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Cerium salts in the oxidative free radical reactions between 2-amino-1,4-naphthoquinones and β-dicarbonyl compounds

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Abstract—The oxidative free radical reactions between 2-amino-1,4-naphthoquinones and β-dicarbonyl compounds mediated by cerium(IV) salts are described. In contrast to those mediated by manganese(III) acetate, the cerium(IV) mediated free radical reaction provides a novel method for the synthesis of benzo[*f*]indole-4,9-diones exclusively. This high selectivity is due to the strong oxaphilicity of the cerium salts. © 2002 Elsevier Science Ltd. All rights reserved.

1. Introduction

Free radical reactions have become increasingly important in organic synthesis in the last two decades.[1] Compounds containing the quinone group represent an important class of biologically active molecules that are widespread in nature.[2,3] The oxidative addition of electrophilic carbon-centered radicals to alkenes mediated by metal salts has received considerable attention in the construction of carbon–carbon bonds. Among these, manganese(III) acetate and cerium(IV) ammonium nitrate have been used most efficiently.[1d–f,4,5] These reactions can be performed

Table 1. Free radical reactions of 2-amino-1,4-naphthoquinones

Entry	Quinone	Cerium(IV) salt	β-Dicarbonyl compound	Reaction time	Product (yield (%))
1	**1a**: R=H	CAN	**2a**: R^1=Me, R^2=Me	40 min	**3a** (76)
2		$Ce(SO_4)_2$		3.5 h	**3a** (77)
3	**1a**: R=H	CAN	**2b**: R^1=Et, R^2=Et	40 min	**3b** (53)
4		$Ce(SO_4)_2$		3.5 h	**3b** (67)
5	**1a**: R=H	CAN	**2c**: R^1=*i*-Pr, R^2=*i*-Pr	40 min	**3c** (39)
6		$Ce(SO_4)_2$		3.5 h	**3c** (62)
7	**1a**: R=H	$Ce(SO_4)_2$	**2d**: R^1=Me, R^2=Ph	3 h	**3d** (64)
8	**1a**: R=H	$Ce(SO_4)_2$	**2e**: R^1=Me, R^2=*t*-Bu	3.5 h	**3e** (73)
9	**1a**: R=H	$Ce(SO_4)_2$	**2f**: R^1=Me, R^2=*i*-Bu	3.5 h	**3f** (57), **4a** (18)
10	**1b**: R=*p*-Tolyl	$Ce(SO_4)_2$	**2a**: R^1=Me, R^2=Me	3.5 h	**3g** (61)
11	**1b**: R=*p*-Tolyl	$Ce(SO_4)_2$	**2b**: R^1=Et, R^2=Et	3.5 h	**3h** (57)
12	**1c**: R=*p*-Tolyl	$Ce(SO_4)_2$	**2d**: R^1=Me, R^2=Ph	3.5 h	**3i** (60)
13	**1a**: R=H	CAN	**2g**: R^1=Me, R^2=OEt	30 min	**3j** (59)
14		$Ce(SO_4)_2$		3 h	**3j** (76)
15	**1b**: R=*p*-Tolyl	CAN	**2g**: R^1=Me, R^2=OEt	40 min	**3k** (61)
16		$Ce(SO_4)_2$		3 h	**3k** (69)
17	**1c**: R=Pr	$Ce(SO_4)_2$	**2g**: R^1=Me, R^2=OEt	3 h	**3l** (73)
18	**1d**: R=*i*-Pr	$Ce(SO_4)_2$	**2g**: R^1=Me, R^2=OEt	3 h	**3m** (61)
19	**1a**: R=H	$Ce(SO_4)_2$	**2h**: R^1=Pr, R^2=OEt	3 h	**3n** (64)
20	**1a**: R=H	$Ce(SO_4)_2$	**2i**: R^1=*i*-Pr, R^2=OMe	3 h	**3o** (58)
21	**1a**: R=H	$Ce(SO_4)_2$	**2j**: R^1=Ph, R^2=OEt	3 h	**3p** (52)
22	**1a**: R=H	$Ce(SO_4)_2$	**2k**: R^1=$MeOCH_2$, R^2=OMe	3 h	**3q** (66)
23	**1b**: R=*p*-Tolyl	$Ce(SO_4)_2$	**2h**: R^1=Pr, R^2=OEt	4.5 h	**3r** (45)
24	**1b**: R=*p*-Tolyl	$Ce(SO_4)_2$	**2i**: R^1=*i*-Pr, R^2=OMe	5.5 h	**3s** (44)
25	**1b**: R=*p*-Tolyl	$Ce(SO_4)_2$	**2j**: R^1=Ph, R^2=OEt	6.5 h	**3t** (23)
26	**21a**: Ar=Ph	$Ce(SO_4)_2$	**2a**: R^1=Me, R^2=Me	5 h	**22a** (48)
27	**21a**: Ar=Ph	$Ce(SO_4)_2$	**2d**: R^1=Me, R^2=Ph	3.5 h	**22b** (31)
28	**21a**: Ar=Ph	$Ce(SO_4)_2$	**2g**: R^1=Me, R^2=OEt	5 h	**22c** (52)
29	**21a**: Ar=Ph	$Ce(SO_4)_2$	**2h**: R^1=Pr, R^2=OEt	5 h	**22d** (37)

Keywords: cerium salts; free radical; 2-amino-1,4-naphthoquinones; β-dicarbonyl compounds.

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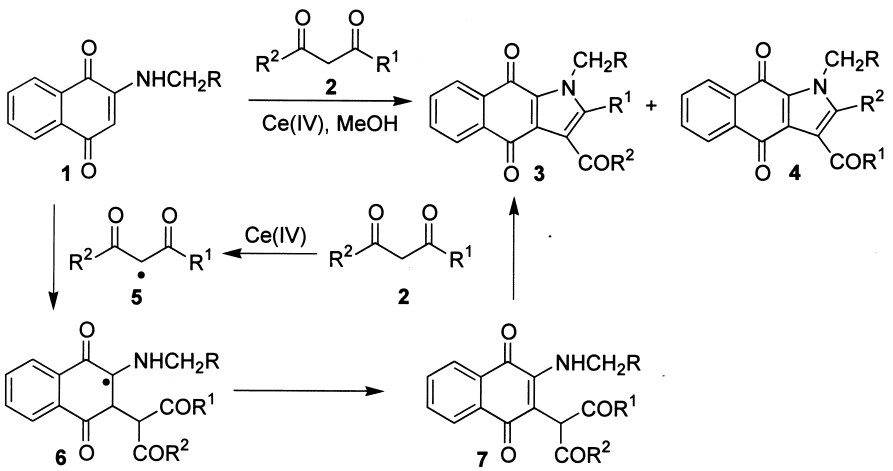


Scheme 1.

intermolecularly or intramolecularly. The free radical reaction of 1,4-naphthoquinone derivatives has been reported.[5c–i,6] In this report, we wish to describe our results on the reactions between 2-amino-1,4-naphthoquinones and β-dicarbonyl compounds via a cerium(IV) mediated oxidative free radical reaction.

2. Results and discussion

We began our studies of this free radical reaction with 2-(alkylamino)-1,4-naphthoquinone **1** and 1,3-diones. When 2-(methylamino)-1,4-naphthoquinone (**1a**) was treated with 2,4-pentanedione (**2a**) and CAN in methanol at room temperature, **3a** was obtained in 76% yield (Table 1, entry 1). A possible mechanism for this reaction is shown in Scheme 1. Initiation occurs with the cerium(IV) oxidation of **2a** to produce radical **5a** (R^1=R^2=Me). This radical intermediate **5a** undergoes intermolecular addition to the quinone ring followed by oxidation to give **7a**, which undergoes a further condensation reaction to produce **3a**. The results of this reaction are summarized in Table 1 (entries 1–12). With cerium(IV) sulfate, this reaction proceeds at a much slower reaction rate but it gives better results. Steric hindrance plays an important role in the final outcome of this reaction. In most cases, the condensation reaction occurs on the less hindered carbonyl group of the 1,3-diones (entries 7–9)[7] and the reaction yield decreases as the size of R, R^1 and R^2 increases.

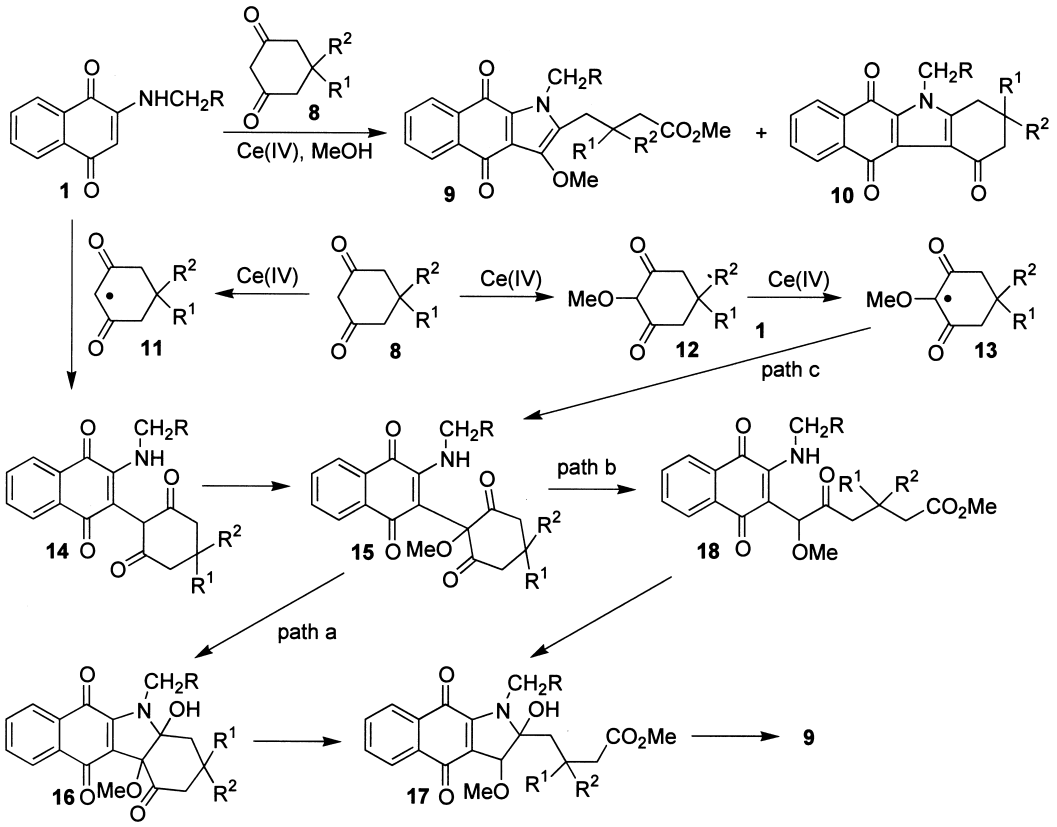
The reaction of 2-(methylamino)-1,4-naphthoquinone (**1a**) with 1,3-cyclohexanedione **8a** (R^1=R^2=Me) and cerium(IV) sulfate in methanol at room temperature gave **9a** in 18% yield and no trace of desired product **10** could be found (Table 2, entry 2). A better result (42% yield) was obtained when CAN was used. Dione **12a**[8] generated from the CAN oxidation of dione **8a** was also produced in 20% yield. Indole **9a** was formed presumably via the reaction routes outlined in Scheme 2. Oxidation of **8a** by CAN produces radical **11a**, which undergoes intermolecular addition to the quinone followed by oxidation to give **14a**. It undergoes further oxidation to produce **15a**. Quinone **15a** undergoes either addition reaction to give **16a**, followed by retro Claisen condensation and dehydration to produce **9a** (path a) or retro Claisen condensation followed by addition and dehydration to produce **9a** (path b).[9] Since dione **12a** is also produced, quinone **15a** may also be produced from the intermolecular addition of radical intermediate **13a** generated from the CAN oxidation of **12a** (path c). To test this possible reaction route, quinone **1a** was treated with **12a** and CAN under similar reaction conditions and no desired product **9a** could be obtained. Based on this result, we believe that path c is not the reaction route for the generation of **9a**. Other 1,3-cyclohexanediones **8** behaved similarly giving the corresponding products **9** (Table 2).

Previously, we reported that the manganese(III) acetate mediated reaction between 2-(alkylamino)-1,4-naphthoquinones **1** and β-keto esters gave **3**, **19** and **20** (Eq. (1)).[5h] The product distributions are highly dependent on the size of substituents on **1** and the β-keto esters used. Treatment of 2-(methylamino)-1,4-naphthoquinone (**1a**) with ethyl acetoacetate (**2g**) and CAN gave indole **3j** exclusively in 59% yield. With cerium(IV) sulfate, the reaction yield of **3j** can be improved to 76% (Table 1, entries 13, 14). Indole **3j** was formed via a similar reaction route as shown in Scheme 1. The effect of substituents was also studied by varying the size of substituents on **1** and the β-keto esters. The reaction yield decreases as the size of R and R^1 increases. As illustrated in Table 1 (entries 13–25), in all cases, indole **3** is

Table 2. Free radical reactions between 2-amino-1,4-naphthoquinone **1** and 1,3-cyclohexanedione **8**

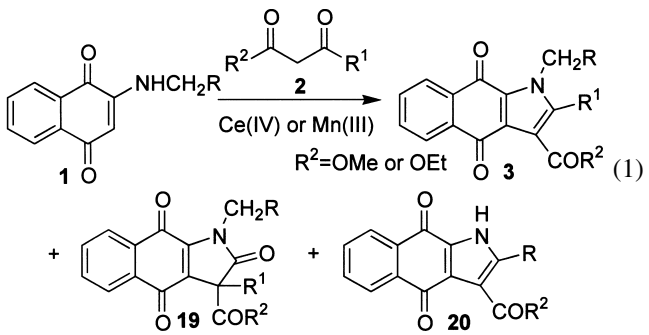
Entry	Quinone	Cerium(IV) salt	β-Dicarbonyl compound	Reaction time (h)	Product (yield (%))	
1	**1a**: R=H	CAN	**8a**: R^1=Me, R^2=Me	3	**9a** (42)	**12a** (20)[a]
2		$Ce(SO_4)_2$		5	**9a** (18)	
3	**1a**: R=H	CAN	**8b**: R^1=Me, R^2=H	3	**9b** (42)	**12b** (19)[a]
4	**1a**: R=H	CAN	**8c**: R^1=Ph, R^2=H	3	**9c** (25)	**12c** (21)[a]
5	**1a**: R=H	CAN	**8d**: R^1=H, R^2=H	3	**9d** (29)	**12d** (20)[a]

[a] The reaction yield of **12** is based on starting **8** used.



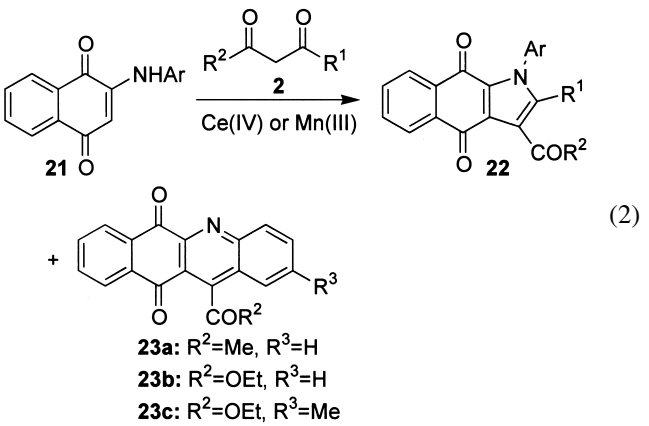
Scheme 2.

the only product even with *N*-benzyl substituted 1,4-naphthoquinone **1b** and ethyl benzoylacetate (**2j**) (entry 25). In this case, **20a** (R=*p*-tolyl, R^2=OEt) was obtained as the only product by using manganese(III) acetate as oxidant.[5h]



(1)

Manganese(III) acetate mediated free radical reactions between 2-(anilino)-1,4-naphthoquinone **21** and β-dicarbonyl compounds produced **22** and **23** (Eq. (2)).[5h] In all cases, acridine **23** is the major product, which is derived from the consecutive addition cyclization of radical intermediate generated from the manganese(III) oxidation. We have continued to study this oxidative free radical reaction with cerium(IV) sulfate. When 2-(anilino)-1,4-naphthoquinone (**21a**) was treated with 2,4-pentanedione (**2a**) and cerium(IV) sulfate, indole **22a** was obtained as the only product in 48% yield and no trace of **23a** could be isolated (Table 1, entry 26). It was generated via a similar reaction route as shown in Scheme 1. With other β-dicarbonyl compounds, it behaved similarly (even with ethyl butyryl acetate (**2h**), **23b** was the only product when this reaction was performed with manganese(III) acetate), giving the corresponding **22** as the only product (Table 1, entries 27–29).



(2)

This different reaction behavior of intermediate **7** can be ascribed to the strong oxaphilicity of cerium salt, which enhances the condensation rate of **7**.[10] To test this hypothesis, we also performed this oxidative free radical reaction with Mn(III)–Ce(III) systems. When 2-(ethylamino)-1,4-naphthoquinone (**1e**) was treated with methyl 4-methoxyacetoacetate (**2k**), manganese(III) acetate and cerium(III) nitrate in acetic acid at room temperature, **3u** and **19a** were obtained in 63 and 6% yields, respectively (Table 3, entry 2). Other examples were also shown in Table 3. In all cases, the ratios of **3**/**19** and **22**/**23** increase as the cerium(III) nitrate is added. This result demonstrates that the condensation rate of **7** is enhanced by the addition of cerium salt.

Table 3. Effect of cerium(III) salt in manganese(III)-based oxidative free radical reactions

Entry	Quinone	Cerium(III) salt	β-Keto ester	Product (yield (%))	
1	**1e**: R=Me	–	**2k**: R^1=$MeOCH_2$, R^2=OMe	**3u** (22)	**19a** (57)[11]
2	**1e**: R=Me	$Ce(NO_3)_3$	**2k**: R^1=$MeOCH_2$, R^2=OMe	**3u** (63)	**19a** (6)
3	**1e**: R=Me	–	**2l**: R^1=$ClCH_2$, R^2=OEt	**3v** (12)	**19b** (59)[11]
4	**1e**: R=Me	$Ce(NO_3)_3$	**2l**: R^1=$ClCH_2$, R^2=OEt	**3v** (54)	**19b** (22)
5	**1e**: R=Me	–	**2h**: R^1=Pr, R^2=OEt	**3w** (35)	**19c** (35)[11]
6	**1e**: R=Me	$Ce(NO_3)_3$	**2h**: R^1=Pr, R^2=OEt	**3w** (72)	**19c** (trace)
7	**21a**: Ar=Ph	–	**2h**: R^1=Pr, R^2=OEt	**22d** (0)	**23b** (54)[11]
8	**21a**: Ar=Ph	$Ce(NO_3)_3$	**2h**: R^1=Pr, R^2=OEt	**22d** (23)	**23b** (22)
9	**21b**: Ar=*p*-Tolyl	–	**2g**: R^1=Me, R^2=OEt	**22e** (7)	**23c** (45)[11]
10	**21b**: Ar=*p*-Tolyl	$Ce(NO_3)_3$	**2g**: R^1=Me, R^2=OEt	**22e** (29)	**23c** (25)

In conclusion, radical **5** can be generated from the cerium(IV) oxidation of β-dicarbonyl compounds and it undergoes efficient addition to the C–C double bond of 2-amino-1,4-naphthoquinones. It proceeded at a much faster reaction rate with CAN. This free radical reaction provides a novel method for the synthesis of benzo[*f*]indole-4,9-dione **3**, **9** and **22** exclusively from readily available 2-amino-1,4-naphthoquinones and β-dicarbonyl compounds.

3. Experimental

General considerations. Melting points are uncorrected. The NMR spectra were recorded on a Bruker AVANCE-300, AMX-400 or AVANCE-600 spectrometer. Chemical shifts are reported in ppm relative to TMS as internal reference. Analytical thin-layer chromatography was performed with precoated silica gel 60 F-254 plates (0.25 mm thick) from EM Laboratories and visualized by UV. The reaction mixture was purified by column chromatography over EM Laboratories silica gel (70–230 mesh). The starting 1,4-naphthoquinone **1** and **21** were synthesized by literature procedure.[12]

3.1. Typical experimental procedure for the reaction mediated by CAN

To a solution of 151 mg (0.80 mmol) of 2-(methylamino)-1,4-naphthoquinone (**1a**) and 320 mg (3.20 mmol) of 2,4-pentanedione (**2a**) in 10 ml of methanol and 2 ml of dichloromethane stirred at room temperature was added 1.54 g (2.81 mmol) of CAN in four portions at 10 min intervals. The reaction mixture was stirred for another 10 min and then diluted with 100 ml of ethyl acetate, washed with 50 ml of saturated aqueous sodium bisulfite, three 50 ml portions of water, dried (Na_2SO_4), and concentrated in vacuo. The residue was chromatographed over 20 g of silica gel (eluted with 2:1 dichloromethane–hexane) followed by recrystallization (hexane–ethyl acetate) to give 164 mg (76%) of **3a**.

3.1.1. 3-Acetyl-1,2-dimethyl-4,9-dihydro-4,9-dioxo-1*H*-benzo[*f*]indole 3a. 76%; yellow needles; mp 180–181°C; IR ($CHCl_3$) 3010, 2960, 1655, 1595, 1465, 1270 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 2.41 (s, 3H, CH_3), 2.71 (s, 3H, CH_3), 4.04 (s, 3H, NCH_3), 7.64–7.73 (m, 2H, ArH), 8.08–8.17 (m, 2H, ArH); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 10.8 (q), 31.6 (q), 32.8 (q), 122.6 (s), 124.8 (s), 126.2 (d), 126.6 (d), 130.0 (s), 133.1 (s+d), 133.3 (d), 133.5 (s), 141.9 (s), 176.3 (s), 180.6 (s), 199.1 (s); anal. calcd for $C_{16}H_{13}NO_3$: N, 5.24; C, 71.90; H, 4.90. Found: N, 5.18; C, 71.76; H, 4.92.

3.1.2. 2-Ethyl-1-methyl-3-propionyl-4,9-dihydro-4,9-dioxo-1*H*-benzo[*f*]indole 3b. 53%; yellow crystals; mp 132–133°C; IR ($CHCl_3$) 2985, 1660, 1595, 1470, 1255 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 1.21 (t, J=7.4 Hz, 3H, CH_3), 1.24 (t, J=7.3 Hz, 3H, CH_3), 2.78 (q, J=7.4 Hz, 2H, CH_2), 3.08 (q, J=7.3 Hz, 2H, CH_2), 4.07 (s, 3H, NCH_3), 7.65–7.72 (m, 2H, ArH), 8.09–8.17 (m, 2H, ArH); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 8.5 (q), 13.5 (q), 17.8 (t), 32.6 (q), 36.7 (t), 122.0 (s), 124.7 (s), 126.1 (d), 126.4 (d), 129.8 (s), 133.0 (d), 133.1 (d), 133.2 (s), 133.4 (s), 146.2 (s), 176.1 (s), 180.5 (s), 202.7 (s); anal. calcd for $C_{18}H_{17}NO_3$: N, 4.74; C, 73.20; H, 5.80. Found: N, 4.72; C, 73.17; H, 5.88.

3.1.3. 3-Isobutyryl-2-isopropyl-1-methyl-4,9-dihydro-4,9-dioxo-1*H*-benzo[*f*]indole 3c. 39%; yellow crystals; mp 155–156°C; IR ($CHCl_3$) 2980, 2940, 1660, 1595, 1455, 1250 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 1.21 (d, J=6.9 Hz, 6H, CH_3), 1.36 (d, J=7.2 Hz, 6H, CH_3), 3.24 (septet, J=7.2 Hz, 1H, CH), 3.44 (septet, J=6.9 Hz, 1H, CH), 4.14 (s, 3H, NCH_3), 7.61–7.72 (m, 2H, ArH), 8.05–8.17 (m, 2H, ArH); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ 18.6 (q×2), 20.8 (q×2), 25.7 (d), 33.7 (q), 41.3 (d), 122.2 (s), 125.4 (s), 126.3 (d), 126.4 (d), 129.6 (s), 133.1 (d×2), 133.3 (s), 133.6 (s), 147.5 (s), 176.2 (s), 180.6 (s), 207.9 (s); anal. calcd for $C_{20}H_{21}NO_3$: N, 4.33; C, 74.28; H, 6.55. Found: N, 4.31; C, 73.97; H, 6.72.

3.1.4. 1,2-Dimethyl-3-ethoxycarbonyl-4,9-dihydro-4,9-dioxo-1*H*-benzo[*f*]indole 3j. 59%; yellow crystals; mp 142–143°C; IR ($CHCl_3$) 2990, 1710, 1655, 1300, 1275 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 1.43 (t, J=7.1 Hz, 3H, CH_3), 2.47 (s, 3H, CH_3), 4.03 (s, 3H, NCH_3), 4.43 (q, J=7.1 Hz, 2H, OCH_2), 7.61–7.71 (m, 2H, ArH), 8.07–8.17 (m, 2H, ArH); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ 10.9 (q), 14.2 (q), 32.9 (q), 61.1 (t), 113.9 (s), 125.5 (s), 126.1 (d), 126.7 (d), 130.5 (s), 132.9 (d), 133.1 (s), 133.2 (d), 133.8 (s), 142.1 (s), 164.5 (s), 176.4 (s), 179.3 (s); anal. calcd for $C_{17}H_{15}NO_4$: N, 4.71; C, 68.68; H, 5.09. Found: N, 4.73; C, 68.63; H, 5.09.

3.1.5. 3-Ethoxycarbonyl-2-methyl-1-(*p*-methylbenzyl)-4,9-dihydro-4,9-dioxo-1*H*-benzo[*f*]indole 3k. 61%; yellow needles; mp 170–171°C; IR ($CHCl_3$) 3010, 1710, 1660, 1435, 1255 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 1.43 (t, J=7.1 Hz, 3H, CH_3), 2.30 (s, 3H, CH_3), 2.41 (s, 3H, CH_3), 4.44 (q, J=7.1 Hz, 2H, OCH_2), 5.77 (s, 2H, NCH_2), 6.96 (d,

J=7.9 Hz, 2H, ArH), 7.11 (d, J=7.9 Hz, 2H, ArH), 7.61–7.69 (m, 2H, ArH), 8.09 (dd, J=7.4, 1.2 Hz, 1H, ArH), 8.15 (dd, J=7.4, 1.2 Hz, 1H, ArH); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ 11.0 (q), 14.2 (q), 21.0 (q), 48.6 (t), 61.2 (t), 114.4 (s), 125.9 (s), 126.2 (d×2), 126.3 (d), 126.7 (d), 129.6 (d×2), 130.2 (s), 132.5 (s), 132.9 (d), 133.2 (s), 133.3 (d), 133.7 (s), 137.5 (s), 142.3 (s), 164.6 (s), 176.2 (s), 179.5 (s); anal. calcd for $C_{24}H_{21}NO_4$: N, 3.62; C, 74.40; H, 5.46. Found: N, 3.62; C, 74.31; H, 5.45.

3.2. Typical experimental procedure for the reaction mediated by cerium sulfate

To a solution of 120 mg (0.64 mmol) of 2-(methylamino)-1,4-naphthoquinone (**1a**) and 256 mg (2.56 mmol) of 2,4-pentanedione (**2a**) in 10 ml of methanol, 2 ml of dichloromethane and 2 ml of water was added 903 mg (2.23 mmol) of cerium sulfate in four portions at 1 h intervals. The reaction mixture was stirred for another 30 min. After workup as described as above, the residue was chromatographed over 20 g of silica gel (eluted with 2:1 dichloromethane–hexane) followed by recrystallization (hexane–ethyl acetate) to give 132 mg (77%) of **3a**.

3.2.1. 3-Acetyl-1,2-dimethyl-4,9-dihydro-4,9-dioxo-1*H*-benzo[*f*]indole 3a. 77%; the spectral data for **3a** was identical to that reported earlier.

3.2.2. 2-Ethyl-1-methyl-3-propionyl-4,9-dihydro-4,9-dioxo-1*H*-benzo[*f*]indole 3b. 67%; the spectral data for **3b** was identical to that reported earlier.

3.2.3. 3-Isobutyryl-2-isopropyl-1-methyl-4,9-dihydro-4,9-dioxo-1*H*-benzo[*f*]indole 3c. 62%; the spectral data for **3c** was identical to that reported earlier.

3.2.4. 3-Benzoyl-1,2-dimethyl-4,9-dihydro-4,9-dioxo-1*H*-benzo[*f*]indole 3d. 64%; yellow crystals; mp 237–238°C; IR ($CHCl_3$) 3010, 2960, 1655, 1600, 1465, 1225 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.34 (s, 3H, CH_3), 4.08 (s, 3H, NCH_3), 7.35–7.48 (m, 2H, ArH), 7.48–7.70 (m, 3H, ArH), 7.88 (d, J=7.7 Hz, 2H, ArH), 7.93 (d, J=7.5 Hz, 1H, ArH), 8.11 (d, J=7.5 Hz, 1H, ArH); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ 10.7 (q), 32.9 (q), 120.8 (s), 126.1 (s), 126.3 (d), 126.6 (d), 128.4 (d×2), 129.3 (d×2), 129.8 (s), 133.1 (d×2), 133.2 (d), 133.3 (s), 133.5 (s), 138.3 (s), 140.7 (s), 176.3 (s), 179.6 (s), 193.0 (s); anal. calcd for $C_{21}H_{15}NO_3$: N, 4.25; C, 76.58; H, 4.59. Found: N, 4.26; C, 76.43; H, 4.63.

3.2.5. 1,2-Dimethyl-3-trimethylacetyl-4,9-dihydro-4,9-dioxo-1*H*-benzo[*f*]indole 3e. 73%; yellow crystals; mp 183–184°C; IR ($CHCl_3$) 2975, 1660, 1595, 1465, 1250 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.28 (s, 9H, CH_3), 2.24 (s, 3H, CH_3), 4.03 (s, 3H, NCH_3), 7.59–7.74 (m, 2H, ArH), 8.04–8.18 (m, 2H, ArH); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ 11.1 (q), 27.1 (q×3), 32.8 (q), 45.8 (s), 122.3 (s), 125.7 (s), 126.4 (d), 126.5 (d), 129.5 (s), 133.16 (s+d), 133.19 (d), 133.8 (s), 135.9 (s), 176.0 (s), 180.3 (s), 211.8 (s); anal. calcd for $C_{19}H_{19}NO_3$: N, 4.53; C, 73.77; H, 6.19. Found: N, 4.54; C, 73.74; H, 6.21.

3.2.6. 1,2-Dimethyl-3-isopentanoyl-4,9-dihydro-4,9-dioxo-1*H*-benzo[*f*]indole 3f. 57%; yellow needles; mp 124–125°C; IR ($CHCl_3$) 2970, 1655, 1595, 1300, 1250 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.96 (d, J=6.8 Hz, 6H, CH_3), 2.19 (nontet, J=6.8 Hz, 1H, CH), 2.38 (s, 3H, CH_3), 2.99 (d, J=6.8 Hz, 2H, CH_2), 4.03 (s, 3H, NCH_3), 7.64–7.73 (m, 2H, ArH), 8.08–8.17 (m, 2H, ArH); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ 10.7 (q), 22.6 (q×2), 25.5 (d), 32.8 (q), 52.4 (t), 123.1 (s), 124.7 (s), 126.2 (d), 126.6 (d), 129.9 (s), 133.1 (d), 133.2 (s+d), 133.5 (s), 141.1 (s), 176.3 (s), 180.5 (s), 202.3 (s); anal. calcd for $C_{19}H_{19}NO_3$: N, 4.53; C, 73.77; H, 6.19. Found: N, 4.57; C, 73.88; H, 6.24.

3.2.7. 3-Acetyl-2-methyl-1-(*p*-methylbenzyl)-4,9-dihydro-4,9-dioxo-1*H*-benzo[*f*]indole 3g. 61%; yellow crystals; mp 197–198°C; IR ($CHCl_3$) 3010, 1650, 1495, 1435, 1270 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.31 (s, 3H, CH_3), 2.36 (s, 3H, CH_3), 2.73 (s, 3H, CH_3), 5.78 (s, 2H, NCH_2), 6.97 (d, J=7.7 Hz, 2H, ArH), 7.12 (d, J=7.7 Hz, 2H, ArH), 7.61–7.75 (m, 2H, ArH), 8.04–8.22 (m, 2H, ArH); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 10.9 (q), 21.0 (q), 31.7 (q), 48.6 (t), 123.1 (s), 125.3 (s), 126.2 (d×2), 126.4 (d), 126.7 (d), 129.6 (d×2), 129.8 (s), 132.5 (s), 133.2 (d), 133.25 (s), 133.34 (d), 133.5 (s), 137.6 (s), 142.0 (s), 176.2 (s), 180.7 (s), 199.2 (s); anal. calcd for $C_{23}H_{19}NO_3$: N, 3.92; C, 77.29; H, 5.36. Found: N, 3.89; C, 77.22; H, 5.36.

3.2.8. 2-Ethyl-1-(*p*-methylbenzyl)-3-propionyl-4,9-dihydro-4,9-dioxo-1*H*-benzo[*f*]indole 3h. 57%; yellow crystals; mp 115–116°C; IR ($CHCl_3$) 2985, 1660, 1595, 1495, 1470 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.13 (t, J=7.5 Hz, 3H, CH_3), 1.22 (t, J=7.2 Hz, 3H, CH_3), 2.31 (s, 3H, CH_3), 2.72 (q, J=7.5 Hz, 2H, CH_2), 3.11 (q, J=7.2 Hz, 2H, CH_2), 5.77 (s, 2H, NCH_2), 6.94 (d, J=7.9 Hz, 2H, ArH), 7.12 (d, J=7.9 Hz, 2H, ArH), 7.61–7.74 (m, 2H, ArH), 8.04–8.21 (m, 2H, ArH); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 8.6 (q), 14.3 (q), 18.1 (t), 21.0 (q), 36.9 (t), 48.4 (t), 122.6 (s), 125.4 (s), 125.9 (d×2), 126.5 (d), 126.6 (d), 129.6 (d×2), 129.7 (s), 133.1 (s), 133.2 (d), 133.3 (d), 133.4 (s), 133.5 (s), 137.5 (s), 146.7 (s), 176.0 (s), 180.8 (s), 202.9 (s); anal. calcd for $C_{25}H_{23}NO_3$: N, 3.63; C, 77.90; H, 6.01. Found: N, 3.63; C, 77.83; H, 6.07.

3.2.9. 3-Benzoyl-2-methyl-1-(*p*-methylbenzyl)-4,9-dihydro-4,9-dioxo-1*H*-benzo[*f*]indole 3i. 60%; yellow crystals; mp 244–245°C; IR ($CHCl_3$) 3010, 1655, 1595, 1505, 1435 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.29 (s, 3H, CH_3), 2.32 (s, 3H, CH_3), 5.82 (s, 2H, NCH_2), 7.04 (d, J=7.9 Hz, 2H, ArH), 7.15 (d, J=7.9 Hz, 2H, ArH), 7.44 (t, J=7.6 Hz, 2H, ArH), 7.51–7.72 (m, 3H, ArH), 7.84–7.94 (m, 2H, ArH), 7.97 (dd, J=7.4, 1.2 Hz, 1H, ArH), 8.13 (dd, J=7.4, 1.2 Hz, 1H, ArH); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 10.8 (q), 21.1 (q), 48.7 (t), 121.2 (s), 126.3 (d×2), 126.48 (d), 126.52 (s), 126.6 (d×2), 128.4 (d), 129.3 (d×2), 129.6 (s), 129.7 (d×2), 132.6 (s), 133.1 (d×2), 133.19 (d), 133.22 (s), 133.6 (s), 137.6 (s), 138.3 (s), 140.8 (s), 176.0 (s), 179.7 (s), 193.0 (s); anal. calcd for $C_{28}H_{21}NO_3$: N, 3.34; C, 80.17; H, 5.05. Found: N, 3.28; C, 77.92; H, 5.08.

3.2.10. 1,2-Dimethyl-3-ethoxycarbonyl-4,9-dihydro-4,9-dioxo-1*H*-benzo[*f*]indole 3j. 76%; the spectral data for **3j** was identical to that reported earlier.

3.2.11. 3-Ethoxycarbonyl-2-methyl-1-(*p*-methylbenzyl)-4,9-dihydro-4,9-dioxo-1*H*-benzo[*f*]indole 3k. 69%; the

spectral data for **3k** was identical to that reported earlier.

3.2.12. 1-Butyl-3-ethoxycarbonyl-2-methyl-4,9-dihydro-4,9-dioxo-1*H*-benzo[*f*]indole 3l. 73%; yellow needles; mp 93–94°C; IR ($CHCl_3$) 2975, 1715, 1655, 1470, 1275 cm^{-1}; ^1H NMR (600 MHz, $CDCl_3$) δ 0.99 (t, J=7.6 Hz, 3H, CH_3), 1.44 (t, J=7.1 Hz, 3H, CH_3), 1.39–1.53 (m, 2H, CH_2), 1.74 (quintet, J=7.6 Hz, 2H, CH_2), 2.48 (s, 3H, CH_3), 4.40–4.48 (m, 4H), 7.61–7.70 (m, 2H, ArH), 8.07–8.16 (m, 2H, ArH); ^{13}C NMR (150.9 MHz, $CDCl_3$) δ 10.7 (q), 13.6 (q), 14.2 (q), 19.9 (t), 32.4 (t), 45.7 (t), 61.0 (t), 114.1 (s), 125.8 (s), 126.1 (d), 126.6 (d), 130.0 (s), 132.8 (d), 133.1 (d), 133.2 (s), 133.8 (s), 141.3 (s), 164.7 (s), 175.9 (s), 179.3 (s); anal. calcd for $C_{20}H_{21}NO_4$: N, 4.13; C, 70.78; H, 6.24. Found: N, 4.11; C, 70.74; H, 6.33.

3.2.13. 3-Ethoxycarbonyl-1-isobutyl-2-methyl-4,9-dihydro-4,9-dioxo-1*H*-benzo[*f*]indole 3m. 61%; yellow needles; mp 118–119°C; IR ($CHCl_3$) 2975, 1715, 1660, 1470, 1260 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 0.97 (d, J=6.9 Hz, 6H, CH_3), 1.44 (t, J=7.1 Hz, 3H, CH_3), 2.17 (nontet, J=6.9 Hz, 1H, CH), 2.48 (s, 3H, CH_3), 4.30 (d, J=6.9 Hz, 2H, NCH_2), 4.44 (q, J=7.1 Hz, 2H, OCH_2), 7.61–7.71 (m, 2H, ArH), 8.06–8.18 (m, 2H, ArH); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 11.3 (q), 14.2 (q), 19.8 (q×2), 29.8 (d), 52.5 (t), 61.6 (t), 114.2 (s), 126.0 (s), 126.2 (d), 126.6 (d), 130.3 (s), 132.9 (d), 133.1 (d), 133.4 (s), 133.8 (s), 141.7 (s), 164.8 (s), 176.0 (s), 179.5 (s); anal. calcd for $C_{20}H_{21}NO_4$: N, 4.13; C, 70.78; H, 6.24. Found: N, 4.17; C, 70.73; H, 6.20.

3.2.14. 3-Ethoxycarbonyl-1-methyl-2-propyl-4,9-dihydro-4,9-dioxo-1*H*-benzo[*f*]indole 3n. 64%; yellow needles; mp 82–83°C; IR ($CHCl_3$) 2975, 1715, 1660, 1595, 1465 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 1.02 (t, J=7.5 Hz, 3H, CH_3), 1.43 (t, J=7.1 Hz, 3H, CH_3), 1.66 (sextet, J=7.5 Hz, 2H, CH_2), 2.85 (t, J=7.5 Hz, 2H, CH_2), 4.05 (s, 3H, NCH_3), 4.32 (q, J=7.1 Hz, 2H, OCH_2), 7.61–7.73 (m, 2H, ArH), 8.06–8.21 (m, 2H, ArH); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 13.8 (q), 14.2 (q), 22.3 (t), 26.5 (t), 32.9 (q), 61.0 (t), 113.9 (s), 125.6 (s), 126.1 (d), 126.6 (d), 130.4 (s), 132.9 (d), 133.2 (s+d), 133.8 (s), 145.7 (s), 164.6 (s), 176.4 (s), 179.4 (s); anal. calcd for $C_{19}H_{19}NO_4$: N, 4.31; C, 70.14; H, 5.89. Found: N, 4.29; C, 70.10; H, 5.93.

3.2.15. 2-Isopropyl-3-methoxycarbonyl-1-methyl-4,9-dihydro-4,9-dioxo-1*H*-benzo[*f*]indole 3o. 58%; yellow crystals; mp 129–130°C; IR ($CHCl_3$) 2980, 1660, 1595, 1275, 1245 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 1.38 (d, J=7.1 Hz, 6H, CH_3), 3.23 (septet, J=7.1 Hz, 1H, CH), 3.98 (s, 3H, NCH_3), 4.10 (s, 3H, OCH_3), 7.61–7.72 (m, 2H, ArH), 8.06–8.17 (m, 2H, ArH); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ 20.6 (q×2), 25.7 (d), 32.8 (q), 52.4 (q), 113.2 (s), 125.3 (s), 126.2 (d×2), 129.1 (s), 133.0 (d×2), 133.1 (s), 133.5 (s), 146.9 (s), 166.5 (s), 175.9 (s), 179.6 (s); anal. calcd for $C_{18}H_{17}NO_4$: N, 4.50; C, 69.44; H, 5.50. Found: N, 4.53; C, 69.24; H, 5.57.

3.2.16. 3-Ethoxycarbonyl-1-methyl-2-phenyl-4,9-dihydro-4,9-dioxo-1*H*-benzo[*f*]indole 3p. 52%; yellow crystals; mp 118–119°C; IR ($CHCl_3$) 3010, 1725, 1495, 1450, 1275 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 1.13 (t, J=7.1 Hz, 3H, CH_3), 3.93 (s, 3H, NCH_3), 4.23 (q, J=7.1 Hz, 2H, OCH_2), 7.37–7.46 (m, 2H, ArH), 7.46–7.56 (m, 2H, ArH), 7.64–7.77 (m, 2H, ArH), 8.09–8.23 (m, 2H, ArH); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 13.8 (q), 34.5 (q), 61.1 (t), 115.5 (s), 125.3 (s), 126.2 (d), 126.7 (d), 128.56 (d×2), 128.61 (s), 129.6 (d), 130.1 (d×2), 130.5 (s), 133.0 (d), 133.3 (s), 133.4 (d), 133.7 (s), 143.2 (s), 146.1 (s), 176.6 (s), 179.5 (s); anal. calcd for $C_{22}H_{17}NO_4$: N, 3.90; C, 73.53; H, 4.77. Found: N, 3.89; C, 73.46; H, 4.84.

3.2.17. 3-Methoxycarbonyl-2-methoxymethyl-1-methyl-4,9-dihydro-4,9-dioxo-1*H*-benzo[*f*]indole 3q. 66%; yellow crystals; mp 159–160°C; IR ($CHCl_3$) 3015, 1715, 1660, 1305, 1275 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 3.39 (s, 3H, OCH_3), 3.98 (s, 3H, NCH_3), 4.14 (s, 3H, OCH_3), 4.68 (s, 2H, OCH_2), 7.65–7.74 (m, 2H, ArH), 8.09–8.19 (m, 2H, ArH); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ 33.7 (q), 52.4 (q), 58.2 (q), 62.7 (t), 115.6 (s), 124.9 (s), 126.3 (d), 126.8 (d), 131.5 (s), 133.1 (s+d), 133.6 (d), 133.8 (s), 139.7 (s), 167.4 (s), 176.9 (s), 179.4 (s); anal. calcd for $C_{17}H_{15}NO_5$: N, 4.47; C, 65.17; H, 4.83. Found: N, 4.44; C, 65.04; H, 4.82.

3.2.18. 3-Ethoxycarbonyl-1-(*p*-methylbenzyl)-2-propyl-4,9-dihydro-4,9-dioxo-1*H*-benzo[*f*]indole 3r. 45%; yellow crystals; mp 100–101°C; IR ($CHCl_3$) 2975, 1715, 1655, 1495, 1270 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 0.94 (t, J=7.7 Hz, 3H, CH_3), 1.44 (t, J=7.1 Hz, 3H, CH_3), 1.54 (sextet, J=7.7 Hz, 2H, CH_2), 2.30 (s, 3H, CH_3), 2.78 (t, J=7.7 Hz, 2H, CH_2), 4.45 (q, J=7.1 Hz, 2H, OCH_2), 5.77 (s, 2H, NCH_2), 6.93 (d, J=7.9 Hz, 2H, ArH), 7.11 (d, J=7.9 Hz, 2H, ArH), 7.57–7.70 (m, 2H, ArH), 8.06 (dd, J=7.2, 1.5 Hz, 1H, ArH), 8.14 (dd, J=7.2, 1.5 Hz, 1H, ArH); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 14.0 (q), 14.2 (q), 21.0 (q), 22.9 (t), 26.7 (t), 48.5 (t), 61.1 (t), 114.3 (s), 125.8 (d×2), 126.1 (s), 126.3 (d), 126.6 (d), 129.5 (d×2), 130.1 (s), 132.9 (d), 133.16 (s), 133.21 (d), 133.24 (s), 133.8 (s), 137.4 (s), 146.1 (s), 164.6 (s), 176.0 (s), 179.5 (s); anal. calcd for $C_{26}H_{25}NO_4$: N, 3.37; C, 75.16; H, 6.06. Found: N, 3.26; C, 74.89; H, 6.12.

3.2.19. 2-Isopropyl-3-methoxycarbonyl-1-(*p*-methylbenzyl)-4,9-dihydro-4,9-dioxo-1*H*-benzo[*f*]indole 3s. 44%; yellow crystals; mp 160–161°C; IR ($CHCl_3$) 2980, 1730, 1655, 1430, 1275 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 1.25 (d, J=7.0 Hz, 6H, CH_3), 2.31 (s, 3H, CH_3), 3.09 (septet, J=7.0 Hz, 1H, CH), 4.00 (s, 3H, OCH_3), 5.82 (s, 2H, NCH_2), 6.92 (d, J=8.0 Hz, 2H, ArH), 7.11 (d, J=8.0 Hz, 2H, ArH), 7.58–7.72 (m, 2H, ArH), 8.03–8.18 (m, 2H, ArH); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 21.0 (q), 21.2 (q), 25.9 (d), 48.4 (t), 52.6 (q), 113.8 (s), 125.7 (d×2), 126.1 (s), 126.4 (d), 126.6 (d), 128.8 (s), 129.6 (d×2), 133.1 (s+d), 133.17 (d), 133.21 (s), 133.3 (s), 133.7 (s), 137.4 (s), 147.7 (s), 166.7 (s), 175.8 (s), 180.0 (s); anal. calcd for $C_{25}H_{23}NO_4$: N, 3.49; C, 74.79; H, 5.77. Found: N, 3.47; C, 74.50; H, 5.81.

3.2.20. 3-Ethoxycarbonyl-1-(*p*-methylbenzyl)-2-phenyl-4,9-dihydro-4,9-dioxo-1*H*-benzo[*f*]indole 3t. 23%; yellow crystals; mp 120–121°C; IR ($CHCl_3$) 2960, 1730, 1660, 1495, 1450 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 1.12 (t, J=7.2 Hz, 3H, CH_3), 2.27 (s, 3H, CH_3), 4.22 (q, J=7.2 Hz, 2H, OCH_2), 5.61 (s, 2H, NCH_2), 6.79 (d, J=7.6 Hz, 2H, ArH), 7.03 (d, J=7.6 Hz, 2H, ArH), 7.27–7.35 (m, 2H, ArH), 7.35–7.49 (m, 3H, ArH), 7.61–7.73 (m, 2H, ArH),

8.03–8.15 (m, 1H, ArH), 8.15–8.23 (m, 1H. ArH); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ 13.8 (q), 21.0 (q), 49.3 (t), 61.2 (t), 116.1 (s), 125.8 (s), 126.1 (d×2), 126.5 (d), 126.7 (d), 128.4 (d×2), 128.6 (s), 129.3 (d×2), 129.7 (d), 130.2 (d×2), 133.1 (d), 133.4 (s+d), 133.6 (s), 133.7 (s), 137.2 (s), 143.5 (s), 164.1 (s), 176.1 (s), 179.6 (s); anal. calcd for $C_{29}H_{23}NO_4$: N, 3.12; C, 77.49; H, 5.16. Found: N, 3.16; C, 77.40; H, 5.19.

3.2.21. 3-Acetyl-2-isobutyl-1-methyl-4,9-dihydro-4,9-dioxo-1*H*-benzo[*f*]indole 4a. 18%; yellow crystals; mp 166–167°C; IR ($CHCl_3$) 3010, 2970, 1655, 1595, 1460, 1265 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 0.96 (d, J=6.8 Hz, 6H, $2CH_3$), 1.92 (nontet, J=6.8 Hz, 1H, CH), 2.69 (s, 3H, CH_3), 2.75 (d, J=6.8 Hz, 2H, CH_2), 4.04 (s, 3H, NCH_3), 7.65–7.74 (m, 2H, ArH), 8.09–8.20 (m, 2H, ArH); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 22.3 (q×2), 29.0 (q), 31.7 (d), 32.5 (t), 33.3 (q), 123.3 (s), 125.0 (s), 126.2 (d), 126.6 (d), 130.1 (s), 133.1 (d), 133.27 (d), 133.3 (s), 133.5 (s), 144.4 (s), 176.3 (s), 180.7 (s), 199.5 (s); anal. calcd for $C_{19}H_{19}NO_3$: N, 4.53; C, 73.77; H, 6.19. Found: N, 4.57; C, 73.84; H, 6.29.

3.2.22. 3-Acetyl-2-methyl-1-phenyl-4,9-dihydro-4,9-dioxo-1*H*-benzo[*f*]indole 22a. 48%; yellow needles; mp 170–171°C; IR ($CHCl_3$) 3015, 1660, 1600, 1495, 1280 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.19 (s, 3H, CH_3), 2.80 (s, 3H, CH_3), 7.24–7.34 (m, 2H, ArH), 7.53–7.61 (m, 3H, ArH), 7.61–7.73 (m, 2H, ArH), 7.99 (dd, J=7.0, 1.1 Hz, 1H, ArH), 8.17 (dd, J=7.0, 1.1 Hz, 1H, ArH); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ 11.8 (q), 31.8 (q), 122.6 (s), 125.1 (s), 126.2 (d), 126.8 (d), 127.1 (d×2), 129.6 (d×3), 131.0 (s), 133.0 (s), 133.3 (d), 133.4 (d), 133.6 (s), 136.9 (s), 142.7 (s), 175.0 (s), 180.9 (s), 199.1 (s); anal. calcd for $C_{21}H_{15}NO_3$: N, 4.25; C, 76.58; H, 4.59. Found: N, 4.25; C, 76.40; H, 4.61.

3.2.23. 3-Benzoyl-2-methyl-1-phenyl-4,9-dihydro-4,9-dioxo-1*H*-benzo[*f*]indole 22b. 31%; yellow crystals; mp 194–195°C; IR ($CHCl_3$) 3015, 1660, 1600, 1500, 1285 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.13 (s, 3H, CH_3), 7.34–7.42 (m, 2H, ArH), 7.44–7.53 (m, 2H, ArH), 7.56–7.68 (m, 6H, ArH), 7.94–8.06 (m, 4H, ArH); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 11.3 (q), 120.8 (s), 126.3 (d), 126.5 (s), 126.6 (d), 127.1 (d×2), 128.4 (d×2), 129.3 (d×2), 129.6 (d×3), 130.7 (s), 133.2 (d×2), 133.4 (s), 136.8 (s), 138.2 (s), 141.2 (s), 174.8 (s), 179.9 (s), 193.0 (s); anal. calcd for $C_{26}H_{17}NO_3$: N, 3.58; C, 79.78; H, 4.38. Found: N, 3.55; C, 79.64; H, 4.47.

3.2.24. 3-Ethoxycarbonyl-2-methyl-1-phenyl-4,9-dihydro-4,9-dioxo-1*H*-benzo[*f*]indole 22c. 52%; yellow needles; mp 181–182°C; IR ($CHCl_3$) 3015, 1715, 1660, 1500, 1285 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.46 (t, J=7.1 Hz, 3H, CH_3), 2.25 (s, 3H, CH_3), 4.48 (q, J=7.1 Hz, 2H, CH_2), 7.25–7.35 (m, 2H, ArH), 7.53–7.74 (m, 5H, ArH), 7.97 (dd, J=7.5, 1.1 Hz, 1H, ArH), 8.18 (dd, J=7.5, 1.1 Hz, 1H, ArH); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ 11.7 (q), 14.2 (q), 61.2 (t), 114.1 (s), 125.8 (s), 126.1 (d), 126.8 (d), 127.2 (d×2), 129.6 (d×3), 131.5 (s), 133.0 (s), 133.03 (d), 133.32 (d), 133.8 (s), 136.9 (s), 142.8 (s), 146.5 (s), 174.9 (s), 179.6 (s); anal. calcd for $C_{22}H_{17}NO_4$: N, 3.90; C, 73.53; H, 4.77. Found: N, 3.89; C, 73.40; H, 4.81.

3.2.25. 3-Ethoxycarbonyl-1-phenyl-2-propyl-4,9-dihydro-4,9-dioxo-1*H*-benzo[*f*]indole 22d. 37%; yellow crystals; mp 156–157°C; IR ($CHCl_3$) 3015, 2975, 1715, 1665, 1495, 1285 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.81 (t, J=7.6 Hz, 3H, CH_3), 1.45 (t, J=7.1 Hz, 3H, CH_3), 1.38–1.54 (m, 2H, CH_2), 2.61 (t, J=7.6 Hz, 2H, CH_2), 4.47 (q, J=7.1 Hz, 2H, OCH_2), 7.28–7.34 (m, 2H, ArH), 7.51–7.71 (m, 5H, ArH), 7.92–8.00 (m, 1H, ArH), 8.13–8.20 (m, 1H, ArH); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ 13.8 (q), 14.1 (q), 22.9 (t), 26.8 (t), 61.1 (t), 113.9 (s), 125.8 (s), 126.1 (d), 126.6 (d), 127.4 (d×2), 129.4 (d×2), 129.6 (d), 131.2 (s), 133.0 (s+d), 133.2 (d), 133.7 (s), 136.7 (s), 146.5 (s), 164.5 (s), 174.9 (s), 179.6 (s); anal. calcd for $C_{24}H_{21}NO_4$: N, 3.62; C, 74.40; H, 5.46. Found: N, 3.67; C, 74.47; H, 5.50.

3.3. Typical experimental procedure for the reaction of 2-amino-1,4-naphthoquinone 1 and 1,3-cyclohexanedione 8 mediated by CAN

To a solution of 120 mg (0.64 mmol) of 2-(methylamino)-1,4-naphthoquinone (**1a**) and 362 mg (2.58 mmol) of 5,5-dimethyl-1,3-cyclohexanedione (**8a**) in 10 ml of methanol and 2 ml of dichloromethane stirred at room temperature was added 1.77 g (3.22 mmol) of CAN in five portions at 30 min intervals. The reaction mixture was stirred for another 30 min. After workup as described as above, the residue was chromatographed over 20 g of silica gel to give 96 mg (42%) of **9a** (eluted with 2:1 dichloromethane–hexane) followed by 87 mg (20%) of **12a** (eluted with 1:1 dichloromethane–ethyl acetate).

3.3.1. 2-(2,2-Dimethyl-3-methoxycarbonylpropyl)-3-methoxy-1-methyl-4,9-dihydro-4,9-dioxo-1*H*-benzo[*f*]-indole 9a. 42%; orange needles; mp 128–129°C; IR ($CHCl_3$) 3010, 2970, 1730, 1645, 1465, 1270 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.09 (s, 6H, CH_3), 2.36 (s, 2H, CH_2), 2.80 (s, 2H, CH_2), 3.69 (s, 3H, OCH_3), 4.00 (s, 3H, CH_3), 4.01 (s, 3H, CH_3), 7.59–7.70 (m, 2H, ArH), 8.06–8.18 (m, 2H, ArH); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ 27.3 (q×2), 33.7 (t), 34.2 (q), 35.9 (s), 45.7 (t), 51.2 (q), 61.6 (q), 117.5 (s), 126.1 (d), 126.2 (d), 126.8 (s), 131.5 (s), 132.7 (d), 132.8 (d), 133.7 (s), 134.0 (s), 145.1 (s), 172.3 (s), 175.0 (s), 179.7 (s); anal. calcd for $C_{21}H_{23}NO_5$: N, 3.79; C, 68.28; H, 6.28. Found: N, 3.80; C, 68.30; H, 6.32.

3.3.2. 3-Methoxy-2-(3-methoxycarbonyl-2-methylpropyl)-1-methyl-4,9-dihydro-4,9-dioxo-1*H*-benzo[*f*]indole 9b. 42%; orange crystals; mp 116–117°C; IR ($CHCl_3$) 3010, 2960, 1730, 1650, 1465, 1270 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.02 (d, J=6.2 Hz, 3H, CH_3), 2.23–2.43 (m, 3H), 2.57 (dd, J=14.7, 7.6 Hz, 1H, CH), 2.70 (dd, J=14.4, 6.3 Hz, 1H, CH), 3.65 (s, 3H, OCH_3), 4.02 (s, 3H, CH_3), 4.05 (s, 3H, CH_3), 7.60–7.70 (m, 2H, ArH), 8.10–8.18 (m, 2H, ArH); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 19.9 (q), 29.3 (t), 29.9 (d), 33.4 (q), 40.7 (d), 51.5 (q), 61.9 (q), 117.6 (s), 126.2 (d), 126.3 (d), 126.6 (s), 132.2 (s), 132.8 (d), 132.9 (d), 133.8 (s), 134.1 (s), 144.4 (s), 173.0 (s), 175.3 (s), 179.8 (s); anal. calcd for $C_{20}H_{21}NO_5$: N, 3.94; C, 67.59; H, 5.96. Found: N, 4.02; C, 67.60; H, 6.01.

3.3.3. 3-Methoxy-2-(3-methoxycarbonyl-2-phenylpropyl)-1-methyl-4,9-dihydro-4,9-dioxo-1*H*-benzo[*f*]indole 9c. 25%; orange crystals; mp 152–153°C; IR ($CHCl_3$) 3010,

2955, 1730, 1650, 1465, 1270 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 2.75 (dd, J=16.2, 7.4 Hz, 1H, CH), 2.83 (dd, J=16.2, 7.4 Hz, 1H, CH), 2.92 (dd, J=14.6, 7.4 Hz, 1H, CH), 3.02 (dd, J=14.6, 7.4 Hz, 1H, CH), 3.46 (quintet, J=7.4 Hz, 1H, CH), 3.61 (s, 3H, OCH_3), 3.77 (s, 3H, CH_3), 3.82 (s, 3H, CH_3), 7.10–7.18 (m, 2H, ArH), 7.18–7.25 (m, 1H, ArH), 7.25–7.32 (m, 2H, ArH), 7.60–7.69 (m, 2H, ArH), 8.06–8.17 (m, 2H, ArH); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 29.9 (t), 33.2 (q), 39.5 (t), 41.3 (d), 51.7 (q), 61.7 (q), 117.5 (s), 126.2 (d), 126.3 (d), 126.6 (s), 127.3 (d×3), 128.8 (d×2), 131.4 (s), 132.8 (d), 132.9 (d), 133.8 (s), 134.1 (s), 142.4 (s), 144.4 (s), 172.4 (s), 175.3 (s), 179.7 (s); anal. calcd for $C_{25}H_{23}NO_5$: N, 3.36; C, 71.93; H, 5.55. Found: N, 3.33; C, 71.74; H, 5.63.

3.3.4. 3-Methoxy-2-(3-methoxycarbonylpropyl)-1-methyl-4,9-dihydro-4,9-dioxo-1*H*-benzo[*f*]indole 9d. 29%; orange crystals; mp 124–125°C; IR ($CHCl_3$) 3010, 2960, 1730, 1650, 1470, 1270 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 1.91 (quintet, J=7.4 Hz, 2H, CH_2), 2.43 (t, J=7.4 Hz, 2H, CH_2), 2.72 (t, J=7.4 Hz, 2H, CH_2), 3.68 (s, 3H, OCH_3), 4.01 (s, 3H, CH_3), 4.05 (s, 3H, CH_3), 7.61–7.71 (m, 2H, ArH), 8.08–8.20 (m, 2H, ArH); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ 21.8 (t), 23.7 (t), 32.9 (t), 33.1 (q), 51.7 (q), 62.1 (q), 117.8 (s), 126.2 (d), 126.3 (d), 126.5 (s), 132.8 (d), 132.9 (d), 133.1 (s), 133.8 (s), 134.1 (s), 143.9 (s), 173.4 (s), 175.4 (s), 179.9 (s); anal. calcd for $C_{19}H_{19}NO_5$: N, 4.10; C, 66.85; H, 5.61. Found: N, 4.11; C, 66.60; H, 5.66.

3.3.5. 5,5-Dimethyl-2-methoxy-1,3-cyclohexanedione 12a. 20%; pale yellow oil; IR ($CHCl_3$) 2970, 1730, 1595, 1385, 1300 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 1.08 (s, 6H, CH_3), 2.22 (s, 2H, CH_2), 2.28 (s, 2H, CH_2), 3.70 (s, 3H, OCH_3), 5.37 (s, 1H, OCH); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ 28.1 (q×2), 32.4 (s), 42.6 (t), 50.6 (t), 55.6 (q), 101.0 (d), 177.0 (s), 199.4 (s); HRMS calcd for $C_9H_{14}O_3$ *m/e* 170.0943, found *m/e* 170.0942.

3.3.6. 2-Methoxy-5-methyl-1,3-cyclohexanedione 12b. 19%; pale yellow oil; IR ($CHCl_3$) 2960, 1730, 1610, 1380, 1250 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 1.08 (d, J=6.4 Hz, 3H, CH_3), 1.94–2.31 (m, 3H), 2.42 (dd, J=16.2, 3.2 Hz, 2H, CH), 3.70 (s, 3H, OCH_3), 5.36 (s, 1H, OCH); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ 20.7 (q), 28.7 (d), 36.8 (t), 44.9 (t), 55.5 (q), 101.7 (d), 177.9 (s), 199.4 (s); HRMS calcd for $C_8H_{12}O_3$ *m/e* 156.0786, found *m/e* 156.0786.

3.3.7. 2-Methoxy-5-phenyl-1,3-cyclohexanedione 12c. 21%; pale yellow oil; IR ($CHCl_3$) 2990, 1730, 1610, 1375, 1250 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 2.51–2.74 (m, 4H, CH_2), 3.29–3.43 (m, 1H, CH), 3.72 (s, 3H, OCH_3), 5.46 (s, 1H, OCH), 7.21–7.30 (m, 3H, ArH), 7.31–7.39 (m, 2H, ArH); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ 36.3 (t), 39.3 (d), 43.8 (t), 55.8 (q), 102.0 (d), 126.6 (d×2), 127.0 (d), 128.7 (d×2), 142.6 (s), 177.6 (s), 198.5 (s); HRMS calcd for $C_{13}H_{14}O_3$ *m/e* 218.0943, found *m/e* 218.0943.

3.3.8. 2-Methoxy-1,3-cyclohexanedione 12d. 20%; pale yellow oil; IR ($CHCl_3$) 2960, 1730, 1610, 1375, 1265 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 1.99 (quintet, J=6.4 Hz, 2H, CH_2), 2.35 (t, J=6.4 Hz, 2H, CH_2), 2.42 (t, J=6.4 Hz, 2H, CH_2), 3.70 (s, 3H, OCH_3), 5.38 (s, 1H, OCH); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ 21.1 (t), 28.7 (t), 36.6 (t), 55.5 (q), 102.2 (d), 178.6 (s), 199.6 (s); HRMS calcd for $C_7H_{10}O_3$ *m/e* 142.0630, found *m/e* 142.0633.

3.4. Typical experimental procedure for the reaction mediated by manganese(III) acetate and cerium(III) nitrate

A solution of 121 mg (0.60 mmol) of 2-(ethylamino)-1,4-naphthoquinone (**1e**), 352 mg (2.41 mmol) of methyl 4-methoxyacetoacetate (**2k**), 520 mg (1.20 mmol) of cerium(III) nitrate and 802 mg (2.99 mmol) of manganese(III) acetate in 10 ml of acetic acid was stirred at room temperature for 8 h. After workup as described as above, The residue was chromatographed over 20 g of silica gel (eluted with 8:1 hexane–ethyl acetate) followed by recrystallization (hexane–ethyl acetate) to give 12 mg (6%) of **19a**, followed by 124 mg (63%) of **3u**.

3.4.1. 1-Ethyl-3-methoxycarbonyl-2-methoxymethyl-4,9-dihydro-4,9-dioxo-1*H*-benzo[*f*]indole 3u. 63%; the spectral data of **3u** has been reported.[5h]

3.4.2. 2-Chloromethyl-3-ethoxylcarbonyl-1-ethyl-4,9-dihydro-4,9-dioxo-1*H*-benzo[*f*]indole 3v. 54%; the spectral data of **3v** has been reported.[5h]

3.4.3. 3-Ethoxycarbonyl-1-ethyl-2-propyl-4,9-dihydro-4,9-dioxo-1*H*-benzo[*f*]indole 3w. 72%; the spectral data of **3w** has been reported.[5h]

3.4.4. 1-Ethyl-3-methoxycarbonyl-3-methoxymethyl-2,3,4,9-tetrahydro-2,4,9-trioxo-1*H*-benzo[*f*]indole 19a. 6%; the spectral data of **19a** has been reported.[5h]

3.4.5. 3-Chloromethyl-3-ethoxylcarbonyl-1-ethyl-2,3,4,9-tetrahydro-2,4,9-trioxo-1*H*-benzo[*f*]indole 19b. 22%; the spectral data of **19b** has been reported.[5h]

3.4.6. 3-Ethoxycarbonyl-1-phenyl-2-propyl-4,9-dihydro-4,9-dioxo-1*H*-benzo[*f*]indole 22d. 23%; yellow crystals; mp 156–157°C; IR ($CHCl_3$) 3015, 2975, 1715, 1665, 1495, 1285 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 0.81 (t, J=7.6 Hz, 3H, CH_3), 1.45 (t, J=7.1 Hz, 3H, CH_3), 1.38–1.54 (m, 2H, CH_2), 2.61 (t, J=7.6 Hz, 2H, CH_2), 4.47 (q, J=7.1 Hz, 2H, OCH_2), 7.28–7.34 (m, 2H, ArH), 7.51–7.71 (m, 5H, ArH), 7.92–8.00 (m, 1H, ArH), 8.13–8.20 (m, 1H, ArH); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ 13.8 (q), 14.1 (q), 22.9 (t), 26.8 (t), 61.1 (t), 113.9 (s), 125.8 (s), 126.1 (d), 126.6 (d), 127.4 (d×2), 129.4 (d×2), 129.6 (d), 131.2 (s), 133.0 (s+d), 133.2 (d), 133.7 (s), 136.7 (s), 146.5 (s), 164.5 (s), 174.9 (s), 179.6 (s); anal. calcd for $C_{24}H_{21}NO_4$: N, 3.62; C, 74.40; H, 5.46. Found: N, 3.67; C, 74.47; H, 5.50.

3.4.7. 3-Ethoxycarbonyl-2-methyl-1-(*p*-tolyl)-4,9-dihydro-4,9-dioxo-1*H*-benzo[*f*]indole 22e. 29%; the spectral data of **22e** has been reported.[5h]

3.4.8. 12-Ethoxycarbonyl-6,11-dihydro-6,11-dioxo-benzo-[*b*]acridine 23b. 22%; the spectral data of **23b** has been reported.[5g]

3.4.9. 12-Ethoxycarbonyl-2-methyl-6,11-dihydro-6,11-dioxo-benzo[*b*]acridine 23c. 25%; the spectral data of **23c** has been reported.[5g]

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