Mechanism of the chemiluminescence of biisoquinolinium salts

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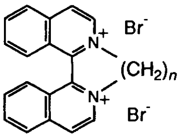
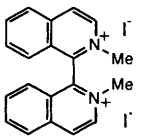
1,1′-Biisoquinolinium salts (BIQ^{2+}2X$^-$) are known to exhibit chemiluminescence on addition of hydrogen peroxide in an alkaline solution. Reduction of BIQ^{2+} with $Na_2S_2O_4$–Na_2CO_3 or Na–Hg gave the radical cation BIQ$^{+\bullet}$ and then the neutral two-electron reduced species, 1,1′-biisoquinolylidene (BIQ), which was characterised by mass spectrometry, UV–VIS and ^{1}H NMR spectroscopy. This electron-rich olefin instantaneously reacted with molecular oxygen showing a blue luminescence in organic solvents. Treatment of BIQ^{2+} or BIQ$^{+\bullet}$ with KO_2 in dimethyl sulfoxide (DMSO) or acetonitrile also caused light emission. The chemiluminescence spectra of both BIQ–$^3O_2$ and BIQ^{2+}–KO_2 reactions were the same as that of BIQ^{2+}–H_2O_2–OH^- and the main product was an isoquinolinone derivative in either case. In the case of 2,2′-ethylene-bridged BIQ^{2+}, the chemiluminescence spectrum coincided with the fluorescence spectrum of the corresponding biisoquinolinone. A plausible reaction pathway for the chemiluminescence of the BIQ^{2+}–H_2O_2–OH^- system is as follows: BIQ^{2+} is reduced by electron donors such as OH^- and OOH^- to BIQ, which reacted with molecular oxygen to give a 1,2-dioxetane. Thermal decomposition of this intermediate generates the excited state of isoquinolinone. The 'photoproducts' from isoquinolinones were obtained in the chemiluminescence reaction as minor products, confirming the chemical formation of the excited state of the isoquinolinones.

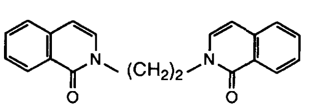
In 1967 Mason and Roberts reported that 1,1-biisoquinolinium salts (BIQ^{2+}2X$^-$), 2,2′-ethylene-1,1′-biisoquinolinium dibromide (1^{2+}2Br$^-$), 2,2′-trimethylene-1,1′-biisoquinolinium dibromide (2^{2+}2Br$^-$) and 2,2′-dimethyl-1,1′-biisoquinolinium diiodide (3^{2+}2I$^-$), produced a blue chemiluminescence (CL) on addition of base in hydroxylic solvents and that further addition of hydrogen peroxide enhanced the light intensity.[1] After CL of 1^{2+}2Br$^-$ had ceased, 1,1′-ethylenebis[1(2*H*)-isoquinolinone] (4) was isolated as a major product. Heller *et al.* proposed the following mechanism of the CL of 1^{2+} in MeOH.[2,3] First, 1^{2+} is attacked by MeO$^-$ or OH$^-$ to give a mixture of electron-rich olefins. The olefins react with O_2 catalysed by the solvent alcohol to give a 1,2-dioxetane *via* formation of a dication of the olefin and hydroperoxy and alkoxy anions [eqn. (1)]. The dioxetane is then cleaved into two carbonyl groups with light emission. Under their conditions, the reduction process of 1^{2+} involved not only electron transfer but also nucleophilic attack at the methylene carbon, and the olefins obtained were characterised only by mass spectrometry.[2]



1^{2+} 2Br$^-$ (n = 2)
2^{2+} 2Br$^-$ (n = 3)



3^{2+} 2I$^-$



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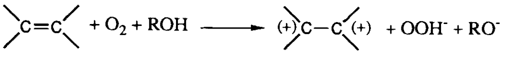


$$>C=C< + O_2 + ROH \longrightarrow (+)>C-C<(+) + OOH^- + RO^- \quad (1)$$

Table 1 Redox potentials[a] (in 0.1 mol dm^{-3} Bu_4NBF_4–CH_3CN, *vs.* Ag/AgCl) of BIQ^{2+}

	BIQ^{2+}/BIQ$^{+\bullet}$		BIQ$^{+\bullet}$/BIQ	
	E_{pc}/V	E_{pa}/V	E_{pc}/V	E_{pa}/V
1^{2+}	−0.13	−0.07	−0.52	−0.45
2^{2+}	−0.36	−0.30	−0.67	−0.60
3^{2+}	−0.53	−0.59	−0.65	−0.59

[a] The concentration of BIQ^{2+} was 7 × 10^{-4} mol dm^{-3}. The scan rate was 300 mV s^{-1}.

In this study we have reinvestigated the CL of BIQ^{2+} in order to characterise the two-electron reduced species and to clarify the detailed mechanism of this light emission. Furthermore, the redox and CL behaviour are compared with those of 10,10′-dimethyl-9,9′-biacridinium salts (BA^{2+}2X$^-$), which have been reported to exhibit CL on addition of hydrogen peroxide in alkaline solution *via* electronic reduction followed by oxygenation.[4]

Results and discussion

Electrochemical studies of BIQ^{2+}

Table 1 lists the redox potentials of 1^{2+}–3^{2+} determined by cyclic voltammetry. The separations of the peak potentials between the anodic and cathodic scans (ΔE_p) of 60–70 mV indicated that both BIQ^{2+}/BIQ$^{+\bullet}$ and BIQ$^{+\bullet}$/BIQ redox processes were reversible. This fact differed from the case of BA^{2+}, in which only one reduction wave (E_{pc} = −0.26 V *vs.* Ag/AgCl) was observed at room temperature.

The difference of redox potentials among 1^{2+}–3^{2+} may result from the different molecular geometries of these dications. X-Ray structure analyses have shown that the dihedral angle between the two isoquinoline rings in 1^{2+} (49.0°)[5] is smaller than that in 2^{2+} (61.9°)[5] or 3^{2+} (108.8°).[6] The larger the dihedral angle, the more negative is the first reduction potential, suggesting that the degree of coplanarity of BIQ^{2+} should affect the stability of the radical cation through delocalisation

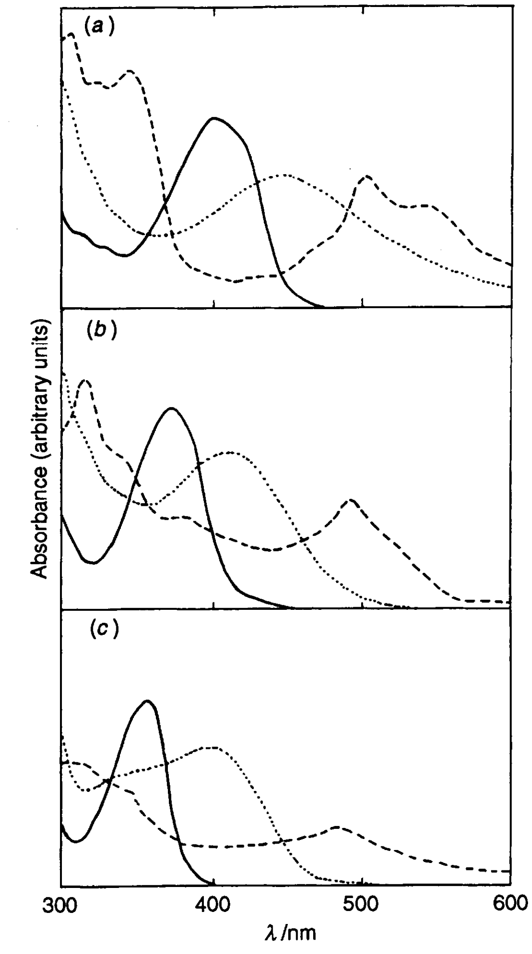


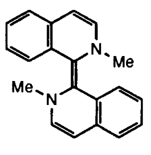
Fig. 1 Absorption spectra of BIQ^{2+} and their reduced forms: (*a*) —— **1**$^{2+}$ (in H_2O); ---- **1**$^{+\bullet}$ (in DMF); ···· **1** (in $CHCl_3$); (*b*) —— **2**$^{2+}$ (in H_2O); ---- **2**$^{+\bullet}$ (in DMF); ···· **2** (in $CHCl_3$); (*c*) —— **3**$^{2+}$ (in MeCN); ---- **3**$^{+\bullet}$ (in MeCN); ···· **3** (in MeCN)

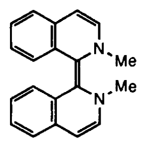
of the unpaired electron. Thummel *et al.* reported a similar trend for bridged bisquaternary salts of 2,2′-biimidazoles.[7]

Reduction of BIQ^{2+}

Photochemical reduction of BIQ^{2+} was attempted for comparison with the case of lucigenin (BA^{2+}2NO_3^-) in which BA^{2+} is reduced by photochemical electron transfer from the counteranion.[8] Neither **1**$^{2+}$2Br$^-$ nor **2**$^{2+}$2Br$^-$ showed CT absorption bands in DMF or MeOH, but a methanolic solution of **1**$^{2+}$2Br$^-$ exhibited a weak absorption in the 450–600 nm region assignable to **1**$^{+\bullet}$ (*vide infra*) even in the dark. When a deaerated solution of **1**$^{2+}$2Br$^-$ (1×10^{-4} mol dm^{-3}) in MeOH was irradiated (> 420 nm), the absorption band of **1**$^{2+}$ around 400 nm decreased with the appearance of a new band at 450–600 nm showing three isosbestic points and an EPR signal consisting of 11 lines was observed. The electronic and EPR spectra coincided with those of the radical cation **1**$^{+\bullet}$ reported by Heller *et al.*[2] Upon irradiation of **2**$^{2+}$2Br$^-$ in DMF, a similar spectral change was observed. These facts indicated that **1**$^{2+}$ and **2**$^{2+}$ were reduced to **1**$^{+\bullet}$ and **2**$^{+\bullet}$, respectively, but further reduction did not occur under these conditions. The absorption spectrum of **3**$^{2+}$2I$^-$ in DMF or DMF–CH_2Cl_2 showed a broad CT band around 440 nm. On irradiation of **3**$^{2+}$2I$^-$ in DMF, however, no spectral variation was observed. Since the first reduction potential of **3**$^{2+}$ is more negative than that of **1**$^{2+}$ or **2**$^{2+}$ (Table 1), reduction of **3**$^{2+}$ will require stronger reducing power.

It has been reported that methylviologen (MV^{2+}) is reduced to give the neutral species (MV^0) by aqueous alkaline sodium dithionite.[9] When BIQ^{2+} was reduced with aqueous sodium dithionite using sodium carbonate as a base, a coloured solid immediately separated out. Mass spectra of the solids obtained from **1**$^{2+}$, **2**^{2} and **3**$^{2+}$ showed molecular ion peaks assignable to BIQ at m/z = 284, 298 and 286, respectively. The solid could be extracted with organic solvents such as chloroform or benzene under vacuum. The greater solubility in organic solvents than in water suggested that the solid should be a neutral two-electron reduced species. Absorption spectra of the reduced species are shown in Fig. 1 together with those of BIQ^{2+} and BIQ$^{+\bullet}$. The ^{1}H NMR spectrum of 2,2′-ethylene-1,1′-biisoquinolylidene (**1**) in CD_2Cl_2 showed signals assignable to four aromatic, two olefinic and methylene protons, which confirmed the structure of **1**.† In the case of **3** the NMR spectrum indicated that the reduced species was a mixture of *E*- and *Z*-isomers in a ratio of *ca.* 1.3:1. The protons at the 8- and 8′-positions of (*Z*)-**3** resonated at higher field than those of (*E*)-**3** because of the shielding effect of the aromatic ring in the other isoquinoline unit.

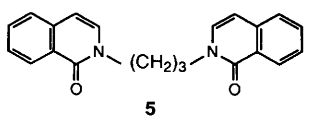

(*E*)-**3**


(*Z*)-**3**

Reduction of **1**$^{2+}$2Br$^-$ with sodium amalgam was also carried out in acetonitrile under vacuum by similar procedures to those for bipyridinium.[10] Monitoring by UV–VIS and EPR spectroscopy indicated that **1**$^{+\bullet}$ was formed first. Upon further reduction the absorption band due to **1**$^{+\bullet}$ was replaced by a broad band around 450 nm assignable to **1** with isosbestic points at 480 and 370 nm, and the EPR signal almost disappeared. These facts indicated that a stepwise two-electron reduction process involving **1**$^{2+}$ took place. Upon reduction of **3**$^{2+}$2I$^-$ with Na–Hg a similar two-step spectral change was observed, although the difference between the first and second reduction potentials was relatively small (120 mV).

Chemiluminescence reaction of BIQ^{2+}

Biisoquinolylidene **1** reacted instantaneously with molecular oxygen emitting a blue light in organic solvents and gave **4** in a high yield. This fact differed from the case of biacridinylidene BA, which reacted with $^1O_2$[11] or O_3[12] to exhibit CL but was inactive to $^3O_2$.[4] The possibility of involvement of radical cation **1**$^{+\bullet}$ in the CL can be ruled out by the fact that **1**$^{+\bullet}$ slowly reacted with O_2 to give **1**$^{2+}$ without light emission. On the other hand, addition of KO_2 to either **1**$^{2+}$ or **1**$^{+\bullet}$ in DMSO or acetonitrile caused intense CL. The CL spectra of both **1**–O_2 and **1**$^{2+}$–$O_2^{-\bullet}$ reactions were closely similar to that of **1**$^{2+}$–H_2O_2 reaction in an alkaline solution and coincided well with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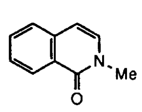
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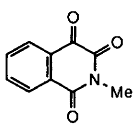
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† Sometimes the signals were rather broad at room temperature, which was probably due to a rapid self-exchange reaction between **1** and **1**$^{+\bullet}$.

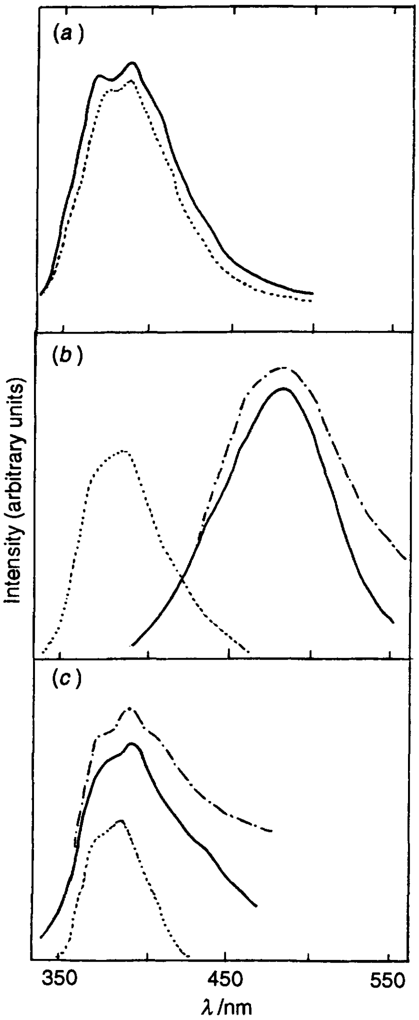
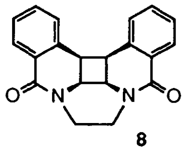


Fig. 2 CL spectra of BIQ and fluorescence spectra of the emitters in benzene: (*a*) —— CL of **1**; · · · · fluorescence of **4**; (*b*) —— CL of **2**; · · · · fluorescence of **5**; — · — · — fluorescence of 2^{2+} (in H_2O); (*c*) —— CL of **3**; · · · · fluorescence of **6**; — · — · — fluorescence of **7** (in $CHCl_3$)

the fluorescence spectrum of **4** [Fig. 2(*a*)]. Thus the emitter in the CL of **1** could be identified as the excited singlet state of **4**.



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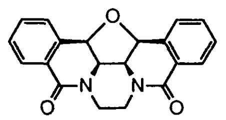

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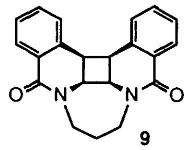

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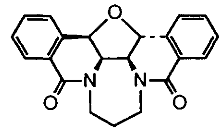

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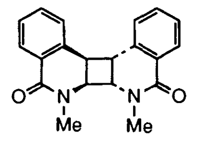

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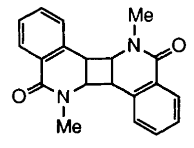

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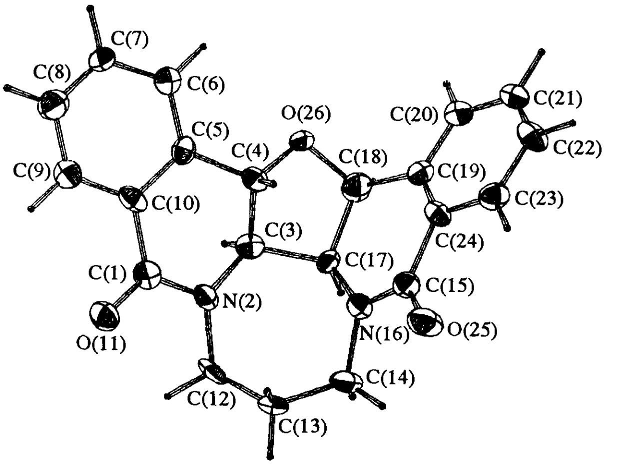

Fig. 3 ORTEP[21] diagram of **11**; the anisotropic ellipsoids for non-H atoms enclose 30% probability

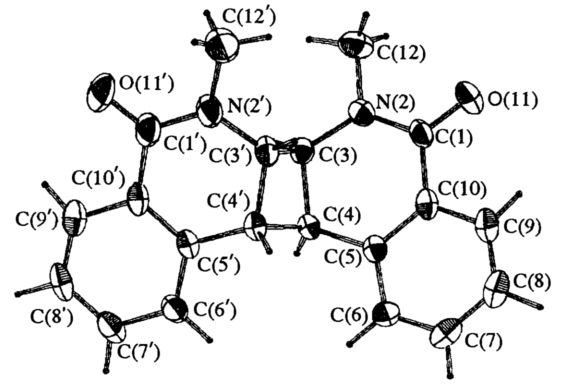

Fig. 4 ORTEP[21] diagram of **12**; the anisotropic ellipsoids for non-H atoms enclose 30% probability

In the CL of 2^{2+} and 3^{2+} and their reduced species, the corresponding carbonyl compounds 2,2′-trimethylene-bis-[isoquinolin-1(2*H*)-one] (**5**) and 2-methylisoquinolin-1(2*H*)-one (**6**) were isolated as the main products. As was seen in Fig. 2(*b*), the CL spectrum of **2** was quite different from the fluorescence spectrum of **5**, indicating that the emitter of **2** must be another species. During the search for the actual emitter causing the CL of **2**, several other products were isolated from the solution after CL had ceased. Although no isolated product was assigned as the emitter, the fluorescence spectrum of 2^{2+} showed rather good agreement with the CL spectrum of **2**. It is likely that 2^{2+}, which was regenerated by electronic oxidation of **2** in the reaction mixture, would be excited by energy transfer from **5***. In the CL spectrum of **3** [Fig. 2(*c*)] the shorter wavelength part corresponds to the fluorescence of **6**, while the longer wavelength part is derived from another emitting species. In order to determine this emitter, products formed during the CL of **3** were isolated. A product whose fluorescence partly coincided with the CL of **3** was identified as 3-methyl isoquinoline-1,2,4-trione (**7**) based on comparison of its mp and spectral data with the reported values.[13] Since the singlet excitation energy of **7** (305 kJ mol^{-1}) was a little lower than that of **6** (319 kJ mol^{-1}), the excited state of **7** must have been generated by energy transfer from **6***.‡ In the CL of both BIQ^{2+}–H_2O_2 and BIQ–O_2 systems some minor products were also isolated, but the amount of each was too small for identification. These products were assumed to be formed from the chemically generated excited state of **4**–**6**, and to test this photochemical reactions of **4**–**6** were carried out. Photolysis of **4** and **5** in deaerated CD_2Cl_2 gave intramolecular [2 + 2] cycloadducts **8** and **9**, respectively, as the sole products. The ^1H NMR spectrum of **9** indicated C_s symmetry for this molecule. Linking of the isoquinolines with a di- or tri-methylene chain

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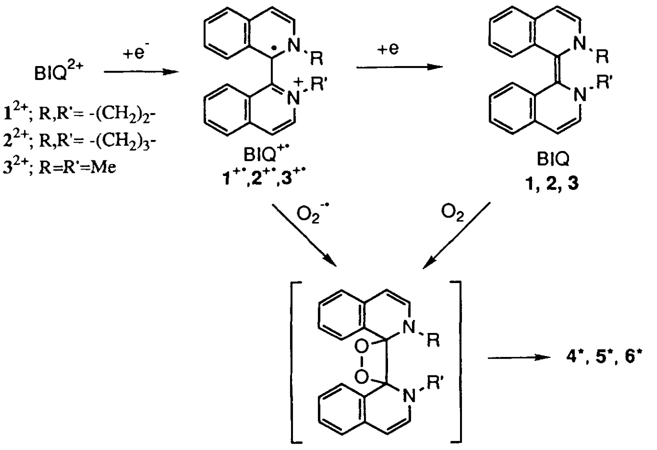
‡ The singlet excitation energy was determined based on the 0–0 band of the fluorescence spectrum.

forces head-to-head *syn* dimerisation, as was reported for 1,1'-trimethylene-biscytosine.[14] Irradiation of **4** and **5** in benzene in the presence of oxygen gave a number of products. Chromatographic separation of the reaction mixture gave oxygenation products **10** (9.4%) and **11** (9.5%), respectively. The structure of **11** was established by X-ray crystal structure analysis (Fig. 3). **8**, **10** and **9**, **11** were also formed by the CL reactions of **1** and **2**, respectively.

When a deaerated solution of **6** in benzene was irradiated, the *anti* head-to-head dimer **12** (Fig. 4) together with the head-to-tail dimer **13** were isolated in 7.3 and 1.6% yields, respectively, and 76% of **6** was recovered. Under aerated conditions, **7**, **12** and **13** were obtained. These three products were also formed in the CL of **3**. Formation of these photoproducts in the CL of **1–3** supported the hypothesis that the excited state of **4–6** was chemically generated. From these facts we propose the reaction pathway shown in Scheme 1 for the CL of BIQ^{2+} salts, which involves the formation of the two-electron reduced species BIQ followed by direct reaction of BIQ with O_2 to give the dioxetane intermediate. CL for the reaction between electron-rich olefins and O_2 has been reported for the tetrakis(dimethylamino)ethylene, although the identity of the emitter is still unclear.[15] In the system containing KO_2, taking into account the more negative redox potential of $O_2/O_2^{-\bullet}$ compared with $BIQ^{+\bullet}/BIQ$, $BIQ^{+\bullet}$ can be reduced to BIQ by $O_2^{-\bullet}$ but the possibility of direct coupling of $BIQ^{+\bullet}$ and $O_2^{-\bullet}$ cannot be ruled out.



Scheme 1

Experimental

Absorption and fluorescence spectra were recorded on a Shimadzu UV240 or UV2200 spectrophotometer and a Shimadzu RF-510 fluorophotometer, respectively. CL spectra were obtained with an Otsuka Electronics Photal IMU6-7000 or a Hamamatsu Photonics PMA-10 spectrophotometric multichannel analyser. ^1H and ^{13}C NMR spectra were recorded on a JEOL JNM-GSX270 or JNM-GSX400 spectrometer in $CDCl_3$ unless otherwise noted. *J* Values are given in Hz. Mass spectra (EI, 70 eV) were obtained with a JEOL JMS-CX300 mass spectrometer. EPR spectra were recorded on a JEOL JES-FE2XG spectrometer. IR spectra were obtained with a JASCO A-302 spectrometer for samples as KBr discs. Melting points were determined on a Yanagimoto micro apparatus. Cyclic voltammograms were recorded on a BAS 100B electrochemical analyser under nitrogen using glassy carbon, Pt wire and Ag/AgCl as working, counter and reference electrodes, respectively.

2,2'-Ethylene-1,1'-biisoquinolinium dibromide ($1^{2+}2Br^-$)

1,1'-Biisoquinoline[16] (0.21 g, 0.83 mmol), which was prepared from 1-chloroisoquinoline[17] by the method of Tiecco *et al.*,[18] was heated under reflux in 5 cm^3 of 1,2-dibromoethane for 4 h. The reaction was cooled, after which the precipitate was filtered off, washed with DMF and recrystallised from MeOH to give $1^{2+}2Br^-$ (0.27 g, 75%). Mp > 300 °C; λ_{max}(MeOH)/nm 403 (ε/dm^3 mol^{-1} cm^{-1} 8000); δ_H(D_2O) 5.37 (2 H, d, *J* 11.1, CH_2), 5.56 (2 H, d, *J* 11.1, CH_2), 7.92 (4 H, m), 8.34 (2 H, ddd, *J* 8.3, 6.5 and 1.5), 8.52 (2 H, d, *J* 8.5), 8.93 (2 H, d, *J* 6.6) and 9.12 (2 H, d, *J* 6.6).

2,2'-Trimethylene-1,1'-biisoquinolinium dibromide ($2^{2+}2Br^-$)

This compound was synthesised from biisoquinoline and 1,3-dibromopropane by a procedure similar to that described for $1^{2+}2Br^-$. Yield 61%; yellow crystals; mp > 300 °C; λ_{max}(MeOH)/nm 375 (ε/dm^3 mol^{-1} cm^{-1} 8600); δ_H(D_2O) 2.85 (2 H, m, CH_2), 4.45 (2 H, m, CH_2), 5.08 (2 H, m, CH_2), 7.52 (2 H, d, *J* 8.8), 7.77 (2 H, ddd, *J* 8.6, 7.1 and 1.2), 8.19 (2 H, m), 8.40 (2 H, d, *J* 8.3), 8.83 (2 H, d, *J* 6.6) and 8.95 (2 H, d, *J* 6.6).

2,2'-Dimethyl-1,1'-biisoquinolinium diiodide ($3^{2+}2I^-$)

1,1'-Biisoquinoline (0.16 g, 0.63 mmol) was dissolved in 6 cm^3 of methyl iodide and stirred at 50 °C. When the yellow precipitate of the monoquaternary salt had separated out, a small amount of DMF was added to dissolve the salt and the solution was stirred at 50 °C for 4 days. The resulting red precipitate was filtered off, washed with benzene, recrystallised from MeOH–EtOH as red plate-like crystals (0.27 g, 81%). Mp 201–202 °C (decomp.); λ_{max}(DMF)/nm 358 (ε/dm^3 mol^{-1} cm^{-1} 7600); δ_H(D_2O) 4.27 (6 H, s, CH_3), 7.74 (2 H, dd, *J* 8.8 and 0.4), 7.98 (2 H, ddd, *J* 8.6, 7.3 and 1.2), 8.36 (2 H, td, *J* 7.7 and 0.4), 8.56 (2 H, d, *J* 7.6), 8.97 (2 H, d, *J* 6.8) and 9.06 (2 H, d, *J* 6.8).

Reduction of BIQ^{2+} with $Na_2S_2O_4$

To an aqueous solution of $BIQ^{2+}2X^-$ excess amounts of $Na_2S_2O_4$ and Na_2CO_3 were added under Ar at room temperature, and a coloured solid immediately separated out. The solid was put into a quartz capillary together with a small amount of the mother liquor and the mass spectrum was recorded. For the ^1H NMR spectrum, reduction was carried out in a Schlenk tube connected to an NMR tube through a stopcock, under vacuum. When the solid separated out, 0.8 cm^3 of CD_2Cl_2 was vacuum-transferred into the Schlenk tube and the solid was extracted. The organic layer was transferred to the NMR tube and sealed off. The ^1H NMR spectra were recorded at −10 °C.

2,2'-Ethylene-1,1'-biisoquinylidene (1). δ_H(CD_2Cl_2) 3.39 (4 H, s, CH_2), 5.49 (2 H, d, *J* 7, 4,4'-H), 6.17 (2 H, d, *J* 7, 3,3'-H), 6.78 (2 H, t, *J* 7, 6,6'-H), 6.89 (2 H, d, *J* 7, 5,5'-H), 7.05 (2 H, dd, *J* 7 and 8, 7,7'-H) and 7.14 (2 H, d, *J* 8, 8,8'-H).

(*E*)- and (*Z*)-2,2'-Dimethyl-1,1'-biisoquinylidene [(*E*)-3 and (*Z*)-3]. (*E*)-Isomer: δ_H(CD_2Cl_2) 2.61 (6 H, s, Me), 5.78 (2 H, d, *J* 7, 4,4'-H), 6.40 (2 H, d, *J* 7, 3,3'-H) and 7.63 (2 H, d, 8,8'-H). (*Z*)-Isomer: δ_H(CD_2Cl_2) 2.97 (6 H, s, Me), 5.5 (2 H, d, *J* 7, 4,4'-H) and 6.47 (2 H, d, *J* 7, 3,3'-H). All the other aromatic signals are observed at δ 6.9–7.2 overlapping with each other. The isomer ratio was determined based on the integration ratio of the methyl protons.

Reduction of BIQ^{2+} with sodium–amalgam

A solution of $BIQ^{2+}2X^-$ in acetonitrile was placed in a Pyrex tube equipped with a UV or an EPR cell and a branch containing 0.5% Na–Hg. The whole system was degassed and stoppered with a vacuum-tight stopcock. The solution and Na–Hg were mixed by shaking the tube, after which the reduction of BIQ^{2+} was monitored by spectroscopy.

Isolation of CL products

To an aqueous solution of $BIQ^{2+}2X^{-}$ were added excess amounts of $Na_2S_2O_4$ and Na_2CO_3 under Ar. When a coloured precipitate separated out from the solution, the precipitate was extracted with $CHCl_3$ under air. After light emission the organic layer was dried over Na_2SO_4 and then concentrated under reduced pressure. The residue was separated by silica gel chromatography using benzene–MeOH as the eluent.

2,2′-Ethylenebis[isoquinolin-1(2*H*)-one] (4). Yield 33%; mp 201–202 °C (lit.,[2] 200–202 °C); ν_{max}/cm^{-1} 1600–1660; δ_H 4.41 (4 H, s, CH_2), 6.34 (2 H, d, J 7.3, 4,4′-H), 6.85 (2 H, d, J 7.3, 3,3′-H), 7.49 (4 H, m, Ar), 7.64 (2 H, m, 6,6′-H) and 8.44 (2 H, d, J 8.1, 8,8′-H).

2,2′-Trimethylenebis[isoquinolin-1(2*H*)-one] (5). Yield 72%; mp 157–158 °C; ν_{max}/cm^{-1} 1650–1660; δ_H 2.32 (2 H, quintet, J 7, CH_2), 4.12 (4 H, t, J 7, CH_2), 6.51 (2 H, d, J 7.5, 4,4′-H), 7.17 (2 H, d, J 7.5, 3,3′-H), 7.49 (4 H, m, Ar), 7.64 (2 H, m, 6,6′-H) and 8.42 (2 H, d, J 7.8, 8,8′-H).

2-Methylisoquinolin-1(2*H*)-one (6). Yield 64%; ν_{max}/cm^{-1} 1600–1660; δ_H 3.58 (3 H, s, CH_3), 6.46 (1 H, d, J 7.3, 4-H), 7.04 (1 H, d, J 7.3, 3-H), 7.47 (2 H, m, 5, 7-H), 7.61 (1 H, ddd, J 6.6, 8.3 and 1.5, 6-H) and 8.41 (1 H, d, J 8.1, 8-H).

3-Methylisoquinoline-1,2,4-trione (7). This compound was isolated by preparative TLC on silica gel as yellow crystals. Mp 186.5–187 °C (lit.,[13] 185–186 °C); δ_C 157.6, 162.4, 174.6 (lit.,[13] 157.6, 162.6, 174.8); m/z 189 (M^+, 3%) and 104 (100).

Reaction of $1^{+\bullet}$ and KO_2

A solution of $1^{+\bullet}$ in acetonitrile was prepared by reduction of 1^{2+} with Na–Hg under vacuum after which solid KO_2 was added to the solution under Ar.

Photochemical reactions of 4–6

A solution of 4–6 in benzene was irradiated with a Pyrex-filtered 400 W high-pressure mercury lamp (> 300 nm) at around 25 °C under degassed or aerated conditions. After photolysis, the reaction mixture was concentrated under reduced pressure and chromatographed on silica gel using benzene–MeOH (10 : 1 v/v) as the eluent.

6a,6b,12b,12c-Tetrahydro-6,7-ethanocyclobuta[1,2-*c*:4,3-*c*′]biisoquinoline-5,8-dione (8). Mp 247–248 °C; ν_{max}/cm^{-1} 1660; δ_H 2.78 (2 H, m, CH_2), 4.45 (2 H, m), 4.59 (2 H, m), 4.87 (2 H, m, CH_2), 6.84 (2 H, dd, J 7.6 and 1.5, Ar), 7.11 (2 H, td, J 7.6 and 1.5, Ar), 7.22 (2 H, td, J 7.6 and 1.5, Ar) and 7.95 (2 H, dd, J 7.8 and 1.5, Ar); m/z 316 (M^+, 9%).

6a,6b,12b,12c-Tetrahydro-6,7-propanocyclobuta[1,2-*c*:4,3-*c*′]biisoquinoline-5,8-dione (9). Mp 287–288 °C; ν_{max}/cm^{-1} 1670; δ_H 1.68 (1 H, m, $CH_2CH_2CH_2$), 2.36 (1 H, m, $CH_2CH_2CH_2$), 2.60 (2 H, m, NCH_2), 4.55 (2 H, m), 4.68 (2 H, m), 4.77 (2 H, m, NCH_2), 6.81 (2 H, dd, J 7.6 and 1.3, Ar), 7.07 (2 H, td, J 7.6 and 1.3, Ar), 7.17 (2 H, td, J 7.6 and 1.3, Ar) and 7.95 (2 H, dd, J 7.6 and 1.3, Ar); δ_C 161.7 (C=O); m/z 330 (M^+, 9%).

6a,6b,12b,13a-Tetrahydro-6,7-ethanofuro[3,2-*c*:4,5-*c*′]biisoquinoline-5,8-dione (10). Mp 172 °C (decomp.); ν_{max}/cm^{-1} 1670; δ_H 3.76 (2 H, d, J 10.0, CH_2), 4.17 (2 H, dd, J 10.0 and 2.7, NCH), 4.44 (2 H, d, J 10.0, CH_2), 5.62 (2 H, dd, J 10.0 and 2.7, OCH), 7.42 (2 H, m, Ar), 7.51 (2 H, m, Ar), 7.60 (2 H, td, J 7.6 and 1.5, Ar) and 8.18 (2 H, dd, J 7.3 and 1.5, Ar); δ_C 163.0 (C=O).

6aα,6bα,12bα,13aβ-Tetrahydro-6,7-propanofuro[3,2-*c*:4,5-*c*′]biisoquinoline-5,8-dione (11). Mp 269 °C (decomp.); ν_{max}/cm^{-1} 1640–1660; δ_H(500 MHz) 2.09 (2 H, m, $CH_2CH_2CH_2$), 2.92 (1 H, m, NCH_2), 2.97 (1 H, m, NCH_2), 3.94 (1 H, dd, J 11.5 and 5.8, NCH), 4.71 (1 H, dd, J 7.3 and 5.9, NCH), 4.83 (1 H, d, J 11.4, OCH), 4.96 (1 H, m, NCH_2), 5.03 (1 H, m, NCH_2), 5.74 (1 H, d, J 7.3, OCH), 7.34 (1 H, d, J 7.6, Ar), 7.39 (1 H, t, J 7.7, Ar), 7.48 (1 H, td, J 7.5 and 1.1, Ar), 7.53 (1 H, td, J 7.6 and 1.1, Ar), 7.56 (1 H, d, J 7.7, Ar), 7.64 (1 H, td, J 7.6 and 1.3, Ar), 8.04 (1 H, d, J 7.7, Ar) and 8.25 (1 H, d, J 7.8, Ar); δ_C 166.0 and 162.8 (C=O); m/z 346 (M^+, 6%).

6aα,6bβ,12bβ,12cα-Tetrahydro-6,7-dimethylcyclobuta[1,2-*c*:4,3-*c*′]biisoquinoline-5,8-dione (12). Mp 279–280 °C (from benzene); ν_{max}/cm^{-1} 1650; δ_H 3.17 (6 H, s, CH_3), 3.92 (2 H, d, J 8.3), 4.26 (2 H, d, J 8.3), 7.33 (2 H, d, J 7.6, Ar), 7.42 (2 H, t, J 7.8, Ar), 7.57 (2 H, td, J 7.6 and 1.5, Ar) and 8.25 (2 H, d, J 7.8, Ar); δ_C 162.5 (C=O); m/z 159 ($M^+/2$, 100%).

6a,6b,12a,12b-Tetrahydro-6,12-dimethyl-6b-H-cyclobuta[1,2-*c*:3,4-*c*′]biisoquinoline-5(6*H*),11-dione (13). Mp 210–211 °C; ν_{max}/cm^{-1} 1630; δ_H 3.25 (6 H, s, CH_3), 4.30 (2 H, t, J 7.3), 4.47 (2 H, td, J 7.6 and 1.5), 6.77 (2 H, d, J 7.8, Ar), 7.07 (2 H, td, J 7.8 and 1.2, Ar), 7.31 (2 H, td, J 7.6 and 1.5, Ar) and 7.61 (2 H, dd, J 7.8 and 1.5, Ar); δ_C 162.5 (C=O); m/z 159 ($M^+/2$, 100%).

X-Ray structure determination of 11

$C_{21}H_{18}N_2O_3$, $M = 346.3$, monoclinic, $a = 11.2285(9)$, $b = 14.769(1)$, $c = 10.127(1)$ Å, $\beta = 104.911(8)°$, $V = 1622.8(3)$ Å^3, space group $P2_1/n$, $Z = 4$, $D_x = 1.417$ g cm^{-3}, $F(000) = 728$, $T = 296$ K. Colourless plates. Crystal dimensions 0.2 × 0.07 × 0.05 mm. $\mu = 0.74$ mm^{-1}. Intensity data were collected on a Rigaku AFC-5R diffractometer with graphite-monochromated Cu-Kα radiation ($\lambda = 1.541\ 84$ Å), using the ω–2θ scan technique up to $2\theta = 125.0°$. 2707 unique reflections were measured and 1061 with $F_o > 2\sigma(F_o)$ were considered as observed and used for structure determination. The structure was solved by direct methods (SHELXS86[19]) and refined by full-matrix least-squares (SHELX76[20]). All the H-atoms were treated as riding on the C atoms with an overall isotropic thermal parameter. The final R and R_w values were 0.092 and 0.088, respectively, for 1061 observed reflections and 236 refined parameters with a weighting scheme of $w = [\sigma^2(F_o) + 0.002\ F_o^{\ 2}]^{-1}$. The maximal shift/esd $(\Delta/\sigma)_{max}$ was 0.08 in the final refinement and the difference map showed $-0.37 < \Delta\rho < 0.39$ e Å^{-3}.

X-Ray structure determination of 12

Data collection and structure determination were carried out by procedures similar to those described for **11**. $C_{20}H_{18}N_2O_2$, $M = 318.34$, orthorhombic, $a = 16.978(3)$, $b = 22.114(4)$, $c = 8.482(2)$ Å, $V = 3184.8(11)$ Å^3, Mo-Kα radiation ($\lambda = 0.710\ 68$ Å), space group $Pbca$, $Z = 8$, $D_x = 1.328$ g cm^{-3}, $F(000) = 1392$, $T = 298$ K. Colourless column-like crystals. Crystal dimensions 0.5 × 0.2 × 0.1 mm. $\mu = 0.08$ mm^{-1}. 2793 unique reflections were measured and 1651 with $F_o > 2\sigma(F_o)$ were considered as observed and used for structure determination. Each methyl group was treated as a rigid group. The final refinement with anisotropic thermal parameters for non-H atoms and isotropic thermal parameters for H atoms converged at $R = 0.058$ and $R_w = 0.063$ for 1651 observed reflections and 271 refined parameters. $(\Delta/\sigma)_{max} = 0.21$, $-0.19 < \Delta\rho < 0.20$ e Å^{-3}.§

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§ Lists of final atomic coordinates, thermal parameters, bond distances and angles have been deposited at the Cambridge Crystallographic Data Centre. For details of the CCDC deposition scheme see 'Instructions for Authors (1996)', *J. Chem. Soc., Perkin Trans. 2*, 1996, issue 1.

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