Synthesis of Angular Quinoid Heterocycles from 2-(2-Nitrovinyl)-1,4-benzoquinone

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Reactions of 2-(2-nitrovinyl)-1,4-benzoquinone with furans, indoles, and endocyclic enol ethers form angular fused heterocyclic quinoid ring systems. The reaction proceeds by a formal inverse electron-demand [4 + 2] cycloaddition reaction of the nitrovinylquinone and a double bond of the heterocycle. The initial quinoid cycloadducts can be readily tautomerized to hydroquinoid species, which may be dehydrogenated to fully aromatic quinones. In the case of furans, the tautomerized adducts may be ring-opened to give 6,7-di- or 5,6,7-tri-substituted-1,4-naphthalenediols. In the case of endocyclic enol ethers, formation of benzofuran products competes with [4 + 2] cycloaddition.

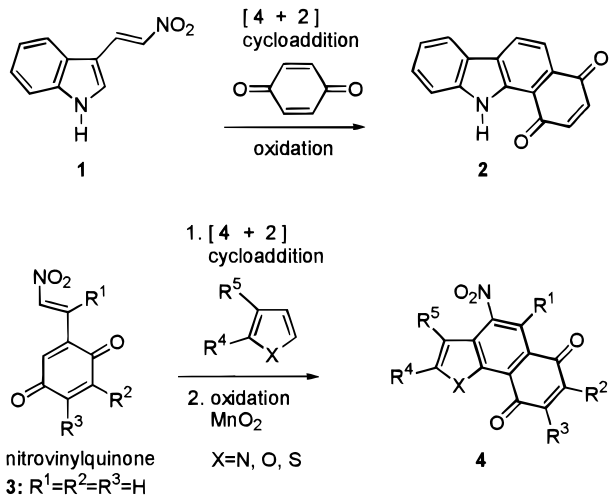
Introduction

We have previously studied the formation of benzo[*a*]-carbazole-1,4-diones (**2**) by normal electron demand [4 + 2] cycloadditions of 3-(2-nitrovinyl)indoles (**1**) with benzoquinone (Scheme 1).[1] Compounds of this type have been of recent interest due to their potential DNA intercalating ability[2a−d] and significant antitumor activity.[2a,3] We were interested in the possibility of accessing a more structurally diverse group of analogues (**4**) by a different route involving inverse electron-demand [4 + 2] cycloadditions of nitrovinyl-substituted quinones (**3**) and electron-rich heterocycles. We were also interested in developing a general method for synthesizing angular quinoid heterocycles from nitrovinylquinones.

Nitrovinylquinones are a little-studied class of electron-deficient molecules with multiple sites and modes potentially available for reaction with electron-rich unsaturated species. Some of the possibilities include the following: (1) inverse electron-demand cycloaddition as a diene; (2) normal electron-demand cycloaddition as a dienophile; (3) 1,4- or 1,6-conjugate addition; (4) 1,2-carbonyl addition; and (5) redox reactions. Testing the selectivity of these reactive molecules is an intriguing proposition. Although many substituted variations of 2-(2-nitrovinyl)quinones are possible, we chose to focus on one of the simplest and most easily obtainable analogues for this preliminary work, 2-(2-nitrovinyl)-1,4-benzoquinone (**3**) itself.

It was found that furans, indoles, and endocyclic enol ethers, such as dihydropyran, react selectively with **3**. The regiochemistry and stereochemistry of the resulting products is consistent with a formal inverse electron demand [4 + 2] cycloaddition, with **3** functioning as the diene and a double bond of the heterocycle functioning as the dienophile. This is an unusual reactivity pattern for furans, but examples of furans acting as dienophiles are known.[4a−c] Indoles are more common inverse electron-demand dienophiles, and reactions with a variety of electron-poor dienes have been reported.[5a−m] Endocyclic enol ethers gave a [4 + 2] cycloaddition product in one case but also formed benzofurans as the preferred reaction pathway. Similar reactivity of the latter type with benzoquinone and quinone imides has been reported previously with silyl enol ethers,[6] 2-(trimethylsiloxy)-

Scheme 1



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Scheme 2

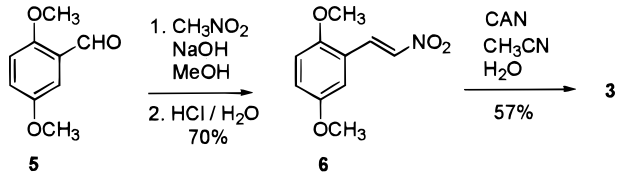
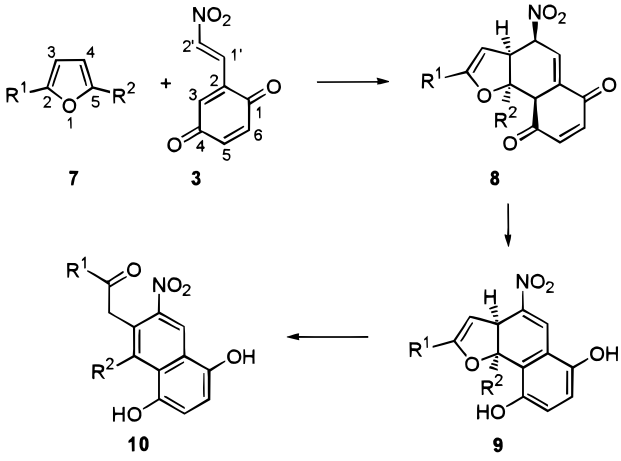


Table 1. Cycloaddition Reactions of 3 with Furans



R^1	R^2	solvent	product	yield, %
H	H	neat[a]	**9a**	87
CH_3	H	neat	**8b**	83
CH_3	H	PhH	**8b**	71
CH_3	CH_3	neat[b]	**8c**	74
CH_2OCH_3	H	neat	**9d**	68
CH_2OCH_3	H	PhH	**8d**	53
CH_2OH	H	neat[a]	**10e**	38

[a] These furans failed to yield cycloaddition products in PhH. [b] 2,5-Dimethylfuran failed to react cleanly in PhH.

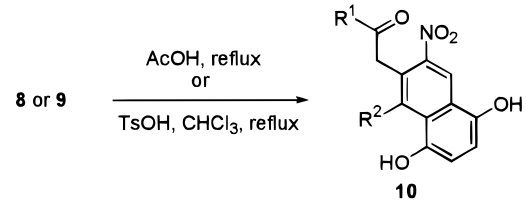
furan,[7a,b] enamines,[8] and styrenes[9] leading to benzofurans and indoles. Attempted reactions of **3** with pyrroles and thiophenes gave either no reaction or produced intractable mixtures.

Results and Discussion

Synthesis of 2-(2-nitrovinyl)-1,4-benzoquinone (**3**) was carried out in two steps from commercially available 2,5-dimethoxybenzaldehyde **5** (Scheme 2), which was converted to 2,5-dimethoxy-β-nitrostyrene (**6**) by reaction with nitromethane and NaOH in methanol, followed by dehydration with HCl.[10] Compound **6** was converted to **3** by oxidative demethylation[11] using ceric ammonium nitrate (CAN) in CH_3CN/H_2O.

Reactions with Furans. Several readily available 2-substituted furans (**7**) were selected as reaction partners for **3**. Reactions led to products of type **8** (Table 1), which often react further, producing **9**, and in one case proceeded even further to give **10e**. Although all carbons in **3** are electrophilic, C-3 was predicted to be the most electrophilic due to simultaneous conjugation with carbonyl and nitro groups. The regiochemistry of **8** is as expected, with bond formation occurring between the most electron-poor end of the diene (C-3) and the most electron-rich carbon of the furan (C-5). The stereochemistry of the cycloadducts **8** was determined to be endo by ^{1}H NMR coupling constant analysis. No exo products were detected. This selectivity for the endo transition state likely results from secondary orbital overlap between C-1′ and C-2 of the diene and C-3 and C-2 of the furan. Compounds of type **8** are highly prone to tautomerization and convert to **9** under conditions as mild as contact with polar solvents. Hence, the quinoid tautomer **8** is often not observed, as it readily converts to the hydroquinoid tautomer **9**. It was sometimes possible to isolate **8**, if it precipitated out of the reaction mixture before tautomerization could take place. A thoroughly dried, nonpolar solvent is required for this purpose. Benzene was used with some success, since the solubility of most of the initially formed cycloadducts is low in this solvent. Some furans failed to give cycloaddition products in benzene, or other more polar solvents such as THF. In these cases, it was found that the reactions would proceed in the neat heterocycle. Where comparison was possible, yields were generally slightly better using the neat heterocycle instead of benzene as solvent. With 2-substituted furans, reaction with **3** occurs through the less hindered C-4 and C-5 double bond of the furan as expected; however, the sterically more hindered 2,5-dimethylfuran still reacts with **3** in good yield. In the case of furfuryl alcohol, a ring-opened compound (**10e**) was isolated as the major product. This compound likely arises from an intermediate **9e** by a rearrangement analogous to that reported for cycloadducts of furans with halogenated thiophene dioxides.[4a] It is significant to note that the similar *O*-methyl ether of furfuryl alcohol does not ring-open by itself. Although most compounds of types **8** and **9** do not ring-open under the reaction conditions, they will ring-open to **10** when heated in the presence of acid (Table 2). Refluxing in AcOH or in $CHCl_3$ with catalytic TsOH was used with varying degrees of success. In cases where **8** was converted to **10**, it presumably first tautomerized to **9** and then ring-opened to **10**.

Table 2. Ring Opening of Furan Cycloadducts under Acidic Conditions



R^1	R^2	reactant	acid	product	yield, %
H	H	**9a**	AcOH	**10a**	72
H	H	**9a**	TsOH	**10a**	26
CH_3	H	**8b**	AcOH	**10b**	60
CH_3	H	**8b**	TsOH	**10b**	39
CH_3	CH_3	**9c**	TsOH[a]	**10c**	79
CH_2OCH_3	H	**9d**	AcOH	**10d**	55
CH_2OCH_3	H	**9d**	TsOH	**10d**	98

[a] This furan cycloadduct failed to yield ring-opened products in AcOH.

Reactions with 5,6-Fused Heterocycles. Benzo[*b*]-furan and several indoles were investigated as dieno-

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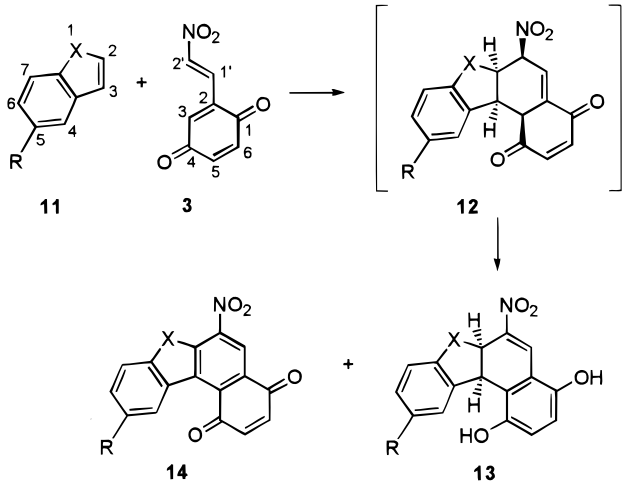
Table 3. Cycloaddition Reactions of 3 with Indoles and Benzofuran

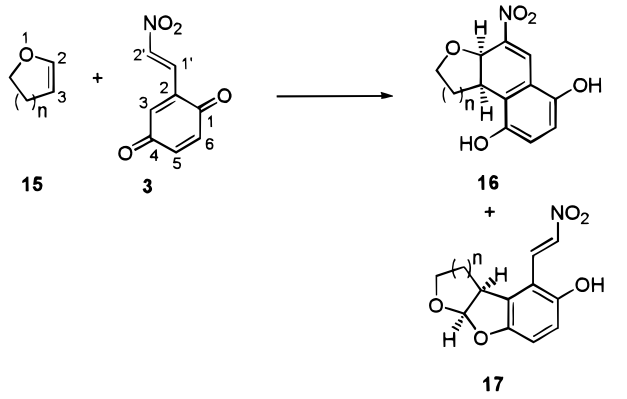


R	X	solvent	product(s)	ratio	yield, %
H	O	neat	**13a**		14
H	NH	PhH	**13b**, **14b**	3.6:1	95
H	NCH_3	PhH	**13c**		57
Br	NH	PhH	**13d**, **14d**	10.8:1	33
OCH_3	NH	PhH	**13e**		53

philes in inverse electron-demand [4 + 2] cyclization reactions with **3** (Table 3). Although benzene was used as the solvent in reactions of indoles with **3**, the initial cycloadducts **12** could not be isolated or detected before tautomerizing to **13**. With benzofuran **11a**, both **12a** and **13a** could be detected in the crude product by ^{1}H NMR; however, attempts at separation of **12a** from **13a** resulted in tautomerization or decomposition of **12a**. To simplify the workup of this reaction, **12a** was converted to **13a** in a controlled manner by tautomerization with Et_3N. The regiochemistry of **13** is as expected, with bond formation occurring between the most electron-poor end of the diene (C-3) and the most electron-rich carbon of the heterocycle (C-3). In the cases of indole derivatives **11b** and **11d** there was some oxidation of products **13b** and **13d** by **3** to form **14b** and **14d**, respectively. Although these were the only cases where isolable amounts of **14** were formed, the reduced, hydroquinone form of **3** could be isolated or detected spectroscopically as a byproduct in all of the reactions with 5,6-fused heterocycles. This was not surprising, since electron-deficient quinones such as DDQ and chloranil are known to be oxidizing agents. Reaction of **3** with 3-methylindole was attempted to test the steric limits of these reactions with indoles. In contrast to the sterically hindered 2,5-dimethylfuran, 3-methylindole failed to produce detectable cycloaddition products. Only reduced **3** was detected.

Reactions with Endocyclic Enol Ethers. In addition to aromatic heterocycles, **3** was also found to react with the endocyclic enol ethers 2,3-dihydrofuran and 3,4-dihydro-2*H*-pyran **15** (n = 1, 2) (Table 4). Cycloadditon products of type **16** were expected, and this was observed, with **16a**. A new reaction pathway leading to **17**, however, was also functioning and was the preferred pathway for these heterocycles. This shift in selectivity may be due to the loss of [4 + 2] transition state stabilizing secondary orbital overlap in going from aromatic dienophiles to endocyclic enol ethers. The regiochemistry of **16a** is as expected, with bond formation occurring between the most electron-poor end of the diene (C-3) and

Table 4. Cycloaddition Reactions of 3 with Endocyclic Enol Ethers



n	solvent	product(s)	ratio	yield, %
1	neat	**16a**, **17a**	1:1.7	85
1	PhH	**16a**, **17a**	1:1	48
2	neat[a]	**17b**		21

[a] This heterocycle failed to yield isolable products in PhH.

the most electron-rich carbon of the heterocycle (C-3). The stereochemistry of **16a** and **17** was determined by NMR coupling-constant analysis and confirmed in **16a** by X-ray crystallography.[12] Products **17** may be formed by conjugate addition of the enol ether to **3**, followed by tautomerization to a phenolic nucleophile which can ring-close to **17**.[6] Compound **17a** is a substituted tetrahydrofurobenzofuran, the core ring system of the mycotoxins aflatoxin B_2 and G_2[13a–j] and dihydro-*O*-methylsterigmatocystin.[14a,b] This methodology might provide a new racemic route to these molecules.

Oxidation of Cycloadducts To Give Fully Aromatic Quinones. Cycloadducts of types **9** and **13** can be oxidized to fully aromatic heterocyclic quinones using activated MnO_2 as the dehydrogenating agent (Table 5). The resulting compounds are analogues of **2**. Compounds of type **14** tended to be rather insoluble in most common solvents, and this led to problems in isolation and characterization in some cases. In many cases, ^{13}C NMR analyses proved impractical due to low solubility. Dehydrogenation of the 5-methoxyindole cycloadduct **13e** was attempted, and the product was detected spectroscopically but was not isolated in pure form.

Conclusions

We have found that 2-(2-nitrovinyl)-1,4-benzoquinone (**3**) serves as a useful precursor in the synthesis of a variety of angular-fused quinoid heterocycles. Inverse

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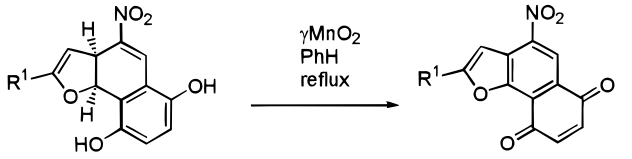
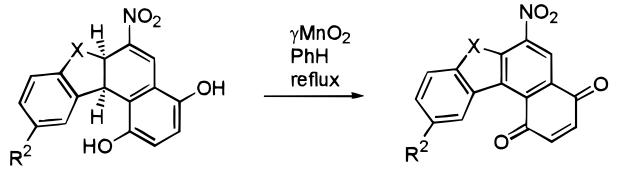
Table 5. Dehydrogenation of Cycloadducts To Give Fully Aromatic Quinones



9 **18**



13 **14**

R^1	R^2	X	product	yield, %
H			**18a**	53
CH_3			**18b**	54
CH_2OCH_3			**18c**	32
	H	O	**14a**	58
	H	NH	**14b**	63
	H	NCH_3	**14c**	41
	Br	NH	**14d**	33

electron-demand [4 + 2] cycloaddition reactions with substituted furans, indoles, and endocyclic enol ethers proceed with good regioselectivity, and the products can be transformed further to give fully aromatic ring systems, or ring-opened in the case of furans. Work is currently under way analyzing the reactivity of **3** and other nitrovinylquinones with a wider array of enol ethers. We are also exploring the prospects of synthesizing aflatoxin B_2 and G_2 and dihydro-*O*-methylsterigmatocystin via reactions related to that which produced **17**.

Experimental Section

General Methods. Benzene was dried by distillation over CaH_2. Liquid reagents were freshly distilled just prior to use, except where noted otherwise. Brine refers to saturated aqueous NaCl solution. Flash chromatography[15] was performed with silica gel (E. Merck 60, 230−400 mesh). Melting points are uncalibrated. ^{1}H NMR and ^{13}C NMR spectra were recorded at 300 and 75 MHz, respectively. Elemental analyses were performed at M−H−W Laboratories, Phoenix, AZ.

2,5-Dimethoxy-β-nitrostyrene (6). A solution of **5** (101.5 g, 611 mmol) and CH_3NO_2 (37.3 g, 611 mmol) in MeOH (600 mL) was cooled to 10 °C in an ice bath. A solution of NaOH (25.58 g, 640 mmol) in H_2O (200 mL) was added dropwise with stirring at a rate such that the temperature stayed between 10 and 15 °C. The reaction mixture was then immediately dripped into 5 N HCl (1.5 L), with stirring, and an orange precipitate formed. The precipitate was vacuum-filtered and crystallized from *i*-PrOH/H_2O, giving **6** as orange needles (80.87 g, 63%): mp 119.5−120 °C; IR (KBr, cm^{-1}) 3106, 2841, 1621, 1498, 1350, 1253, 1224; ^{1}H NMR ($CDCl_3$, δ ppm) 8.11 (d, J = 13.5 Hz, 1 H), 7.85 (d, J = 13.5 Hz, 1H), 7.01 (dd, J = 3.0, 9.0 Hz, 1 H), 6.95 (d, J = 3.0 Hz, 1 H), 6.90 (d, J = 9.0 Hz, 1 H), 3.93 (s, 3 H), 3.83 (s, 3 H); ^{13}C NMR ($CDCl_3$, δ ppm) 150.8, 150.4, 135.2, 132.2, 116.3, 116.0, 113.2, 109.3, 52.9, 52.7; EI HRMS m/z (M^+) calcd 209.0688, found 209.0688. Anal. Calcd for $C_{10}H_{11}NO_4$: C, 57.41; H, 5.30; N, 6.70. Found: C, 57.50; H, 5.40; N, 6.79.

2-(2-Nitrovinyl)-1,4-benzoquinone (3). A solution of ceric ammonium nitrate (115.20 g, 210.1 mmol) in 3:1 H_2O/CH_3CN (200 mL) was poured with rapid stirring into a solution of **6** (20.00 g, 95.6 mmol) in CH_3CN (500 mL). The reaction solution was stirred for 5 min and then washed with brine (100 mL), and the brine layer was extracted with CH_3CN (2 × 100 mL). The CH_3CN fractions were combined and concentrated until the product began to phase-separate. (It is important that the solution not be concentrated to dryness, as flash detonations have occurred under these conditions). The mixture was partitioned between $CHCl_3$ (500 mL) and H_2O (200 mL), and the resulting aqueous layer was extracted with $CHCl_3$ (200 mL). The $CHCl_3$ fractions were combined, washed with H_2O (100 mL), and dried over anhydrous $MgSO_4$. The $CHCl_3$ was removed under reduced pressure, and the residual brown solid was crystallized twice from THF/cyclohexane, giving **3** as golden yellow needles (7.68 g, 45%): mp 104−106 °C; IR (KBr, cm^{-1}) 3126, 1652, 1522, 1344; ^{1}H NMR ($CDCl_3$, δ ppm) 8.12 (d, J = 13.8 Hz, 1 H), 7.62 (d, J = 13.8 Hz, 1 H), 6.98 (m, 1 H), 6.93−6.84 (m, 2 H); ^{13}C NMR (acetone-d_6, δ ppm) 185.4, 183.9, 142.3, 136.1, 135.9, 135.4, 135.1, 129.0; CI HRMS m/z (M^+ + H) calcd 180.0297, found 180.0289. Anal. Calcd for $C_8H_5NO_4$: C, 53.64; H, 2.81; N, 7.82. Found: C, 53.81; H, 2.92; N, 7.75.

***cis*-3a,9b-Dihydro-6,9-dihydroxy-4-nitronaphtho[1,2-*b*]furan (9a).** Compound **3** (0.200 g, 1.12 mmol) was dissolved in furan (7.5 mL) and stirred in the dark for 20 h. The precipitate that formed was vacuum-filtered and dried under high vacuum, giving **9a** as an orange powder (0.240 g, 87%): mp 188 °C dec; IR (KBr, cm^{-1}) 3424, 1637, 1490, 1320, 1265; ^{1}H NMR (acetone-d_6, δ ppm) 8.92 (s, exchanges with D_2O, 1 H), 8.39 (s, exchanges with D_2O, 1 H), 8.26 (d, J = 1.5 Hz, 1 H), 7.02 (d, J = 9.0 Hz, 1 H), 6.95 (d, J = 9.0 Hz, 1 H), 6.66 (t, J = 2.4 Hz, 1 H), 6.09 (d, J = 11.1 Hz, 1 H), 5.34 (t, J = 2.7 Hz, 1 H), 4.39 (m, 1 H); ^{13}C NMR (acetone-d_6, δ ppm) 149.6, 149.5, 148.2, 146.6, 123.6, 121.2, 117.7, 117.5, 116.9, 100.3, 76.7, 40.0; CI HRMS m/z (M + NH_4^+) calcd 265.0824, found 265.0820. Anal. Calcd for $C_{12}H_9NO_5$: C, 58.30; H, 3.67; N, 5.67. Found: C, 58.08; H, 3.80; N, 5.41.

[(±)-(3aβ,4α,9aα,9bβ)]-3a,4,9a,9b-Tetrahydro-2-methyl-4-nitronaphtho[1,2-*b*]furan-6,9-dione (8b). A. Reaction in Neat Heterocycle. Compound **3** (0.200 g, 1.12 mmol) was dissolved in 2-methylfuran (7.5 mL) and stirred. Within minutes, a heavy precipitate formed, which was vacuum-filtered after 30 min and dried under high vacuum, giving **8b** as a pale yellow microcrystalline solid (0.243 g, 83%): mp 120 °C; IR (KBr, cm^{-1}) 2932, 1691, 1670, 1553, 1373, 1304; ^{1}H NMR ($CDCl_3$, δ ppm) 7.70 (dt, J = 0.9, 3.0, 3.0 Hz, 1 H), 7.04 (d, J = 10.8 Hz, 1 H), 6.96 (d, J = 10.8 Hz, 1 H), 5.70 (dd, J = 3.3, 9.6 Hz, 1 H), 4.97 (ddd, J = 2.1, 3.0, 6.6 Hz, 1 H), 4.33 (dq, J = 1.2, 1.2, 1.2, 2.4 Hz, 1 H), 4.29 (ddddq, J = 0.9, 1.2, 1.2, 1.2, 2.4, 6.6, 9.6 Hz, 1 H), 3.32 (ddd, J = 2.4, 3.0, 3.3 Hz, 1 H), 1.65 (t, J = 1.2 Hz, 3 H); ^{13}C NMR ($CDCl_3$, δ ppm) 192.8, 182.1, 160.4, 142.7, 141.8, 133.8, 131.0, 93.1, 83.0, 79.9, 48.3, 47.7, 13.3; CI HRMS m/z (M^+ + H) calcd 262.0715, found 262.0711. Anal. Calcd for $C_{13}H_{11}NO_5$: C, 59.77; H, 4.24; 5.36 N. Found: C, 59.62; H, 4.30; N, 5.20.

B. Reaction in Benzene. Compound **3** (0.200 g, 1.12 mmol) was partially dissolved in benzene (5 mL), and 2-methylfuran (0.184 g, 2.24 mmol) was added with stirring. After 18 h of stirring, a precipitate formed, which was filtered and dried under high vacuum, giving **8b** as a pale yellow solid (0.208 g, 71%): mp 119 °C; the mixture melting point with material from part A showed no depression; the ^{1}H NMR spectrum was identical with that of the material obtained in part A.

[(±)-(3aβ,4α,9aα,9bβ)]-3a,4,9a,9b-Tetrahydro-2,9b-dimethyl-4-nitronaphtho[1,2-*b*]furan-6,9-dione (8c). Compound **3** (0.400 g, 2.24 mmol) was dissolved in 2,5-dimethylfuran (10.0 mL) and stirred for 15.5 h, during which time a yellow precipitate formed. The entire reaction mixture was poured into hexane (20 mL), with stirring, and more precipitate formed. The precipitate was filtered and dried under high vacuum, giving **8c** as a yellow powder (0.452 g, 74%): mp 104−106 °C; IR (KBr, cm^{-1}) 2923, 1682, 1542, 1375, 1300; ^{1}H NMR ($CDCl_3$, δ ppm) 7.64 (ddd, J = 1.2, 2.7, 3.3 Hz, 1 H), 6.94 (d, J = 10.5 Hz, 1 H), 6.88 (d, J = 10.5 Hz, 1 H), 4.97 (ddd, J = 1.8, 3.3, 6.6 Hz, 1 H), 4.22 (dq, J = 1.2, 1.2, 1.2, 2.3 Hz, 1 H), 3.84 (dddq, J = 1.2, 1.5, 1.5, 1.5, 2.3, 6.6 Hz, 1 H), 3.05 (dd, J =

(15) Still, W. C.; Kahn, M.; Mitra, A. *J. Org. Chem.* **1978**, *43*, 2923−2925.

1.8, 2.7 Hz, 1 H), 1.75 (s, 3 H), 1.61 (dd, J = 1.2, 1.5 Hz, 3 H); ^{13}C NMR ($CDCl_3$, δ ppm) 193.0, 182.6, 159.4, 142.8, 141.2, 133.9, 132.7, 92.0, 88.3, 83.2, 56.7, 51.9, 25.0, 13.4; EI HRMS m/z (M^+) calcd 275.0794, found 275.0794. Anal. Calcd for $C_{14}H_{13}NO_5$: C, 61.09; H, 4.76; N, 5.09. Found: C, 60.89; H, 5.00; N, 5.04.

***cis*-3a,9b-Dihydro-6,9-dihydroxy-2-(methoxymethyl)-4-nitronaphtho[1,2-*b*]furan (9d).** Compound **3** (0.200 g, 1.12 mmol) was dissolved in 2-(methoxymethyl)furan[16] (5 mL) and stirred. After 30 min of stirring, an orange precipitate formed, and after 18 h, the precipitate was vacuum-filtered and dried under high vacuum, giving **9d** as an orange powder (0.222 g, 68%): mp 167−169 °C; IR (KBr, cm^{-1}) 3412, 1638, 1488, 1322, 1299, 1260; ^{1}H NMR (acetone-d_6, δ ppm) 8.89 (bs, 1 H), 8.39 (bs, 1 H), 8.25 (d, J = 1.5 Hz, 1 H), 7.02 (d, J = 8.7 Hz, 1 H), 6.94 (d, J = 8.7 Hz, 1 H), 6.18 (d, J = 10.5 Hz, 1 H), 5.28 (d, J = 2.7 Hz, 1 H), 4.41 (m, 1 H), 3.92 (m, 2 H), 3.29 (s, 3 H); ^{13}C NMR (DMSO-d_6, δ ppm) 157.6, 150.0, 149.4, 146.3, 124.4, 122.0, 118.3, 116.9, 116.6, 98.3, 77.1, 66.5, 58.1, 40.4; EI HRMS m/z (M^+) calcd 291.0743, found 291.0744. Anal. Calcd for $C_{14}H_{13}NO_6$: C, 57.73; H, 4.50; N, 4.81. Found: C, 57.56; H, 4.38; N, 4.61.

[(±)-(3aβ,4α,9aα,9bβ)]-3a,4,9a,9b-Tetrahydro-2-(methoxymethyl)-4-nitronaphtho[1,2-*b*]furan-6,9-dione (8d). Compound **3** (0.200 g, 1.12 mmol) was partially dissolved in benzene (5 mL), and 2-(methoxymethyl)furan[16] (0.250 g, 2.23 mmol) was added with stirring. Stirring was continued for 18 h, during which time a precipitate formed, which was vacuum-filtered, washed with benzene, and dried, giving **8d** as a pale yellow microcrystalline solid (0.172 g, 53%): mp 134−137 °C; IR (KBr, cm^{-1}) 3065, 2879, 1688, 1667, 1622, 1546, 1371; ^{1}H NMR ($CDCl_3$, δ ppm) 7.71 (dt, J = 1.2, 3.0, 3.0 Hz, 1 H), 7.04 (d, J = 10.8 Hz, 1 H), 6.95 (d, J = 10.8 Hz, 1 H), 5.77 (dd, J = 3.3, 9.9 Hz, 1 H), 5.01 (ddd, J = 2.1, 3.0, 7.2 Hz, 1 H), 4.66 (dt, J = 1.2, 1.2, 2.4 Hz, 1 H), 4.36 (ddddt, J = 1.2, 1.5, 1.5, 2.4, 7.2, 9.9 Hz, 1 H), 3.78 (dd, J = 1.2, 1.5 Hz, 2 H), 3.33 (ddd, J = 2.1, 3.0, 3.3 Hz, 1 H), 3.25 (s, 3 H); ^{13}C NMR ($CDCl_3$, δ ppm) 192.2, 181.7, 159.7, 142.5, 141.7, 133.4, 131.2, 95.7, 82.5, 80.3, 66.2, 58.3, 48.1, 47.0; FAB HRMS m/z ($M + H^+$) calcd 292.0821, found 292.0834. Anal. Calcd for $C_{14}H_{13}NO_6$: C, 57.73; H, 4.50; N, 4.81. Found: C, 57.59; H, 4.53; N, 4.62.

1-(5,8-Dihydroxy-3-nitro-2-naphthyl)-3-hydroxypropanone (10e). Compound **3** (0.200 g, 1.12 mmol) was dissolved in furfuryl alcohol (5 mL) and stirred for 18 h, during which time a fine precipitate formed. The reaction mixture was poured into benzene (15 mL), with stirring, causing more precipitate to form. The precipitate was filtered and vacuum-dried, giving **10e** as an orange solid (0.118 g, 38%): mp 245 °C dec; IR (KBr, cm^{-1}) 3348, 3186, 1715, 1604, 1335, 1303; ^{1}H NMR (DMSO-d_6, δ ppm) 10.07 (s, exchanges with D_2O, 1 H), 9.83 (s, exchanges with D_2O, 1 H), 8.80 (s, 1 H), 8.03 (s, 1 H), 6.94 (d, J = 8.4 Hz, 1 H), 6.84 (d, J = 8.4 Hz, 1 H), 5.36 (t, exchanges with D_2O, J = 6.0 Hz, 1 H), 4.36 (s, 2 H), 4.24 (d, J = 6.0 Hz, 2 H); ^{13}C NMR (DMSO-d_6, δ ppm) 208.0, 147.4, 146.2, 145.6, 128.0, 126.7, 125.1, 123.4, 121.0, 113.4, 110.5, 67.9, 44.1; CI HRMS m/z ($M + NH_4^+$) calcd 295.0930, found 295.0930. Anal. Calcd for $C_{13}H_{11}NO_6$: C, 56.32; H, 4.00; N, 5.05. Found: C, 56.55; H, 4.32; N, 4.85.

2-(5,8-Dihydroxy-3-nitro-2-naphthyl)ethanal (10a). A. Ring Opening with AcOH. Compound **9a** (0.264 g, 1.07 mmol) was mixed with glacial acetic acid (25 mL) and refluxed for 20 min with stirring. Acetic acid was removed under reduced pressure, and the residual solid was recrystallized from EtOH/H_2O, giving **10a** as a dark red microcrystalline solid (0.189 g, 72%): mp >350 °C; IR (KBr, cm^{-1}) 3396, 3324, 2860, 1710, 1632, 1603, 1481; ^{1}H NMR (acetone-d_6, δ ppm) 10.07 (s, 1 H), 9.06 (s, exchanges with D_2O, 1 H), 8.96 (s, 1 H), 8.84 (s, exchanges with D_2O, 1 H), 8.17 (s, 1 H), 6.99 (d, J = 8.3 Hz, 1 H), 6.91 (d, J = 8.3 Hz, 1 H), 4.38 (s, 2 H); ^{13}C NMR (acetone-d_6, δ ppm) 198.0, 147.3, 146.5, 145.6, 127.6, 126.7, 123.8, 123.5, 120.7, 112.6, 110.0, 48.5; EI HRMS m/z (M^+) calcd 247.0481, found 247.0475. Anal. Calcd for $C_{12}H_9NO_5$: C, 58.30; H, 3.67; N, 5.67. Found: C, 58.11; H, 3.79; N, 5.69.

B. Ring Opening with TsOH. Compound **9a** (0.120 g, 0.495 mmol) was mixed with $CHCl_3$ (12 mL), TsOH·H_2O (1 mg, 0.005 mmol) was added, and the solution was refluxed with stirring for 90 min. The resulting precipitate was vacuum-filtered, giving **10a** as a red powder (0.031 g, 26%): mp >350 °C; the mixture melting point with material from part A showed no depression; the ^{1}H NMR spectrum was identical with that of the material obtained in part A.

1-(5,8-Dihydroxy-3-nitro-2-naphthyl)propanone (10b). A. Ring Opening with AcOH. Compound **8b** (0.243 g, 0.930 mmol) was mixed with glacial AcOH (10 mL) and stirred until all solid dissolved. The solution was allowed to evaporate overnight, producing an oily dark red solid, which was triturated with boiling AcOH, giving **10b** as a maroon microcrystalline solid (0.146 g, 60%): mp 229−233 °C dec; IR (KBr, cm^{-1}) 3422, 3228, 1707, 1603, 1484, 1327; ^{1}H NMR (acetone-d_6, δ ppm) 9.04 (s, 1 H), 8.94 (s, 1 H), 8.81 (s, 1 H), 8.10 (s, 1 H), 6.97 (d, J = 8.4 Hz, 1 H), 6.89 (d, J = 8.4 Hz, 1 H), 4.42 (s, 2 H), 2.29 (s, 3 H); ^{13}C NMR (acetone-d_6, δ ppm) 203.8, 147.4, 146.7, 145.7, 127.5, 126.9, 125.8, 123.7, 120.6, 112.6, 110.0, 48.4, 29.0; EI HRMS m/z (M^+) calcd 261.0637, found 261.0633. Anal. Calcd for $C_{13}H_{11}NO_5$: C, 59.77; H, 4.24; N, 5.36. Found: C, 60.00; H, 4.40; N, 5.45.

B. Ring Opening with TsOH. Compound **8b** (0.132 g, 0.505 mmol) was mixed with $CHCl_3$ (15 mL), TsOH·H_2O (1 mg, 0.005 mmol) was added, and the solution was refluxed for 2 h, during which time a precipitate formed. The mixture was concentrated to half its original volume, vacuum-filtered, and dried, giving **10b** as a maroon solid (0.052 g, 39%): mp 228−231 °C dec; the mixture melting point with material from part A showed no depression; the ^{1}H NMR spectrum was identical with that of the material obtained in part A.

1-(5,8-Dihydroxy-1-methyl-3-nitro-2-naphthyl)propanone (10c). Compound **9c** (0.134 g, 0.487 mmol) was mixed with $CHCl_3$ (12 mL), and the mixture was heated to reflux, with stirring, until the solid dissolved. Next, TsOH·H_2O (1 mg, 0.005 mmol) was added, and the solution was refluxed for 90 min more, during which time a color change from orange to red occurred and a precipitate formed. The mixture was concentrated to half its original volume and cooled, and the solid was vacuum-filtered and vacuum-dried, giving **10c** as a maroon powder (0.106 g, 79%): mp 186−189 °C; IR (KBr, cm^{-1}) 3418, 3340, 1708, 1618, 1506, 1329; ^{1}H NMR (acetone-d_6, δ ppm) 8.94 (s, 1 H), 8.68 (s, 1 H), 8.64 (s, 1 H), 6.97 (d, J = 8.4 Hz, 1 H), 6.87 (d, J = 8.4 Hz, 1 H), 4.22 (s, 2 H), 2.89 (s, 3 H), 2.32 (s, 3 H); ^{13}C NMR (acetone-d_6, δ ppm) 203.3, 148.1, 147.9, 147.1, 138.1, 126.1, 124.0, 123.6, 117.3, 114.1, 109.6, 43.4, 28.8, 18.6; EI HRMS m/z (M^+) calcd 275.0794, found 275.0792; Anal. Calcd for $C_{14}H_{13}NO_5$: C, 61.09; H, 4.76; N, 5.09. Found: C, 61.18; H, 5.00; N, 4.87.

1-(5,8-Dihydroxy-3-nitro-2-naphthyl)-3-methoxypropanone (10d). A. Ring Opening with AcOH. Compound **9d** (0.164 g, 0.563 mmol) was mixed with glacial AcOH (25 mL) and refluxed for 1 h, with stirring. The AcOH was removed under reduced pressure, and the residual dark red solid was crystallized from EtOH/H_2O, giving **10d** as maroon needles (0.090 g, 55%): mp 210−212 °C; IR (KBr, cm^{-1}) 3367, 3291, 2968, 1717, 1604, 1490, 1331, 1298; ^{1}H NMR (acetone-d_6, δ ppm) 9.06 (s, 1 H), 8.96 (s, 1 H), 8.83 (s, 1 H), 8.13 (s, 1 H), 6.98 (d, J = 8.1 Hz, 1 H), 6.89 (d, J = 8.1 Hz, 1 H), 4.43 (s, 2 H), 4.24 (s, 2H), 3.44 (s, 3H); ^{13}C NMR (acetone-d_6, δ ppm) 204.6, 147.3, 146.4, 145.6, 127.7, 126.7, 125.0, 123.5, 120.6, 112.5, 109.9, 77.1, 58.5, 44.3; EI HRMS m/z (M^+) calcd 291.0743, found 291.0741. Anal. Calcd for $C_{14}H_{13}NO_6$: C, 57.73; H, 4.50; N, 4.81. Found: C, 57.78; H, 4.76; N, 4.73.

B. Ring Opening with TsOH. Compound **9d** (0.050 g, 0.017 mmol) was mixed with $CHCl_3$ (5 mL) and heated to reflux, with stirring. Next, TsOH·H_2O (1 mg, 0.005 mmol) was added, and the solution was refluxed for 90 min more, during which time a color change from orange to red occurred and a precipitate formed. The mixture was concentrated to half its original volume and cooled, and the solid was vacuum-filtered and vacuum-dried, giving **10d** as a red powder (0.049 g, 98%):

(16) Prepared from furfuryl alcohol, KOH, benzyltriethylammonium chloride, and MeI, in ether, stirred for 2 days, 60%.

mp 210−212 °C; the mixture melting point with material from part A showed no depression; the ^{1}H NMR spectrum was identical with that of the material obtained in part A.

***cis*-6a,11b-Dihydro-1,4-dihydroxy-6-nitrobenzo[*b*]naphtho[1,2-*d*]furan (13a).** Compound **3** (0.550 g, 3.07 mmol) was dissolved in benzo[*b*]furan (5.5 mL, used as received from Aldrich Chemical Co.) and stirred for 72 h in the dark. A black precipitate formed, and the mixture was poured into hexane (20 mL), with stirring, using another portion of hexane (20 mL) to aid in the transfer. The resulting solid was vacuum-filtered, dissolved in THF (27.5 mL), and cooled to 0 °C under N_2, and 10% Et_3N/THF (1 drop) was added with stirring, causing a color change from red to darker red. After 1 h of stirring at 0 °C, the THF was evaporated in a stream of N_2, and the residual dark red solid was purified by flash chromatography, eluting successively with 2:1 and 1:1 hexane/EtOAc. Band 2 was concentrated under reduced pressure, giving a red oil, which was recrystallized from EtOH/H_2O, giving **13a** as red needles (0.131 g, 14%): mp 188−190 °C; IR (KBr, cm^{-1}) 3504, 3358, 1638, 1492, 1476, 1269; ^{1}H NMR (acetone-d_6, δ ppm) 8.91 (bs, 1H), 8.58 (bs, 1 H), 8.21 (d, J = 1.5 Hz, 1 H), 7.50 (bd, J = 7.5, $w_{1/2}$ = 2.8 Hz, 1 H), 7.18 (dt, J = 1.5, 7.5, 7.5 Hz, 1 H), 7.05 (d, J = 8.7 Hz, 1 H), 6.96 (d, J = 8.7 Hz, 1 H), 6.89 (dt, J = 1.2, 7.5, 7.5 Hz, 1 H), 6.80 (bd, J = 7.5 Hz, $w_{1/2}$ = 2.2 Hz, 1 H), 6.37 (d, J = 9.3 Hz, 1 H), 5.03 (d, J = 9.3 Hz, $w_{1/2}$ = 3.3 Hz, 1 H); ^{13}C NMR (acetone-d_6, δ ppm) 159.1, 149.6, 149.4, 146.0, 129.0, 126.9, 125.9, 124.4, 121.3, 120.9, 117.9, 117.0, 116.6, 109.4, 78.4, 40.3; EI HRMS m/z (M$^+$) calcd 297.0637, found 297.0635. Anal. Calcd for $C_{16}H_{11}NO_5$: C, 64.65; H, 3.73; N, 4.71. Found: C, 64.46; H, 3.90; N, 4.58.

***cis*-6a,11b-Dihydro-1,4-dihydroxy-6-nitro-7*H*-benzo[*c*]carbazole and 6-Nitro-7*H*-benzo[*c*]carbazole-1,4-dione (13b and 14b).** Indole (0.261 g, 2.23 mmol) was dissolved in benzene (5 mL), and compound **3** (0.200 g, 1.12 mmol) was added with stirring; after 18 h, a brown precipitate formed. After the mixture was kept for 24 h, an orange paste developed, which was vacuum-filtered with the aid of benzene (10 mL). The solid was purified by flash chromatography, eluting successively with 2:1 and 1:1 hexane/EtOAc, giving two orange colored bands.

The solvent was removed from band 1 under reduced pressure, giving **14b** as an orange powder (0.047 g, 43%): mp 294−296 °C; IR (KBr, cm^{-1}) 1661, 1590, 1334; ^{1}H NMR (DMSO-d_6, δ ppm) 12.77 (s, 1 H), 9.16 (bd, J = 8.4 Hz, $w_{1/2}$ = 2.4 Hz, 1H), 8.74 (s, 1 H), 7.83 (dt, J = 0.9, 0.9, 8.4 Hz, 1 H), 7.63 (ddd, J = 1.2, 7.2, 8.4 Hz, 1 H), 7.36 (ddd, J = 1.2, 7.2, 8.4 Hz, 1 H), 7.20 (d, J = 10.2 Hz, 1 H), 7.14 (d, J = 10.2 Hz, 1 H); ^{13}C NMR, too insoluble; EI HRMS m/z (M$^+$) calcd 292.0484, found 292.0500. Anal. Calcd for $C_{16}H_8N_2O_4$: C, 65.75; H, 2.76; N, 9.59. Found: C, 66.02; H, 2.80; N, 9.41.

The solvent was removed from band 2 under reduced pressure, and the residual solid was crystallized from acetone/H_2O, giving **13b** as maroon needles (0.171 g, 52%): mp 190 °C dec; IR (KBr, cm^{-1}) 3407, 1634, 1489, 1275; ^{1}H NMR (acetone-d_6, δ ppm) 8.80 (bs, 1 H), 8.49 (bs, 1 H), 8.21 (d, J = 2.4 Hz, 1 H), 7.07 (d, J = 8.7 Hz, 1 H), 6.96−6.90 (m, 2 H), 6.79 (d, J = 9.0 Hz, 1 H), 6.68 (d, J = 7.8 Hz, 1 H), 6.52 (dt, J = 0.9, 7.5, 7.5 Hz, 1 H), 5.56 (bs, 1 H), 5.38 (dd, J = 2.4, 10.5 Hz, 1 H), 5.17 (d, J = 10.5 Hz, 1 H); ^{13}C NMR (acetone-d_6, δ ppm) 150.0, 149.4, 147.7, 146.0, 130.3, 127.7, 127.2, 124.3, 122.5, 121.4, 117.9, 115.9, 115.1, 108.9, 57.0, 41.6; EI HRMS m/z (M$^+$) calcd 296.0797, found 296.0794. Anal. Calcd for $C_{16}H_{12}N_2O_4$: C, 64.86; H, 4.08; N, 9.46. Found: C, 65.06; H, 4.26; N, 9.22.

***cis*-6a,11b-Dihydro-1,4-dihydroxy-7-methyl-6-nitro-7*H*-benzo[*c*]carbazole (13c).** 1-Methylindole[17] (0.293 g, 2.23 mmol) was dissolved in benzene (5 mL), and compound **3** (0.200 g, 1.12 mmol) was added, with stirring. After 18 h of stirring, a yellow-brown precipitate formed, which was vacuum-filtered and purified by flash chromatography, eluting with 1:1 hexane/EtOAc. The solvent was removed from the second band under reduced pressure, giving a red oil. Addition of CH_2Cl_2 (5 mL) caused **13c** to precipitate as a red microcrystalline solid (0.197 g, 57%): mp 195−196 °C dec; IR (KBr, cm^{-1}) 3484, 3388, 1632, 1483, 1320, 1267; ^{1}H NMR (acetone-d_6, δ ppm) 8.70 (bs, 1 H), 8.43 (bs, 1 H), 8.04 (d, J = 0.6 Hz, 1 H), 7.10 (dt, J = 1.2, 1.2, 7.8 Hz, 1 H), 7.08−7.02 (m, 1 H), 7.00 (d, J = 8.7 Hz, 1 H), 6.76 (d, J = 8.7 Hz, 1 H), 6.629 (dt, J = 0.9, 7.5, 7.5 Hz, 1H), 6.625 (dd, J = 0.9, 7.8 Hz, 1H), 5.40 (d, J = 10.5 Hz, 1H), 5.22 (dd, J = 0.6, 10.5 Hz, 1H), 3.07 (s, 3H); ^{13}C NMR (acetone-d_6, δ ppm) 151.6, 149.7, 148.0, 146.7, 132.7, 128.1, 125.7, 125.1, 122.5, 120.8, 119.2, 115.9, 115.0, 110.5, 63.0, 41.9, 38.7; EI HRMS m/z (M$^+$) calcd 310.0953, found 310.0943. Anal. Calcd for $C_{17}H_{14}N_2O_4$: C, 65.80; H, 4.55; N, 9.03. Found: C, 65.80; H, 4.70; N, 8.86.

***cis*-10-Bromo-6a,11b-dihydro-1,4-dihydroxy-6-nitro-7*H*-benzo[*c*]carbazole and 10-Bromo-6-nitro-7*H*-benzo[*c*]carbazole-1,4-dione (13d and 14d).** 5-Bromoindole (0.438 g, 2.23 mmol) was dissolved in benzene (5 mL), and compound **3** (0.200 g, 1.12 mmol) was added with stirring. After 18 h of stirring, a black precipitate developed, which was vacuum-filtered and washed with benzene (5 mL) and then triturated with boiling H_2O (5 mL). The solid mixture was extracted with acetone (5 mL) and filtered. The solid was recrystallized from acetone, giving **14d** as dark red needles (0.010 g, 7%): mp 350−351 °C; IR (KBr, cm^{-1}) 3287, 1717, 1654, 1598, 1472, 1334; ^{1}H NMR (acetone-d_6, δ ppm) 12.29 (s, 1 H), 9.64 (d, J = 1.5 Hz, 1 H), 9.05 (s, 1 H), 7.91 (d, J = 8.1 Hz, 1 H), 7.84 (dd, J = 1.8, 8.4 Hz, 1 H), 7.29 (d, J = 10.2 Hz, 1 H), 7.21 (d, J = 10.2 Hz, 1 H); ^{13}C NMR, too insoluble; EI HRMS m/z (M$^+$) calcd 369.9589, found 369.9590. Anal. Calcd for $C_{16}H_7BrN_2O_4$: C, 51.78; H, 1.90; N, 7.55. Found: C, 51.32; H, 1.48; N, 7.40.

The filtrate from the acetone extraction was concentrated under vacuum, giving a dark red oil, which was precipitated as a dark red solid by addition of CH_2Cl_2 (5 mL). This solid was redissolved in a minimum amount of acetone and purified by flash chromatography, giving **13d** as a red oil. Addition of CH_2Cl_2 (5 mL) caused precipitation of **13d** as a red powder (0.109 g, 26%): mp 180−185 °C dec; IR (KBr, cm^{-1}) 3395, 1698, 1490, 1262; ^{1}H NMR (acetone-d_6, δ ppm) 8.92 (s, 1 H), 8.54 (s, 1 H), 8.23 (d, J = 0.9 Hz, 1 H), 7.09 (d, J = 8.7 Hz, 1 H), 7.08 (ddd, J = 1.2, 2.1, 8.4 Hz, 1 H), 7.05−7.02 (m, 1 H), 6.82 (d, J = 9.0 Hz, 1 H), 6.64 (d, J = 8.4 Hz, 1 H), 5.79 (bs, 1 H), 5.44 (ddd, J = 0.9, 2.8, 10.5 Hz, 1 H), 5.22 (dt, J = 0.9, 0.9, 10.8 Hz, 1 H); ^{13}C NMR (acetone-d_6, δ ppm) 150.3, 148.8, 147.5, 145.5, 133.3, 130.4, 127.2, 127.1, 121.7, 121.6, 115.8, 115.5, 110.6, 108.7, 57.2, 41.5; EI HRMS m/z (M$^+$) calcd 373.9902, found 373.9892. Anal. Calcd for $C_{16}H_{11}BrN_2O_4$: C, 51.22; H, 2.96; N, 7.47. Found: C, 51.41; H, 2.84; 7.40.

***cis*-6a,11b-Dihydro-1,4-dihydroxy-10-methoxy-6-nitro-7*H*-benzo[*c*]carbazole (13e).** 5-Methoxyindole[18] (0.329 g, 2.23 mmol) was dissolved in benzene (5 mL), and compound **3** (0.200 g, 1.12 mmol) was added with stirring. After 18 h of stirring, a dark precipitate developed, which was vacuum-filtered and purified by flash chromatography, eluting successively with 2:1 and 1:1 hexane/EtOAc. The second band was concentrated under reduced pressure, giving a red oil. CH_2Cl_2 (5 mL) was added to the oil with stirring, precipitating **13e** as a red powder (0.192 g, 53%): mp 211−212 °C dec; IR (KBr, cm^{-1}) 3398, 2943, 1636, 1490, 1323, 1274; ^{1}H NMR (acetone-d_6, δ ppm) 8.83 (s, exchanges with D_2O, 1 H), 8.43 (s, exchanges with D_2O, 1 H), 8.20 (s, 1 H), 7.07 (d, J = 8.7 Hz, 1 H), 6.79 (d, J = 8.7 Hz, 1 H), 6.63−6.53 (m, 3 H), 5.36 (d, J = 9.9 Hz, 1 H), 5.23 (s, exchanges with D_2O, 1 H), 5.15 (d, J = 9.9 Hz, 1 H), 3.89 (s, 3 H); ^{13}C NMR (DMSO-d_6, δ ppm) 152.7, 150.4, 147.5, 146.1, 143.5, 132.6, 127.4, 122.3, 122.2, 115.7, 115.5, 112.5, 111.7, 109.9, 56.9, 55.9, 42.0; EI HRMS m/z (M$^+$) calcd 326.0903, found 326.0905. Anal. Calcd for $C_{17}H_{14}N_2O_5$: C, 62.57; H, 4.32; N, 8.58. Found: C, 62.66; H, 4.52; N, 8.39.

***cis*-1,2,3a,9b-Tetrahydro-6,9-dihydroxy-4-nitronaphtho-[2,1-*b*]furan and *cis*-2,3,3a,8a-Tetrahydro-5-hydroxy-4-(2-nitrovinyl)furo[2,3-*d*]benzo[*b*]furan (16a and 17a). A.**

(17) Heaney, H.; Ley, S. V. In *Organic Syntheses*; Noland, W. E., Ed.; John Wiley and Sons: New York, 1988; Collect. Vol. VI, pp 104−105.

(18) Batcho, A. D.; Leimgruber, W. In *Organic Syntheses*; Freeman, J. P., Ed.; John Wiley and Sons: New York, 1990; Collect. Vol. VII, pp 34−41.

Reaction in Neat Heterocycle. Compound **3** (0.200 g, 1.12 mmol) was dissolved in 2,3-dihydrofuran (7.5 mL), with stirring. An orange precipitate developed after 2 h, and the mixture was kept for an additional 16 h. The dihydrofuran was removed under reduced pressure, and the residual solid was separated by flash chromatography, eluting successively with 3:2 and 1:1 hexane/EtOAc, giving two major orange colored bands.

The solvent containing the second band was removed under reduced pressure, giving **16a** as an orange-red powder (0.086 g, 31%): mp 216 °C dec; IR (KBr, cm^{-1}) 3491, 3276, 1640, 1490, 1266; ^1H NMR (300 MHz, DMSO-d_6, δ ppm) 9.88 (bs, 1 H), 9.25 (bs, 1 H), 8.10 (d, J = 1.8 Hz, 1 H), 6.86 (d, J = 8.7 Hz, 1 H), 6.67 (d, J = 8.7 Hz, 1 H), 5.28 (d, J = 9.9 Hz, 1 H), 3.85 (dt, J = 8.4, 8.4, 9.9 Hz, 1 H), 3.67−3.52 (m, 2 H), 2.63 (dddd, J = 4.5, 6.0, 8.4, 12.6 Hz, 1 H), 1.73 (dq, J = 7.5, 7.5, 7.5, 12.3 Hz, 1 H); ^{13}C NMR (DMSO-d_6, δ ppm) 150.3, 147.6, 144.6, 127.0, 125.2, 121.5, 115.1, 114.9, 71.5, 64.8, 38.7, 35.8; EI HRMS m/z (M^+) calcd 249.0637, found 249.0634. Anal. Calcd for $C_{12}H_{11}NO_5$: C, 57.83; H, 4.45; N, 5.62. Found: C, 57.72; H, 4.61; N, 5.62.

The solvent containing the first band was removed under reduced pressure, giving **17a** as a yellow powder (0.151 g, 54%): mp 222−223 °C dec; IR (KBr, cm^{-1}) 3258, 2884, 1514, 1496, 1338, 1247; ^1H NMR (acetone-d_6, δ ppm) 9.45 (bs, 1 H), 8.20 (d, J = 13.5 Hz, 1 H), 8.14 (d, J = 13.5 Hz, 1H), 6.89 (d, J = 8.7 Hz, 1 H), 6.81 (d, J = 8.7 Hz, 1 H), 6.40 (d, J = 5.7 Hz, 1 H), 4.41 (dd, J = 6.0, 9.0 Hz, 1 H), 4.10 (ddd, J = 0.9, 7.8, 8.7 Hz, 1 H), 3.61 (ddd, J = 5.1, 8.7, 12.0 Hz, 1 H), 2.48 (ddt, J = 7.8, 9.3, 12.0, 12.0 Hz, 1 H), 2.13−2.04 (m, 1 H); ^{13}C NMR (DMSO-d_6, δ ppm) 154.0, 152.2, 139.4, 133.0, 130.3, 116.3, 114.0, 113.9, 111.7, 67.0, 46.5, 33.1; EI HRMS m/z (M^+) calcd 249.0637, found 249.0634. Anal. Calcd for $C_{12}H_{11}NO_5$: C, 57.83; H, 4.45; N, 5.62. Found: C, 57.84; H, 4.38; N, 5.44.

B. Reaction in Benzene. Compound **3** (0.200 g, 1.12 mmol) was partially dissolved in benzene (5 mL), and 2,3-dihydrofuran (0.086 g, 1.23 mmol) was added with stirring. After 18 h of stirring, an orange precipitate formed. The solvent was removed under reduced pressure, and the residual solid was separated as in part A. Compound **16a** was obtained as an orange-red powder (0.066 g, 24%): mp 215 °C dec; the mixture melting point with **16a** from part A showed no depression; the ^1H NMR spectrum was identical with that of the material obtained in part A. Compound **17a** was obtained as a dark yellow solid, which was crystallized from THF/cyclohexane, giving **17a** as a yellow powder (0.066 g, 24%): mp 222−223 °C dec; the mixture melting point with **17a** from part A showed no depression; the ^1H NMR spectrum was identical with that of the material obtained in part A.

***cis*-3,4,4a,9a-Tetrahydro-6-hydroxy-5-(2-nitrovinyl)-2*H*-pyrano[2,3-*b*]benzofuran (17b).** Compound **3** (0.200 g, 1.12 mmol) was dissolved in 3,4-dihydro-2*H*-pyran (7.5 mL), and the solution was refluxed for 2 h with stirring. Unreacted 3,4-dihydro-2*H*-pyran was removed under reduced pressure, leaving a dark red glass. The glass was dissolved in a minimum amount of CH_2Cl_2 and eluted through a short plug of silica gel. The CH_2Cl_2 solvent was removed under reduced pressure, giving a red glass. Addition of benzene (3 mL) caused **17b** to separate as yellow needles (0.061 g, 21%): mp 198−199 °C; IR (KBr, cm^{-1}) 3334, 3152, 2933, 1495, 1442, 1341; ^1H NMR (acetone-d_6, δ ppm) 9.46 (bs, 1 H), 8.18 (d, J = 13.5 Hz, 1 H), 8.01 (d, J = 13.5 Hz, 1 H), 6.85 (d, J = 8.7 Hz, 1 H), 6.82 (d, J = 8.7 Hz, 1 H), 5.87 (d, J = 6.0 Hz, 1 H), 3.84 (dd, J = 3.6, 8.1 Hz, 2H), 3.55 (dt, J = 6.6, 6.6, 9.6 Hz, 1 H), 2.27−2.15 (m, 1 H), 1.83−1.38 (m, 3 H); ^{13}C NMR (acetone-d_6, δ ppm) 152.4, 150.1, 139.6, 134.9, 132.1, 115.0, 114.1, 113.9, 104.8, 61.1, 37.3, 25.9, 21.0; EI HRMS m/z (M^+) calcd 263.0794, found 263.0783. Anal. Calcd for $C_{13}H_{13}NO_5$: C, 59.31; H, 4.98; N, 5.32. Found: C, 59.35; H, 5.10; N, 5.29.

General Procedure Dehydrogenation of 9 and 13 to 18 and 14. Compound **9** or **13** was mixed with activated MnO_2 (10 equiv) and benzene and refluxed for 2 h with stirring, using a Dean−Stark trap to remove H_2O. The mixture was then cooled to room temperature and vacuum-filtered through a bed of Celite. The Celite was washed with CH_2Cl_2, unless otherwise specified, until the washings were colorless. The filtrate and washings were combined, and the solvents removed under reduced pressure, giving **18** or **13**.

4-Nitronaphtho[1,2-*b*]furan-6,9-dione (18a). Compound **18a** was obtained as a yellow powder (0.105 g, 53%): mp 200−201 °C; IR (KBr, cm^{-1}) 3159, 1676, 1603, 1515, 1302; ^1H NMR ($CDCl_3$, δ ppm) 8.93 (s, 1 H), 8.23 (d, J = 2.4 Hz, 1 H), 7.68 (d, J = 1.8 Hz, 1 H), 7.15 (d, J = 10.5 Hz, 1 H), 7.10 (d, J = 10.5 Hz, 1 H); ^{13}C NMR (DMSO-d_6, δ ppm) 183.5, 183.0, 156.0, 152.8, 142.6, 140.0, 138.7, 129.1, 128.4, 120.7, 117.1, 107.3; EI HRMS m/z (M^+) calcd 243.0168, found 243.0173. Anal. Calcd for $C_{12}H_5NO_5$: C, 59.27; H, 2.07; N, 5.76. Found: C, 59.30; H, 1.99; N, 5.79.

2-Methyl-4-nitronaphtho[1,2-*b*]furan-6,9-dione (18b). Compound **8b** (0.630 g, 2.41 mmol) was converted to **9b** in situ by dissolving in benzene (160 mL), adding 10% Et_3N/THF (1 drop), and stirring for 5 min. The general procedure was then followed, giving **18b** as yellow needles (0.335 g, 54%): mp 201−202 °C dec; IR (KBr, cm^{-1}) 3101, 1673, 1584, 1530, 1335, 1299; ^1H NMR (acetone-d_6, δ ppm) 8.76 (s, 1 H), 7.34 (q, J = 1.2 Hz, 1 H), 7.18 (d, J = 10.5 Hz, 1 H), 7.12 (d, J = 10.5 Hz, 1 H), 2.72 (d, J = 1.2 Hz, 3 H); ^{13}C NMR (DMSO-d_6, δ ppm) 183.6, 183.2, 167.6, 152.8, 141.4, 140.0, 138.9, 131.0, 127.3, 119.7, 117.1, 104.1, 15.0; EI HRMS m/z (M^+) calcd 257.0324, found 257.0319. Anal. Calcd for $C_{13}H_7NO_5$: C, 60.71; H, 2.74; N, 5.45. Found: C, 60.67; H, 2.73; N, 5.22.

2-(Methoxymethyl)-4-nitronaphtho[1,2-*b*]furan-6,9-dione (18c). The reaction mixture was refluxed for 30 min. Washing of the Celite filter was accomplished with benzene and $CHCl_3$ successively. Evaporation under reduced pressure gave a yellow oil, which precipitated **18c** upon addition of MeOH. Recrystallization from MeOH gave **18c** as golden needles (0.035 g, 32%): mp 121−122 °C; IR (KBr, cm^{-1}) 3064, 1676, 1606, 1522, 1340, 1306; ^1H NMR ($CDCl_3$, δ ppm) 8.90 (s, 1 H), 7.57 (t, J = 0.6 Hz, 1 H), 7.12 (d, J = 10.5 Hz, 1 H), 7.05 (d, J = 10.5 Hz, 1 H), 4.77 (d, J = 0.6 Hz, 2 H), 3.56 (s, 3 H); ^{13}C NMR ($CDCl_3$, δ ppm) 182.7, 182.6, 165.1, 153.1, 142.5, 139.1, 138.6, 130.2, 127.9, 119.8, 118.0, 105.0, 67.0, 59.4; EI HRMS m/z (M^+) calcd 287.0430, found 287.0424. Anal. Calcd for $C_{14}H_9NO_6$: C, 58.54; H, 3.16; N, 4.88. Found: C, 58.55; H, 3.10; N, 4.69.

6-Nitrobenzo[*b*]naphtho[1,2-*d*]furan-1,4-dione (14a). The reaction mixture was refluxed for 2.5 h. Compound **14a** was obtained as a yellow solid, which was triturated with CH_2Cl_2, giving **14a** as a yellow powder (0.021 g, 58%): mp 261−263 °C; IR (KBr, cm^{-1}) 3084, 1676, 1618, 1531, 1302, 1273; ^1H NMR ($CDCl_3$, δ ppm) 8.87 (s, 1 H), 8.63 (ddd, J = 0.6, 1.2, 8.1 Hz, 1 H), 7.87 (ddd, J = 0.9, 1.2, 8.7 Hz, 1 H), 7.76 (ddd, J = 1.5, 7.2, 8.3 Hz, 1 H), 7.56 (ddd, J = 1.2, 7.2, 8.2 Hz, 1 H), 7.16 (d, J = 10.2 Hz, 1 H), 7.11 (d, J = 10.2 Hz, 1 H); ^{13}C NMR, too insoluble; EI HRMS m/z (M^+) calcd 293.0324, found 293.0338. Anal. Calcd for $C_{16}H_7NO_5$: C, 65.54; H, 2.41; N, 4.78. Found: C, 65.61; H, 2.24; N, 4.68.

6-Nitro-7*H*-benzo[*c*]carbazole-1,4-dione (14b). The reaction mixture was refluxed for 3 h. Washing of the Celite filter was accomplished with CH_2Cl_2 and acetone successively. After evaporation, the residual solid was crystallized from acetone, giving **14b** as red needles (0.056 g, 63%): mp 296−297 °C; the mixture melting point with **14b** prepared previously showed no depression; the ^1H NMR spectrum was identical with that of **14b** prepared previously.

7-Methyl-6-nitro-7*H*-benzo[*c*]carbazole-1,4-dione (14c). The reaction mixture was refluxed for 3 h. Washing of the Celite filter was accomplished with acetone. After evaporation, the residual solid was crystallized from acetone, giving **14c** as maroon needles (0.060 g, 41%): mp 256−258 °C; IR (KBr, cm^{-1}) 3073, 1656, 1585, 1514, 1342; ^1H NMR ($CDCl_3$, δ ppm) 9.42 (ddd, J = 0.6, 0.9, 8.4 Hz, 1 H), 8.65 (s, 1H), 7.73 (ddd, J = 1.2, 7.2, 8.4 Hz, 1 H), 7.56 (ddd, J = 1.2, 1.2, 8.4 Hz, 1 H), 7.47 (ddd, J = 1.2, 7.2, 8.4 Hz, 1 H), 7.12 (d, J = 10.2 Hz, 1 H), 7.05 (d, J = 10.2 Hz, 1 H), 3.84 (s, 3H); ^{13}C NMR, too insoluble; EI HRMS m/z (M^+) calcd 306.0641, found 306.0642.

Anal. Calcd for $C_{17}H_{10}N_2O_4$: C, 66.67; H, 3.29; N, 9.15. Found: C, 66.73; H, 3.28; N, 9.22.

10-Bromo-6-nitro-7*H*-benzo[*c*]carbazole-1,4-dione (14d). The reaction mixture was refluxed for 3 h. Washing of the Celite filter was accomplished with acetone. After evaporation, the residual solid was crystallized from acetone, giving **14d** as red needles (0.049 g, 33%): mp 350−351 °C; the mixture melting point with **14d** prepared previously showed no depression; the ^{1}H NMR spectrum was identical to that of **14d** prepared previously.

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Supporting Information Available: X-ray crystallographic data for **16a**; detailed coupling constant analyses for **8b**−**d** (37 pages). This material is contained in libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

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