 129.32, 129.11, 128.93, 128.88, 128.77, 128.07, 127.94, 127.92, 127.38, 127.35, 123.98, 123.29, 123.15, 120.49, 119.51, 116.64, 116.61, 115.06, 102.31, 79.69, 77.85 ppm; IR (KBr) *v* 3034, 2870, 1719, 1624, 1492, 1106, 1022, 986, 759 cm^{-1}; MS (ESI) m/z 409.3 ([M+Na]$^+$); HRMS (ESI) calcd for $C_{24}H_{15}ClO_3$ ([M+Na]$^+$), 409.0602; found, 409.0598.

2-(4-Chlorophenyl)-9-methyl-4-phenylpyrano[3,2-*c*]chromen-5(4*H*)-one (3k+3k′): A white solid; mp 172-173 ºC; ^{1}H NMR (400 MHz, $CDCl_3$) (**3k**/**3k′** = 7:3) δ 7.61-7.59 (m, 1 H), 7.55-7.49 (m, 2 H), 7.45-7.38 (m, 3 H), 7.35-7.30 (m, 4 H), 7.28-7.24 (m, 1 H), 7.20-7.18 (m,1 H), 6.11 (d, *J* = 4.4 Hz, 0.69

H), 6.08 (d, *J* = 4.4 Hz, 0.31 H), 5.72-5.70 (m,1 H), 2.39 (s, 3 H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 161.52, 161.14, 158.82, 158.70, 151.77, 138.09, 137.72, 136.65, 136.41, 135.75, 135.24, 134.27, 133.86, 133.82, 133.76, 133.74, 133.64, 129.31, 129.11, 128.93, 128.76, 128.05, 127.89, 127.43, 127.35, 122.84, 122.71, 120.38, 119.41, 116.41, 116.38, 114.67, 114.65, 102.23, 78.73, 20.83 ppm; IR (KBr) *ν* 3066, 2924, 1721, 1632, 1560, 1492, 1400, 1120, 1007, 812, 727 cm^{-1}; MS (ESI) m/z 422.9 ([M+Na]$^+$); HRMS (ESI) calcd for $C_{25}H_{17}ClO_3$ ([M+Na]$^+$), 423.0758; found, 423.0751.

2-(2-Chlorophenyl)-9-methyl-4-phenylpyrano[3,2-*c*]chromen-5(4*H*)-one (3l+3l′): A white solid; mp 198-199 ºC; ^{1}H NMR (400 MHz, $CDCl_3$) (**3l**/**3l′** = 3:1) δ 7.65-7.63 (m, 2 H), 7.47-7.44 (m, 1 H), 7.36-7.29 (m, 8 H), 7.19 (d, *J* = 8.4 Hz, 1 H), 6.54 (d, *J* = 4.0 Hz, 1 H), 5.69 (d, *J* = 3.6 Hz, 1 H), 2.38 (s, 2.25 H), 2.36 (s, 0.75 H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 161.42, 158.78, 151.78, 137.75, 135.67, 135.37, 133.80, 133.77, 133.57, 133.51, 133.11, 132.93, 130.29, 130.14, 129.87, 129.29, 128.94, 128.86, 127.87, 127.35, 127.24, 122.92, 122.79, 119.06, 116.36, 114.48, 102.54, 102.43, 75.39, 20.89, 20.83 ppm; IR (KBr) *ν* 3057, 2926, 1723, 1627, 1556, 1493, 1397, 1285, 1202, 1114, 1009, 760, 698 cm^{-1}; MS (ESI) m/z 422.8 ([M+Na]$^+$); HRMS (ESI) calcd for $C_{25}H_{17}ClO_3$ ([M+Na]$^+$), 423.0753; found, 423.0751.

ACKNOWLEDGEMENTS

This work was supported by the National Natural Science Foundation of China (No. 20702047 and Jo830413) as well as the Natural Science Foundation of Zhejiang Province (R407106 and Y4090028).

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