Platinum- and Ruthenium-Catalyzed Aromatization of Enediynes via Intramolecular Nucleophilic Additions

Bhanu Pratap Taduri, Arjan Odedra, Cheng-Yi Lung, Rai-Shung Liu*

Department of Chemistry, National Tsing-Hua University, 101 Sec 2, Kuang Fu Rd., Hsinchu 30034, Taiwan
E-mail: rsliu@mx.nthu.edu.tw

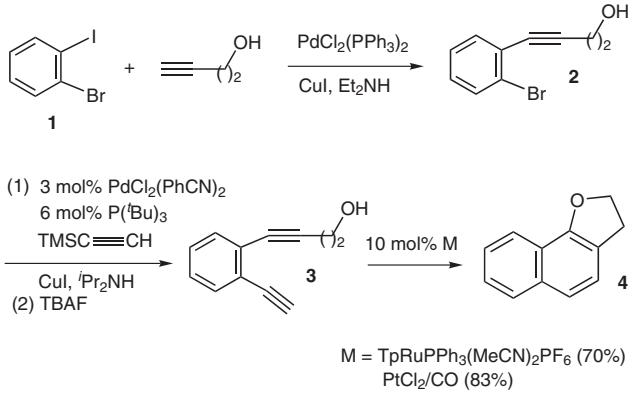
Received 1 April 2007

Abstract: Catalytic cyclization of enediynes via intramolecular nucleophilic addition was achieved with $TpRuPPh_3(MeCN)_2PF_6$ and platinum dichloride, giving naphthalene-fused 2,3-dihydrofurans and -pyrroles in good yields. On the basis of experimental results, the mechanism is proposed to involve nucleophilic addition to a π-alkyne intermediate, followed by alkyne insertion.

Key words: enediynes, aromatization, intramolecular nucleophilic addition, ruthenium, platinum

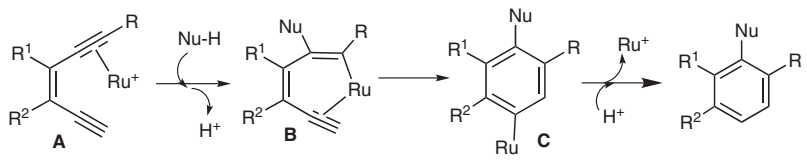
The Bergman aromatization of enediynes[1] has attracted considerable attention because of its potential application in medicinal and materials chemistry.[2,3] The Bergman reaction of unstrained enediynes can be implemented by metal complexes under mild conditions via metal–vinylidene intermediates[4a,b] or through a metal-chelated effect.[4c–f] This cyclization is synthetically useful because organic functional groups can be introduced onto benzene products via suitable nucleophiles. Recently, we reported the aromatization of unstrained enediynes via regiocontrolled nucleophilic addition catalyzed by the ruthenium catalyst, $TpRuPPh_3(MeCN)_2PF_6$ (10 mol%). The mechanism of this cyclization has been elucidated to proceed via nucleophilic addition to π-alkyne intermediate **A**, followed by an alkyne insertion reaction of intermediate **B** (Scheme 1).[5] In this investigation, we extend this catalytic cyclization to intramolecular nucleophilic additions catalyzed by platinum dichloride ($PtCl_2$) and $TpRuPPh_3(MeCN)_2PF_6$.

Scheme 2 shows a typical procedure to prepare enediyne substrate **3**, which was obtained conveniently from sequential palladium-catalyzed coupling of 1-bromo-2-iodobenzene (**1**) with but-3-yn-1-ol and then trimethylsilylacetylene, followed by desilylation using tetrabutylammonium fluoride. Treatment of alcohol **3** (0.50 M) with $TpRuPPh_3(MeCN)_2PF_6$ (10 mol%) in hot pentan-3-one (100 °C, 12 h) afforded cyclized 2,3-dihydrofuran product **4** in 70% yield. The same cyclization was performed more efficiently with 10% $PtCl_2$ under carbon monoxide (1 atm)[6] in hot pentan-3-one (100 °C, 3 h) and gave **4** in 83% yield.



Scheme 2 Synthesis of 2,3-dihydronaphtho[1,2-*b*]furan

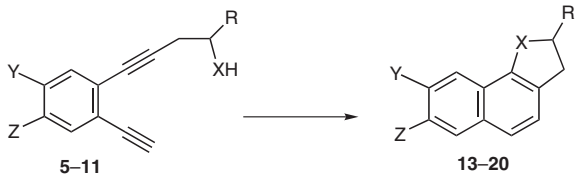
We also prepared various enediynes **5**–**12** bearing a tethered alcohol or amine to examine the generality of this nucleophilic aromatization. The cyclizations were studied using $PtCl_2$/carbon monoxide and $TpRuPPh_3(MeCN)_2PF_6$. In most cases, the use of the $PtCl_2$ system appeared to be superior to that of the ruthenium catalyst in terms of the observed product yields and reaction periods required. As shown in Table 1 (entries 1–3), this intramolecular cyclization was applicable to substrates **5**–**7** bearing a secondary alcohol; the yield was particularly low for the phenyl-substituted product **15**. Electron-rich benzene substrates **8** and **9** did not show an enhancement in the cyclization efficiency; both catalysts gave desired cyclized



Scheme 1 Ruthenium-catalyzed cyclization of enediynes via nucleophilic addition

SYNTHESIS 2007, No. 13, pp 2050–2054
Advanced online publication: 26.06.2007
DOI: 10.1055/s-2007-983739; Art ID: C02807SS

Table 1 Ruthenium- and Platinum-Catalyzed Cyclization of Enediynes



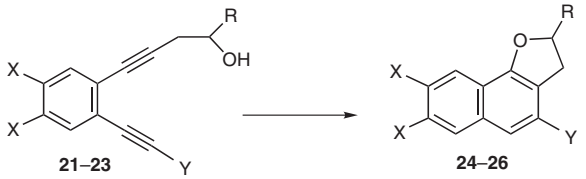
Entry	Enediyne[a]	Product	Yield[b] (%)	
			Using $PtCl_2$/CO	Using $TpRuPPh_3(MeCN)_2PF_6$
1	X = O, Y = Z = H, R = Me (**5**)	**13**	76	72
2	X = O, Y = Z = H, R = Pr (**6**)	**14**	78	73
3	X = O, Y = Z = H, R = Ph (**7**)	**15**	51	40
4	X = O, Y = OMe, Z = R = H (**8**)	**16**	71	70
5	X = O, Y = R = H, Z = OMe (**9**)	**17**	73	67
6	X = NPh, Y = Z = R = H (**10**)	**18**	79	72
7	X = NPh, Y = R = H, Z = OMe (**11**)	**19**	75	68
8	X = NPh, Y = Z = OMe, R = H (**12**)	**20**	76	68

[a] 10 mol% $TpRuPPh_3(MeCN)_2PF_6$ or $PtCl_2$/CO, 0.50 M enediyne, pentan-3-one, 100 °C, 12 h for Ru catalyst and 4 h for Pt catalyst.
[b] Yields were reported after separation using a silica gel column.

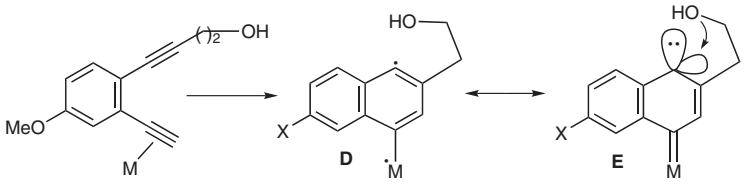
products **16** and **17**, respectively, in good yields (67–73%). This cyclization also worked well for nitrogen-based nucleophiles, as in substrates **10**–**12**; in these cases, $TpRuPPh_3(MeCN)_2PF_6$ again seemed to be less efficient than $PtCl_2$ in producing the corresponding 2,3-dihydropyrrole products **18**–**20**. Table 1 shows that electron-rich benzenes **8**, **9**, **11**, and **12** (entries 4, 5, 7, and 8, respectively) work with equal efficiency as unsubstituted benzene derivatives **5**–**7** and **11** (entries 1–3 and 6, respectively) for both two catalysts; a similar phenomenon was previously observed for ruthenium-catalyzed intermolecular aromatization (see Scheme 1).[5]

Table 2 shows additional examples of the cyclization using platinum and ruthenium catalysts with iodoalkynes **21**–**23** as the substrates. The corresponding cyclization products **24**–**26** were obtained without a 1,2-iodo shift according to the ^1H NOE spectra. The lack of a 1,2-iodo shift suggests that metal–vinylidene is not involved in the cyclization. To assert the role of a π-alkyne intermediate, we prepared enediyne d_1-**3**, bearing a 96% deuterium content at the alkyne terminus; its corresponding platinum catalysis gave fused 2,3-dihydrofuran d_1-**4** which does not show a 1,2-hydrogen shift. This information clearly excludes the involvement of a vinylidene intermediate in the reaction mechanism.

Table 2 Aromatization of Enediynes Bearing Deuterium or Iodo Substituents



Entry	Enediyne	Product	Yield (%)	
			Using $PtCl_2$/CO	Using $TpRuPPh_3(MeCN)_2PF_6$
1	X = R = H, Y = I (**21**)	**24**	61	52
2	X = H, R = Me, Y = I (**22**)	**25**	62	55
3	X = OMe, R = H, Y = I (**23**)	**26**	61	53
4	X = R = H, Y = 96% D (d_1-**3**)	d_1-**4** (Y = 74% D)	72	–



Scheme 3 An alternative mechanism for the aromatization

The results in Table 2 support the idea that the intramolecular nucleophilic aromatization proceeds via the same mechanism as that of the intermolecular process.[5] An alternative mechanism involving metal diradical **D**/carbenoid intermediate **E** seems to be incompatible with our experimental observations (Scheme 3). Although this mechanism has been postulated in the tethered alkane carbon–hydrogen bond insertion,[7] it is expected that the electron-rich benzene (X = OMe) would stabilize carbenoid intermediate **E** to facilitate the nucleophilic addition. This hypothesis is opposed to our observation that electron-rich benzenes fail to show cyclization enhancement as depicted in Table 1.

In summary, we report platinum- and ruthenium-catalyzed cyclizations of enediynes via intramolecular nucleophilic addition. This cyclization enables one-pot syntheses of naphthalene-fused 2,3-dihydrofurans and -pyrroles. On the basis of experimental results, the mechanism is proposed to involve nucleophilic addition to a π-alkyne intermediate, followed by alkyne insertion, indentical to that reported for the intermolecular process.[5]

Unless otherwise noted, all reactions were carried out under an N_2 atmosphere in oven-dried glassware using standard syringe, cannula and septa apparatus. Benzene, Et_2O, THF, and hexane were dried (sodium benzophenone) and distilled before use. The ruthenium catalyst, $TpRuPPh_3(MeCN)_2PF_6$, was prepared by heating $TpRu(PPh_3)_2Cl$ with $LiPF_6$ in MeCN.[8] IR spectra were collected on a BOMEM MB100 FT-IR spectrometer. NMR spectroscopy was performed on a Varian Mercury-400 spectrometer, with residual undeuterated solvent as an internal standard. High-resolution mass spectrometry was carried out on a Jeol JMS-HX 100 instrument using electron ionization method.

4-(2-Ethynylphenyl)but-3-yn-1-ol (3); Typical Procedure

To an Et_2NH soln (40 mL) of 1-bromo-2-iodobenzene (**1**; 4.00 g, 14.1 mmol) was added $PdCl_2(PPh_3)_2$ (198 mg, 0.28 mmol) and CuI (54 mg, 0.28 mmol) at 28 °C, and the mixture was stirred for 5 min before addition of but-3-yn-1-ol (1.18 g, 16.9 mmol). The solution was stirred for 12 h and concentrated in vacuo, sat. $NaHCO_3$ soln was added and the mixture was extracted with Et_2O. The Et_2O extract was washed with sat. NaCl soln, dried (anhyd $MgSO_4$), and concentrated under reduced pressure. The residues were chromatographed through a silica gel column (hexane–EtOAc, 4:1) to afford compound **2** as a yellow oil; yield: 2.84 g (89%).

To $PdCl_2(PhCN)_2$ (195 mg, 0.51 mmol) and CuI (99 mg, 0.51 mmol) was added anhyd toluene (20 mL). Then P(*t*-Bu)$_3$ (206 mg 1.02 mmol), *i*-Pr_2NH (1.29 g, 12.7 mmol), bromobenzene **2** (1.91 g, 8.49 mmol), and trimethylsilylacetylene (1.20g, 12.2 mmol) were added via syringe to the stirred mixture. After 10 h, the mixture was diluted with Et_2O (40 mL), filtered through a small pad of silica gel (with Et_2O rinsing), concentrated, and purified by flash chromatography. This silyl derivative was dissolved in THF (10 mL) and added to a 1.0 M THF soln of TBAF (3.0 mL). The mixture was stirred for 2 h before treatment with H_2O (30 mL). The solution was extracted with Et_2O (3 × 15 mL) and the extract was concentrated under reduced pressure. The residue was purified by column chromatography (Et_2O) to afford **3**; yield: 1.00 g (69%).

IR (neat): 3650 (s), 3020 (w), 2112 (w), 1622 (w) cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 7.46 (d, 1 H, *J* = 7.2 Hz), 7.39 (d, 1 H, *J* = 7.2 Hz), 7.27–7.20 (m, 2 H), 3.80 (t, 2 H, *J* = 6.0 Hz), 3.31 (s, 1 H), 2.70 (t, 2 H, *J* = 6.0 Hz).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 132.4, 131.5, 128.5, 127.6, 126.2, 124.5, 91.0, 82.6, 81.2, 80.6, 60.9, 24.0.

HRMS: *m*/*z* calcd for $C_{12}H_{10}O$: 170.0732; found: 170.0729.

Ruthenium-Catalyzed Aromatization of Enediynes; Typical Procedure

To a solution of enediyne **3** (100 mg, 0.59 mmol) and pentan-3-one (0.60 mL) was added $TpRuPPh_3(MeCN)_2PF_6$ (44 mg, 0.059 mmol), and the mixture was brought to 100 °C and heated at that temperature for 12 h. The solution was concentrated and eluted through a silica gel column (hexane–EtOAc, 5:1) to give 2,3-dihydrofuran **4**; yield: 70 mg (70%).

IR (neat): 3016 (w), 1620 (s) cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 7.92 (d, 1 H, *J* = 8.8 Hz), 7.79 (d, 1 H, *J* = 8.8 Hz) 7.44–7.39 (m, 2 H), 7.37–7.32 (m, 2 H), 4.76 (t, 2 H, *J* = 8.8 Hz), 3.37 (t, 2 H, *J* = 8.8 Hz).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 155.3, 133.8, 127.8, 125.5, 125.2, 122.8, 121.3, 120.4, 120.0, 119.8, 71.7, 30.5.

HRMS: *m*/*z* calcd for $C_{12}H_{10}O$: 170.0732; found: 170.0730.

5-(2-Ethynylphenyl)pent-4-yn-2-ol (5)

IR (neat): 3016 (w), 1620 (s) cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 7.47 (d, 1 H, *J* = 7.2 Hz), 7.39 (d, 1 H, *J* = 6.8 Hz), 7.28–7.21 (m, 2 H), 4.10–4.02 (m, 1 H), 3.30 (s, 1 H), 2.67 (dd, 1 H, *J* = 16.8, 4.8 Hz), 2.55 (dd, 1 H, *J* = 16.8, 5.6 Hz), 1.32 (d, 3 H, *J* = 6.0 Hz).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 132.6, 131.7, 128.6, 127.5, 126.4, 124.6, 90.8, 82.7, 81.7, 80.5, 66.3, 30.3, 22.2.

HRMS: *m*/*z* calcd for $C_{13}H_{12}O$: 184.0888; found: 184.0885.

1-(2-Ethynylphenyl)hept-1-yn-4-ol (6)

IR (neat): 3653 (s), 3019 (w), 2111 (w), 1627 (w) cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 7.47 (d, 1 H, *J* = 7.2 Hz), 7.39 (d, 1 H, *J* = 6.8 Hz), 7.28–7.20 (m, 2 H), 3.87–3.81 (m, 1 H), 3.30 (s, 1 H), 2.68 (dd, 1 H, *J* = 16.8, 4.8 Hz), 2.56 (dd, 1 H, *J* = 16.8, 5.6 Hz), 2.32 (d, 1 H, *J* = 5.6 Hz), 1.65–1.55 (m, 2 H), 1.53–1.46 (m, 1 H), 1.43–1.34 (m, 1 H), 0.93 (t, 3 H, *J* = 7.2 Hz).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 132.6, 131.8, 128.7, 127.8, 126.6, 124.8, 91.1, 83.0, 81.9, 80.8, 70.0, 38.6, 28.8, 19.1, 14.2.

HRMS: *m*/*z* calcd for $C_{15}H_{16}O$: 212.1201; found: 212.1200.

4-(2-Ethynylphenyl)-1-phenylbut-3-yn-1-ol (7)

IR (neat): 3650 (s), 3017 (w), 2116 (w), 1620 (w) cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.49–7.40 (m, 3 H), 7.39–7.30 (m, 3 H), 7.30–7.25 (m, 3 H), 4.98–4.96 (m, 1 H), 3.30 (s, 1 H), 2.98–2.80 (m, 2 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 142.5, 132.4, 132.2, 131.6, 128.4, 127.8, 127.7, 126.2 (× 2), 125.7 (× 2), 124.6, 90.5, 82.6, 82.0, 72.3, 30.9.

HRMS: *m*/*z* calcd for $C_{18}H_{14}O$: 246.1045; found: 246.1040.

4-(2-Ethynyl-5-methoxyphenyl)but-3-yn-1-ol (8)
IR (neat): 3650 (s), 3014 (w), 2110 (w), 1627 (w) cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.38 (d, 1 H, *J* = 8.8 Hz), 6.90 (s, 1 H), 6.78 (d, 1 H, *J* = 8.8 Hz), 3.81–3.77 (m, 2 H), 3.77 (s, 3 H), 3.22 (s, 1 H), 2.71 (t, 2 H, *J* = 6.4 Hz).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 159.5, 133.8, 127.6, 117.0, 116.2, 114.5, 90.9, 82.6, 81.3, 76.6, 60.9, 55.3, 24.0.

HRMS: *m*/*z* calcd for $C_{13}H_{12}O_2$: 200.0837; found: 200.0834.

4-(2-Ethynyl-4-methoxyphenyl)but-3-yn-1-ol (9)
IR (neat): 3652 (s), 3016 (w), 2113 (w), 1623 (w) cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.31 (d, 1 H, *J* = 8.8 Hz), 6.98 (s, 1 H), 6.82 (d, 1 H, *J* = 8.8 Hz), 3.81–3.77 (m, 2 H), 3.78 (s, 3 H), 3.29 (s, 1 H), 2.70 (t, 2 H, *J* = 6.4 Hz).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 158.7, 132.8, 125.7, 118.7, 117.0, 115.5, 89.1, 82.5, 81.0, 80.4, 60.9, 55.3, 24.0.

HRMS: *m*/*z* calcd for $C_{13}H_{12}O_2$: 200.0837; found: 200.0833.

***N*-[4-(2-Ethynylphenyl)but-3-ynyl]benzenamine (10)**
IR (neat): 3650 (w), 3285 (s), 2100 (w), 1683 (w) cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.49 (d, 1 H, *J* = 7.6 Hz), 7.48 (d, 1 H, *J* = 7.2 Hz), 7.29–7.22 (m, 2 H), 7.19 (t, 2 H, *J* = 7.6 Hz), 6.73 (t, 1 H, *J* = 7.2 Hz), 6.67 (d, 2 H, *J* = 7.2 Hz), 3.34 (t, 2 H, *J* = 6.4 Hz), 3.28 (s, 1 H), 2.77 (t, 2 H, *J* = 6.4 Hz).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 147.7, 132.5, 131.7, 129.2 (× 2), 128.5, 127.5, 126.4, 124.5, 117.7, 113.2 (× 2), 91.7, 82.5, 80.6 (× 2), 42.5, 20.2.

HRMS: *m*/*z* calcd for $C_{18}H_{15}N$: 245.1204; found: 245.1200.

***N*-[4-(2-Ethynyl-4-methoxyphenyl)but-3-ynyl]benzenamine (11)**
IR (neat): 3640 (w), 3282 (s), 2104 (w), 1681 (w) cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.40 (d, 1 H, *J* = 8.4 Hz), 7.18 (t, 2 H, *J* = 7.2 Hz), 6.91 (s, 1 H), 6.79 (d, 1 H, *J* = 7.2 Hz), 6.74 (t, 1 H, *J* = 7.2 Hz), 6.67 (d, 2 H, *J* = 8.4 Hz), 3.78 (s, 3 H), 3.40 (t, 2 H, *J* = 6.4 Hz), 3.19 (s, 1 H), 2.76 (t, 2 H, *J* = 6.4 Hz).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 159.4, 147.7, 133.8, 129.2 (× 2), 127.7, 117.8, 116.9, 116.4, 114.5, 113.3 (× 2), 91.6, 82.6, 80.8, 79.1, 55.3, 42.5, 20.2.

HRMS: *m*/*z* calcd for $C_{19}H_{17}NO$: 275.1310; found: 275.1306.

***N*-[4-(2-Ethynyl-4,5-dimethoxyphenyl)but-3-ynyl]benzenamine (12)**
IR (neat): 3655 (w), 3285 (s), 2105 (w), 1680 (w) cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.17 (t, 2 H, *J* = 7.2 Hz), 6.93 (s, 1 H), 6.85 (s, 1 H), 6.71 (t, 1 H, *J* = 7.2 Hz), 6.66 (d, 2 H, *J* = 7.2 Hz), 3.84 (s, 6 H), 3.39 (t, 2 H, *J* = 6.4 Hz), 3.22 (s, 1 H), 2.75 (t, 2 H, *J* = 6.4 Hz).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 149.2, 148.5, 147.7, 129.2 (× 2), 119.5, 117.7, 117.2, 114.5, 113.9, 113.2 (× 2), 90.1, 82.7, 80.7, 79.3, 55.9 (× 2), 42.5, 20.2.

HRMS: *m*/*z* calcd for $C_{20}H_{19}NO_2$: 305.1416; found: 305.1411.

2-Methyl-2,3-dihydronaphtho[1,2-*b*]furan (13)
IR (neat): 3014 (w), 1624 (s) cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.92 (d, 1 H, *J* = 8.2 Hz), 7.77 (d, 1 H, *J* = 8.2 Hz), 7.42–7.36 (m, 2 H), 7.35–7.27 (m, 2 H), 5.17–5.08 (m, 1 H), 4.48 (dd, 1 H, *J* = 14.4, 8.8 Hz), 2.97 (dd, 1 H, *J* = 14.4, 7.2 Hz), 1.54 (d, 3 H, *J* = 6.8 Hz).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 154.7, 133.9, 127.8, 125.4, 125.1, 122.9, 121.4, 120.5, 119.8, 119.7, 80.2, 37.9, 22.0.

HRMS: *m*/*z* calcd for $C_{13}H_{12}O$: 184.0888; found: 184.0884.

2-Propyl-2,3-dihydronaphtho[1,2-*b*]furan (14)
IR (neat): 3019 (w), 1626 (s) cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.93 (d, 1 H, *J* = 8.8 Hz), 7.77 (d, 1 H, *J* = 8.8 Hz), 7.40–7.36 (m, 2 H), 7.34–7.27 (m, 2 H), 5.02–4.95 (m, 1 H), 3.44 (dd, 1 H, *J* = 15.2, 9.6 Hz), 3.00 (dd, 1 H, *J* = 15.2, 8.2 Hz), 1.93–1.86 (m, 1 H), 1.75–1.69 (m, 1 H), 1.63–1.49 (m, 2 H), 0.99 (t, 3 H, *J* = 8.0 Hz).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 154.8, 133.8, 127.7, 125.4, 125.0, 122.9, 121.4, 120.5, 119.7, 119.6, 83.3, 38.4, 36.2, 18.6, 14.0.

HRMS: *m*/*z* calcd for $C_{15}H_{16}O$: 212.1201; found: 212.1198.

2-Phenyl-2,3-dihydronaphtho[1,2-*b*]furan (15)
IR (neat): 3026 (w), 1630 (s) cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 8.02 (d, 1 H, *J* = 8.8 Hz), 7.81 (d, 1 H, *J* = 8.8 Hz), 7.45–7.28 (m, 9 H), 5.96 (t, 1 H, *J* = 9.6 Hz), 3.82 (dd, 1 H, *J* = 15.6, 9.6 Hz), 3.36 (dd, 1 H, *J* = 15.6, 9.6 Hz).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 154.9, 142.3, 134.0, 128.6 (× 2), 127.9, 127.8, 125.7, 125.6 (× 2), 125.3, 122.7, 121.5, 120.3, 119.2, 84.6, 39.4.

HRMS: *m*/*z* calcd for $C_{18}H_{14}O$: 246.1045; found: 246.1041.

8-Methoxy-2,3-dihydronaphtho[1,2-*b*]furan (16)
IR (neat): 3023 (w), 1628 (s) cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.81 (d, 1 H, *J* = 8.8 Hz), 7.29–7.22 (m, 2 H), 7.08–7.05 (m, 2 H), 4.73 (t, 2 H, *J* = 8.8 Hz), 3.88 (s, 3 H), 3.33 (t, 2 H, *J* = 8.8 Hz).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 157.5, 154.4, 135.2, 123.4, 123.0, 118.9, 118.0, 117.8, 116.0, 105.9, 71.8, 55.2, 30.4.

HRMS: *m*/*z* calcd for $C_{13}H_{12}O_2$: 200.0837; found: 200.0833.

7-Methoxy-2,3-dihydronaphtho[1,2-*b*]furan (17)
IR (neat): 3020 (w), 1625 (s) cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.68 (d, 1 H, *J* = 8.8 Hz), 7.29 (d, 1 H, *J* = 8.4 Hz), 7.19 (d, 2 H, *J* = 8.4 Hz), 7.06 (d, 1 H, *J* = 8.4 Hz), 4.75 (t, 2 H, *J* = 9.6 Hz), 3.90 (s, 3 H), 3.36 (t, 2 H, *J* = 9.6 Hz).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 157.3, 154.4, 133.8, 129.6, 128.4, 121.2, 120.4, 120.0, 118.7, 99.0, 71.6, 55.3, 30.7.

HRMS: *m*/*z* calcd for $C_{13}H_{12}O_2$: 200.0837; found: 200.0834.

1-Phenyl-2,3-dihydro-1*H*-benzo[*g*]indole (18)
IR (neat): 3019 (w), 1614 (s) cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.81 (d, 1 H, *J* = 8.0 Hz), 7.46 (d, 1 H, *J* = 8.4 Hz), 7.40–7.31 (m, 3 H), 7.26–7.18 (m, 3 H), 7.1–6.96 (m, 3 H), 4.19 (t, 2 H, *J* = 8.4 Hz), 3.26 (t, 2 H, *J* = 8.4 Hz).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 149.3, 143.0, 129.0, 128.9 (× 2), 128.6, 128.5, 124.7, 124.4, 124.3, 123.2, 122.8, 122.2 122.0, 121.4 (× 2), 58.5, 30.1.

HRMS: *m*/*z* calcd for $C_{18}H_{15}N$: 245.1204; found: 245.1200.

7-Methoxy-1-phenyl-2,3-dihydro-1*H*-benzo[*g*]indole (19)
IR (neat): 3023 (w), 1614 (s) cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 7.70 (d, 1 H, *J* = 9.2 Hz), 7.40 (d, 1 H, *J* = 8.0 Hz), 7.25 (t, 3 H, *J* = 8.4 Hz), 7.02–6.69 (m, 4 H), 6.57 (s, 1 H), 4.16 (t, 2 H, *J* = 8.8 Hz), 3.50 (s, 3 H), 3.25 (t, 2 H, *J* = 8.8 Hz).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 156.4, 148.9, 142.1, 130.0, 129.5, 129.4, 128.8, 128.5 (× 2), 123.5, 122.0, 121.4 (× 2), 120.8, 117.8, 102.8, 58.4, 55.2, 29.7.

HRMS: *m*/*z* calcd. for $C_{19}H_{17}NO$: 275.1310; found: 275.1306.

8-Dimethoxy-1-phenyl-2,3-dihydro-1*H*-benzo[*g*]indole (20)
IR (neat): 3024 (w), 1612 (s) cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 7.30 (d, 1 H, *J* = 8.4 Hz), 7.26–7.22 (m, 3 H), 7.09 (s, 1 H), 6.99–6.95 (m, 3 H), 6.57 (s, 1 H), 4.16 (t, 2 H, *J* = 8.0 Hz), 3.95 (s, 3 H), 3.35 (s, 3 H), 3.22 (t, 2 H, *J* = 8.0 Hz).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 148.7, 148.5, 148.0, 142.0, 129.8, 128.7, 128.5 (× 2), 127.1, 122.0, 121.5, 120.4 (× 2), 117.9, 106.9, 103.6, 58.3, 55.6, 55.2, 30.0.

HRMS: *m*/*z* calcd for $C_{20}H_{19}NO_2$: 305.1416; found: 305.1412.

4-[2-(Iodoethynyl)phenyl]but-3-yn-1-ol (21)
IR (neat): 3603 (w), 3200 (s), 2104 (w), 1684 (w) cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 7.39–7.35 (m, 2 H), 7.24–7.18 (m, 2 H), 3.81 (t, 2 H, *J* = 6.4 Hz), 2.71 (t, 2 H, *J* = 6.4 Hz).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 132.4, 131.5, 128.3, 127.4, 126.6, 125.7, 93.0, 91.0, 80.8, 60.9, 23.9, 10.0.

HRMS: *m*/*z* calcd for $C_{12}H_9IO$: 295.9698; found: 295.9693.

4-[2-(Iodoethynyl)phenyl]pent-4-yn-1-ol (22)
IR (neat): 3609 (w), 3203 (s), 2102 (w), 1685 (w) cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 7.41–7.36 (m, 2 H), 7.25–7.19 (m, 2 H), 4.08–4.02 (m, 1 H), 2.71–2.55 (m, 2 H), 1.35 (d, 3 H, *J* = 6.0 Hz).

^{13}C NMR (150 MHz, $CDCl_3$): δ = 132.6, 131.5, 128.5, 127.6, 126.7, 125.8, 93.2, 90.7, 81.5, 66.4, 30.3, 22.3, 10.0.

HRMS: *m*/*z* calcd for $C_{13}H_{11}IO$: 309.9855; found: 309.9851.

4-[2-(Iodoethynyl)-4,5-dimethoxyphenyl]but-3-yn-1-ol (23)
IR (neat): 3609 (w), 3203 (s), 2102 (w), 1685 (w) cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 6.84 (s, 1 H), 6.81 (s, 1 H), 3.84 (s, 6 H), 3.80 (t, 2 H, *J* = 6.1 Hz), 2.70 (t, 2 H, *J* = 6.1 Hz).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 149.3, 148.4, 119.8, 118.7, 114.4, 113.5, 93.7, 89.4, 80.9, 61.3, 56.1 (× 2), 24.5, 14.1.

HRMS: *m*/*z* calcd for $C_{14}H_{13}IO_3$: 355.9909; found: 355.9904.

4-Iodo-2,3-dihydronaphtho[1,2-*b*]furan (24)
IR (neat): 3026 (w), 1617 (s) cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 7.85 (d, 1 H, *J* = 9.2 Hz), 7.78 (s, 1 H), 7.65 (d, 1 H, *J* = 9.2 Hz), 7.41–7.38 (m, 2 H), 4.77 (t, 2 H, *J* = 9.2 Hz), 3.34 (t, 2 H, *J* = 9.2 Hz).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 154.3, 135.3, 128.4, 126.6, 126.4, 125.6, 124.6, 121.6, 91.8, 89.7, 70.5, 35.2.

HRMS: *m*/*z* calcd for $C_{12}H_9IO$: 295.9698; found: 295.9694.

4-Iodo-2-methyl-2,3-dihydronaphtho[1,2-*b*]furan (25)
IR (neat): 3029 (w), 1610 (s) cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 7.85 (d, 1 H, *J* = 9.2 Hz), 7.76 (s, 1 H), 7.64 (d, 1 H, *J* = 9.2 Hz), 7.40–7.37 (m, 2 H), 5.18–5.09 (m, 1 H), 3.44 (dd, 1 H, *J* = 15.2, 9.2 Hz), 2.94 (dd, 1 H, *J* = 15.2, 9.2 Hz), 1.54 (d, 3 H, *J* = 6.0 Hz).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 153.7, 135.3, 128.1, 126.6, 126.3, 125.5, 124.3, 121.7, 119.9, 89.9, 79.2, 42.4, 22.2.

HRMS: *m*/*z* calcd for $C_{13}H_{11}IO$: 309.9855; found: 309.9853.

4-Iodo-7,8-dimethoxy-2,3-dihydronaphtho[1,2-*b*]furan (26)
IR (neat): 3019 (w), 1613 (s) cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 7.19 (s, 1 H), 7.16 (s, 1 H), 7.08 (s, 1 H), 4.73 (t, 2 H, *J* = 8.8 Hz), 3.96 (s, 3 H), 3.95 (s, 3 H), 3.34 (t, 2 H, *J* = 8.8 Hz).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 154.5, 153.5, 149.4, 131.3, 129.7, 126.7, 123.2, 121.0, 118.5, 87.0, 71.7, 55.9, 55.8, 30.0.

HRMS: *m*/*z* calcd for $C_{14}H_{13}IO_3$: 355.9909; found: 355.9904.

Acknowledgment

The authors wish to thank the National Science Council, Taiwan, for supporting this work.

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