ELSEVIER

Dyes and Pigments, Vol. 32, No. 1, pp. 43–58, 1996

PII: S0143-7208(96)00009-5 0143-7208/96 $15.00 + 0.00

Synthesis and Chromophoric Properties of Symmetrical bis-Heteroannelated Diketopiperazines: Diimidazo- and Dipyrazolo-Piperazinediones

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(Received 14 December 1995; accepted 8 January 1996)

ABSTRACT

Several derivatives of the symmetrical diimidazopiperazinedione and dipyrazolopiperazinedione chromophoric systems have been synthesised and their light absorption properties investigated with the aid of PPP-MO theory. In the case of the diimidazopiperazinedione system, yellow to red derivatives can be obtained by introducing amino substituents in the 1,6- or 3,8-positions. The system is appreciably less sensitive than the 9,10-anthraquinone system towards the bathochromic effect of amino substituents, but resultant dyes have molar absorption coefficients 2–3 times greater than those of the anthraquinones, with smaller half-bandwidths. The dipyrazolopiperazinediones show a somewhat greater bathochromic shift when two donor groups are introduced into the 3,8-positions, and (theoretically) the 2,7-positions, but the system is also not as sensitive to donors as the anthraquinone system and dyes have low absorption intensities similar to the anthraquinones. Copyright © 1996 Elsevier Science Ltd

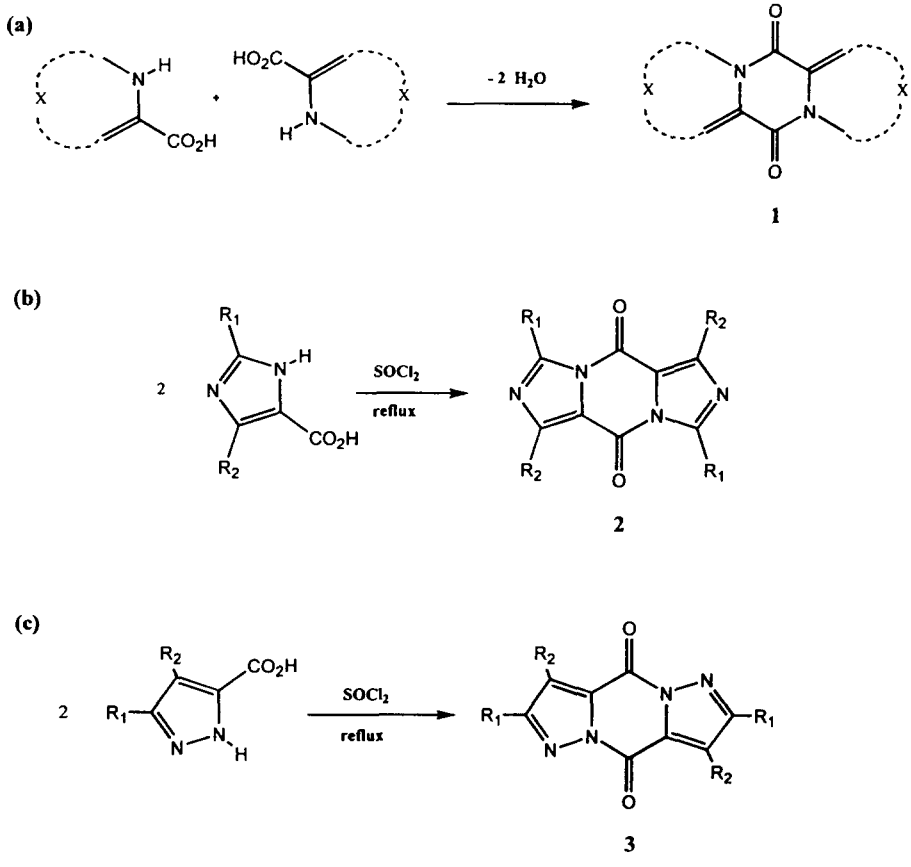
INTRODUCTION

Cross-conjugated chromophores offer considerable potential in dye chemistry, and in suitable cases they can provide such desirable colour properties as long wavelength absorption for a small molecular size, high molar extinction coefficients, and narrow absorption bands. The classical example is of course the *H-chromophore* of indigo, and more recently the benzodifuranones and diketopyrolopyrroles have provided examples of outstanding technical importance. In the search for new cross-conjugated

chromophores with similar colouristic advantages, predictive molecular orbital procedures such as the PPP-SCF-CI method are extremely useful for screening candidate chromophores with minium expenditure of time and effort.

In such a screening exercise, we found that the PPP method predicted that annelated diketopiperazines of general structure **1**, where X completes a heterocyclic ring substituted with electron donor groups, have the potential to absorb strongly in the visible region. Interestingly only a small number of such compounds have been described in the literature, few of which are coloured, and very little is known about their UV/visible absorption spectroscopic properties. Thus the synthesis of representative examples was examined with a view to evaluating their light absorption characteristics, and at the same time testing the predictive reliability of the PPP-MO method.

The synthetic strategy towards **1** is attractively simple (Scheme 1a)[1–4] and requires condensing together two molecules of a suitable heterocyclic



Scheme 1.

compound which contains a carboxy group *ortho* to a ring NH group, with effectively the elimination of two molecules of water. The cyclo-condensation can be achieved with the agency of thionyl chloride, for example. With due regard to the availability of suitable carboxy-heterocycles, two series of chromophores were selected for closer study, namely the diimidazo[1,5-a:1′,5′-d]piperazine-5,10-diones (**2**) (Scheme 1b) and the dipyrazolo[1,5-a:1′,5′-d]piperazine-4,9-diones (**3**) (Scheme 1c). Attempts were made to prepare related systems from carboxypyrroles and carboxyindoles but these were unsuccessful.

Several derivatives of **2** and **3** were prepared, most of which were colourless, but by introducing electron donor groups some coloured derivatives could also be obtained. UV/visible absorption spectroscopic properties have been measured and these are discussed and interpreted with the aid of PPP MO theory.

EXPERIMENTAL

General

Melting points were determined by differential scanning calorimetry with a Du Pont Analyzer 2000. Fast atom bombardment (FAB) mass spectra were performed on a VG AutoSpec instrument using caesium ion bombardment and 3-nitrobenzyl alcohol as matrix liquid. Electron impact (EI) and chemical ionisation (CI) spectra were recorded on a VG Model 12-253 quadrupole instrument. Electronic absorption spectra were measured on a Perkin Elmer Lambda 15 spectrophotometer.

General procedure for synthesis of diimidazo[1,5-a:1′,5′-d]piperazine-5,10-diones (2)

A suspension of the appropriate imidazole-5-carboxylic acid (0.02 mol) in thionyl chloride (30 cm^3) was stirred under reflux for 18 h. After cooling, the suspension was filtered and the white residue washed with toluene and dried to give the diimidazopiperazinedione.

In all the cases the product was pure by TLC, also indicated by the single sharp m.p. by DSC, and did not require further purification. New products were characterised by microanalysis and/or mass spectrometry. Melting points were generally in excess of 300°C. The following known products were synthesised in yields shown: **2a**[5] (quant.); **2b**[6] (quant.); **2c**[7] (96%); **2d**[8] (95%); **2f**[8] (94%, from the acid chloride **2c**).

The 1,6-bis cyclohexylamide derivative **2e** was prepared from **2d** and cyclohexylamine in a two step reaction. Thus addition of the amine gave the ring opened product, which was cyclised to **2e** by reaction with $SOCl_2$. Overall yield 38%; *m/z* (FAB) 439, $[M+H]^+$.

1,6-Dicarboxyethyl- 3,8-di-*n*-butyldiimidazo[1,5-a:1′,5′-d]piperazine-5,10-dione (2g)

2-*n*-Butylimidazole-4,5-dicarboxylic acid (0.024 mol) was refluxed in thionyl chloride (6 cm^3) for 4 h. The brown mixture was cooled to below 0°C and the pale yellow solid filtered off, washed with toluene and dried under vacuum, giving the 1,6-bis-acid chloride. This was then reacted with ethanol to give the 1,6-bis ethyl ester (**2h**) as a white solid in 96% yield. Found: C, 58.9; H, 6.3; N, 12.85%; $C_{22}H_{28}N_4O_6$ requires C, 59.4; H, 6.45; N, 12.6%; *m/z* (FAB) 445, $[M + H]^+$.

1,6-Diamino-diimidazo[1,5-a:1′,5′-d]piperazine-5,10-dione (2h)

A suspension of the dinitro compound **2b** (0.50 g, 0.018 mol) in ethanol (7 cm^3) and concentrated hydrochloric acid (18 cm^3) was stirred at 43°C, and iron powder was added in portions at a rate such that the temperature did not rise above 45°C. After addition was complete, stirring was continued for 10 min and the mixture was then cooled to room temperature. Water (200 cm^3) was added and the precipitate filtered off. This was washed several times with ethanol and dried to give **2i** as a yellow solid (4.3 g, quant.), pure by TLC (*m/z* (EI) 218, M^+).

1,3,6,8,-Tetrabromo-diimidazo[1,5-a:1′,5′-d]piperazine-5,10-dione (2i)

This was prepared from 2,4-dibromoimidazole-5-carboxylic acid by the general procedure outlined above. It was isolated in 98% yield as a pale yellow solid, m.p. 361°C (DSC); *m/z* (EI): 500, 502, 504, 506, 508; M^+.

General procedure for reaction of 2i with arylamines

A mixture of **2i** (1.00 g, 1.98 mmol), the arylamine (3.0 g) and acetic acid (50 cm^3) was stirred under reflux for 7 h. After cooling, the deposited solid was filtered off, washed several times with ethanol and dried under vacuum. Purification was effected by column chromatography, using silica gel (Type 60) as adsorbent and chloroform: ethyl acetate (20:1 by volume) as eluent.

1-Bromo-3,6,8-triphenylamino-diimidazo[1,5-a:1′,5′-d]piperazine-5,10-dione (**2j**) was obtained in 93% yield from aniline; m.p. 275°C (DSC); *m/z* (FAB) 539, 541; M^+.

1-Bromo-3,6,8-tri(3′-methoxyphenylamino)-diimidazo[1,5-a:1′,5′-d]piperazine-5,10-dione (**2k**) was obtained as a bright yellow solid in 96% yield from 3-methoxyaniline; m.p. 312°C (DSC); *m/z* (FAB) 629, 631; M^+.

1,6-Dibromo-3,8-di(4′-methoxyphenylamino)-diimidazo[1,5-a:1′,5′-d]piperazine-5,10-dione (**2l**) was formed from 4-methoxyaniline as a bright orange solid in 86% yield; m.p. 249°C (DSC); *m/z* (EI) 586, 588 and 590; M^+.

1,6-Dibromo-3,8-di(4′-aminophenylamino)-diimidazo[1,5-a:1′,5′-d]piperazine-5,10-dione (2m)

A mixture of **2i** (0.50 g, 1 mmol), *p*-phenylenediamine (1.5 g, *ca* 14 mmol) and acetic acid (30 cm^3) was stirred at 37°C for 7 h. The suspension was cooled to room temperature, poured into ethanol (200 cm^3) and filtered to give a dark red solid. This was washed several times with hot ethanol and dried, giving **2m** (0.55g; 99%), pure by TLC; m.p. 250°C (DSC); *m/z* (FAB) 556, 558, 560; M^+.

1,6-Dibromo-3,8-di(4′-*NN*-diethylaminophenylamino)- and 1-bromo-3,6,8-tri(4′-*NN*-diethylaminophenylamino)- diimidazo[1,5-a:1′,5′-d]piperazine-5,10-diones; 2n and 2o, respectively

A mixture of **2i** (1.00 g, 1.99 mmol), *NN*-diethyl-*p*-phenylenediamine (3.0 g, *ca* 18 mmol) and acetic acid (50 cm^3) was stirred at 75°C for 5 h. The dark mixture was poured into ice-water (200 g) and neutralised to pH 5.5 with dilute sodium hydroxide solution. The reddish-violet solid that deposited was filtered off, washed with water and dried. The solid was dissolved in chloroform-ethyl acetate (20:1) and chromatographed over silica gel (Type 60) in the same solvent mixture. The first of the two coloured components to be eluted was **2n**, affording after evaporation of the solvent, a violet solid (0.80 g, 60%); *m/z* (FAB) 668, 670, 672; M^+. The second component **2o** was isolated as a brown solid (0.60 g, 40%); *m/z* (FAB) 752, 754; M^+. Both products were pure by TLC.

General procedure for the synthesis of dipyrazolo[1,5-a:1′,5′-d]piperazine-4,9-diones (3)

A mixture of the appropriate pyrazole-5-carboxylic acid (13 mmol) and thionyl chloride (15 cm^3) was stirred under reflux for 18 h. After cooling to room temperature the solid was filtered off, washed thoroughly with toluene and dried. The product was pure by TLC and DSC and required no further purification. Known derivatives prepared by this method were **3a**[4] (quant.; m.p. 298°C; *m/z* (FAB) 188, M^+), **3b**[2] (91%; m.p. 352°C), **3d**[3] (93%; m.p.

356°C (dec.), **3k**[9] (85%; m.p. 403°C; *m/z* (EI) 372, 374, 376; M^+), and **3m**[10] (70%; m.p. 371°C; *m/z* (EI) 340; M^+). New derivatives prepared by this method were as follows:

3c, from 3-t-butylpyrazole-5-carboxylic acid (quant.; m.p. 312°C; *m/z* (CI) 301, $[M+H]^+$)
3f, from 3-t-butyl-4-nitropyrazole-5-carboxylic acid (49%; m.p. 345°C; *m/z* (EI) 391, $[M+H]^+$)
3j, from 4-bromopyrazole-5-carboxylic acid (75%; m.p. 326°C; *m/z* (EI) 344,346, 348; M^+)
3l, from 4-bromo-3-t-butylpyrazole-5-carboxylic acid (68%; m.p. 366°C; *m/z* (EI) 456, 458, 460; M^+)
3n, from 3-(4′-methoxyphenyl)pyrazole-5-carboxylic acid (96%; m.p. 384°C; *m/z* (EI) 400, M^+)
3o, from 3-(2′-thienylpyrazole)-5-carboxylic acid (58%; *m/z* (FAB) 353, $[M+H]^+$)
3p, from 4-bromo-3-(4′-methoxyphenyl)pyrazole-5-carboxylic acid (53%; m.p. 326°C; *m/z* (EI) 556,558,560; M^+)
3q, from 4-bromo-(4′-bromo-2′-thienyl)-5-carboxylic acid (70%; *m/z* (EI) 664, 666, 668, 670, 672; M^+)

Dipyrazolo[1,5-a:1′,5′-d]piperazine-4,9-dione-2,7-dicarboxylic acid chloride (3g) and derived dicarboxylic acid (3h) and diethyl ester (3i)

Thionyl chloride (6 cm^3) was added to a stirred mixture of pyrazole 3,5-dicarboxylic acid monohydrate (5 g), dimethylformamide (0.8 cm^3) and dry benzene (20 cm^3) and the mixture refluxed for 7 h. The solvent was evaporated under vacuum and the residue stirred with toluene (8 cm^3) for 30 min at room temperature, filtered off, washed with more toluene and dried under vacuum to give pure **3g** (1.45 g, 93%). Found: C 38.35, H 0.5, N 18.5%; $C_{10}H_2N_4O_4Cl_2$ requires C 38.4, H 0.6, N 17.9%.

Hydrolysis of the product was effected by stirring **3g** (1.33 g, 4.2 mmol) in water (10 cm^3) at 40°C for 5 h. The white solid was filtered off, washed with ice water and acetone and dried to give the dicarboxylic acid **3h** (1.24 g, 93%). Found: C 38.25, H 2.2, N 18.45%; $C_{10}H_4N_4O_6 \cdot 2H_2O$ requires C 38.5, H 2.6, N 17.9%.

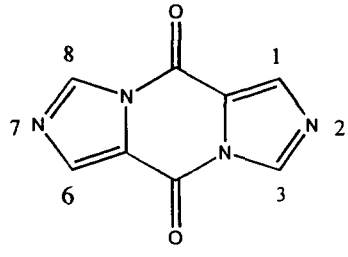
The diethyl ester **3i** was prepared by stirring **3g** (1.32 g, 4.2 mmol) in dry ethanol (28 cm^3) for 18 h. The solid was filtered off, washed successively with ethanol and ether, and dried to give pure **3i** (1.13 g, 81%). Found: C 50.65, H 3.6, N 17.2%; $C_{14}H_{12}N_4O_6$ requires C 50.6, H 3.6, N 16.9%.

RESULTS AND DISCUSSION

Synthesis of intermediates and dyes

*Diimidazopiperazinediones (**2**)*

The colourless unsubstituted derivative **2a**[5] was prepared by the route shown in Scheme 1b, and was obtained in near quantitative yield by refluxing



2

a:	**unsubstituted**
b:	**1,6-di-NO_2**
c:	**1,6-di-COCl**
d:	**1,6-di-CO_2H**
e:	**1,6-di-$CONHC_6H_{11}$**
f:	**1,6-di-CO_2Et**
g:	**3,8-di-n-Bu-1,6-di-CO_2Et**
h:	**1,6-di-NH_2**
i:	**1,3,6,8-tetra-Br**
j:	**1-Br -3,6,8-tri-PhNH-**
k:	**1-Br-3,6,8-tri-(m-$CH_3OC_6H_4NH$-)**
l:	**1,6-di-Br-3,8-di-(p-$CH_3OC_6H_4NH$-)**
m:	**1,6-di-Br-3,8-di-(p-$NH_2C_6H_4NH$-)**
n:	**1,6-di-Br-3,8-di-(p-$Et_2NC_6H_4NH$-)**
o:	**1-Br-3,6,8-tri-(p-$Et_2NC_6H_4NH$-)**

5-carboxyimidazole in thionyl chloride for 18 h. Various derivatives with electron withdrawing groups were investigated. The dinitro derivative **2b**[6] was prepared analogously from 5-carboxy-4-nitroimidazole in good yield. Imidazole 4,5-dicarboxylic acid reacted with thionyl chloride to give the bis-acid chloride **2c**[7], which was readily hydrolysed to the dicarboxylic acid **2d**[8]. The bis-cyclohexylamide **2e** was made by heating **2d** with cyclohexylamine and then recyclising the intermediate with thionyl chloride. The bis-acid chloride **2c** could be converted to the diethyl ester **2f**[8] by reaction with ethanol. Reaction of 2-*n*-butyl-imidazole-4,5-dicarboxylic acid with thionyl chloride analogously gave the bis-*n*-butyl dicarboxylic acid chloride which reacted with ethanol to give the diethyl ester **2g**.

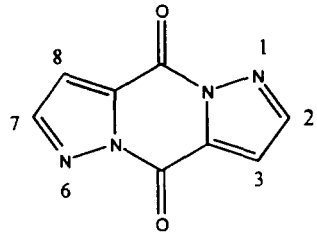
In order to obtain coloured derivatives it was necessary to introduce electron donor groups into the system and this was most readily achieved by reducing the dinitro derivative **2b**[6] to the diamino compound **2h** with iron powder and hydrochloric acid in ethanol, at temperatures below 45°C. This derivative was yellow.

To examine the effect of electron donor groups in the alternative 3,8-positions, a different strategy was employed. It was shown by Burak[11] that

the chlorine atoms in the 3,8-dichloro-1,6-dimethyl substituted diimidazopiperazinedione system (**2**) were readily replaced by amines. The synthesis of the 1,3,6,8-tetrabromo derivative (**2i**) was therefore undertaken, in order to examine the possibility of introducing amino functionality at several positions. Derivative **2i** was prepared by self-condensation of 2,4-dibromoimidazole-5-carboxylic acid in thionyl chloride and was isolated in 98% yield. Reaction with nucleophiles would, on simple mechanistic grounds for an S_NAr reaction, be expected to proceed much more readily at the 3,8-positions than at the 1,6-positions. In agreement with this, it was found that reaction of **2i** with excess 4-methoxyaniline in refluxing acetic acid resulted in displacement of two bromine atoms only, thus affording the orange 3,8-bis(4′-methoxyphenylamino)-derivative **2l** in 86% yield. The replacement of two bromine atoms was shown readily by mass spectrometry. 1,4-Diaminobenzene reacted similarly, giving the red 3,8-bis(4′-aminophenylamino) compound **2m** in near quantitative yield. However, reactions of **2i** with other primary arylamines showed a curious dependence of the degree of ring substitution on the structure of the arylamine. Reaction with excess aniline in boiling acetic acid led exclusively to replacement of three bromine atoms, and the tris-anilino-bromo derivative **2j** was isolated in 93% yield after purification by column chromatography. This yellow compound was characterised by mass spectrometry, the two equally intense molecular ions (m/z = 539, 541) confirming that three of the bromine atoms had been replaced. 3-Methoxyaniline, in marked contrast to 4-methoxyaniline, behaved similarly and gave a high yield of the tri-substituted product **2k** (yellow crystals). Interestingly, 4-*NN*-diethylaminoaniline gave a mixture of the di- and tri-substituted products **2n** and **2o**, respectively, which could be separated chromatographically (**2n**, 60%; violet solid (λ_{max} 495 nm in DMF); **2o**, 40%; brown solid (λ_{max} 491 nm in DMF)). In solution the various arylamino-derivatives **2j–o** ranged from yellow to red in colour.

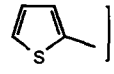
*Dipyrazolopiperazinediones (**3**)*

No coloured derivatives of the dipyrazolpiperazinediones (**3**) appear to be known, but PPP-MO calculations suggested that substitution with strong electron donor groups such as NH_2 should shift the longest wavelength absorption band into the visible region. Several derivatives (**3**) were synthesised in order to investigate the light absorption characteristics of the chromophoric system in detail. The synthetic route to these materials parallels that for the diimidazopiperazinediones (**2**), and is summarised in Scheme 1c. The parent system **3a**[4], and the 2,7-dimethyl and 2,7-di-t-butyl derivatives **3b**[2] and **3c**, respectively, were formed in near quantitative yields by heating the corresponding 5-carboxypyrazoles in thionyl chloride and were isolated as white crystalline solids. When 3-methyl-5-carboxy-4-nitropyrazole

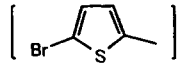


3

a: unsubstituted
b: 2,7-di-Me
c: 2,7-di-t-Bu
d: 2,7–di-Me-3,8–di-NO_2
e: 2,7-di-Me-3,8-di-NH_2
f: 2,7-di-t-Bu-3,8-di-NO_2
g: 2,7-di-COCl
h: 2,7-di-CO_2H
i: 2,7-di-CO_2Et
j: 3,8-di-Br
k: 2,7-di-Me-3,8-di-Br
l: 2,7-di-t-Bu-3,8-di-Br
m: 2,7-di-Ph
n: 2,7-di-(p-$MeOC_6H_4$-)

o: 2,7-di- 

p: 2,7-di-(p-$MeOC_6H_4$)-3,8-di-Br

q: 2,7-di- 

-3,8-di-Br

was similarly reacted with thionyl chloride, the 2,7-dimethyl-3,8-dinitro derivative **3d**[3] was formed in 93% yield, and this could be reduced quantitatively with iron powder and hydrochloric acid in ethanol to the corresponding 3,8-diamino compound **3e**. As predicted by MO theory this product was coloured, giving a yellow solution in DMF (λ_{max} 428 nm). Using 3-t-butyl-5-carboxy-4-nitropyrazole, the 2,7-di-t-butyl-3,8-dinitro-derivative **3f** was also synthesised.

The commercially available pyrazole-3,5-dicarboxylic acid behaved in expected fashion, and with thionyl chloride gave the bis-acid chloride **3g**. This could be hydrolysed readily to the dicarboxylic acid **3h** with water, and converted to the diethyl ester **3i** by reaction with ethanol.

3,8-Dibromo derivatives of the dipyrazolopiperidinedione system were readily prepared by the route shown in Scheme 1c using 4-bromo-5-carboxypyrazoles. Thus, the parent 3,8-dibromo compound **3j** and the corresponding 2,7-dimethyl and 2,7-di-t-butyl derivatives **3k** and **3l**, respectively, were prepared in moderate yields. Attempts to displace the bromine atoms by amines, e.g. by heating with aniline in acetic acid, were unsuccessful. The unreactivity of halogen in the 3- and 8-positions towards S_NAr substitution is not unexpected because of the deactivating +M effect of the bridgehead nitrogen atoms.

PPP-MO calculations suggested that an increase in absorption intensity of the dipyrazolopiperazinedione system should be obtainable by introducing aryl substituents in the 2,7-positions. To prepare derivatives of this type, the requisite 3-aryl-5-carboxypyrazole starting materials were synthesised by standard methods. Thus acetophenone or a substituted derivative was condensed with diethyl oxalate in the presence of sodium metal, and the resultant ethyl 4-aryl-2,4-diketobutyrate was condensed with hydrazine hydrate to give the 3-aryl-5-carboxyethylpyrazole. Hydrolysis of the ester group with dilute aqueous sodium hydroxide gave the 3-aryl-5-carboxypyrazole. Using the appropriate arylcarboxypyrazoles, the 2,7-diaryl derivatives **3m**[10] and **3n** were prepared as shown in Scheme 1c. The 2,7-bisthienyl derivative **3o** was prepared from the corresponding commercially available 3-thienyl-5-carboxypyrazole. Brominated analogues were prepared by first brominating the parent 3-aryl-5-carboxypyrazoles and then cyclising the product in thionyl chloride. Thus bromination of 3-(4′-methoxyphenyl)-5-carboxypyrazole gave the 4-bromopyrazole derivative and this was cyclised to **3p** in 53% yield. However, similar bromination of 3-(2′-thienyl)-5-carboxypyrazole gave a dibrominated product, in which both the pyrazole and the thiophene rings had been brominated. Cyclisation of this intermediate gave **3q**. As noted previously, the 3,8-bromine atoms in **3p** and **3q** were resistant to nucleophilic replacement by arylamines.

According to PPP predictions, the introduction of amino groups into the 2,7-positions would give useful red shifts, but we were unable to synthesise examples of these. For example, 2,3,7,8-tetrabromodipyrazolopiperazinedione would have provided a possibly useful intermediate for such derivatives, if the 2- and 7-bromine atoms could be replaced by amines. However, various attempts to synthesise the requisite 3,4-dibromopyrazole-5-carboxylic acid were unsuccessful.

Light absorption properties of the diimidazo- and dipyrazolo-piperazinediones

PPP-MO method

The absorption spectra of all derivatives **2** and **3** were calculated by the PPP-MO method, using the non-variable β approximation and confining configuration interaction to the first nine singly excited singlet states. Planar structures were assumed, and with the amino-substituted derivatives, intramolecular hydrogen bonding between the NH proton and the adjacent carbonyl group was assumed to be as in related anthraquinones. Planarity and hydrogen bonding of this type has been confirmed by X-ray crystallography for one example of system **2**.[11] Preliminary calculations showed that C–C bond orders in the general system **2** showed a high degree of uniformity, and thus for simplicity bond resonance integrals were assumed to be the same throughout and were given the usual aromatic value of −2.4 eV.[12] On the other hand, system **3** showed a much higher degree of bond alternation and so conventional olefinic/allylic resonance integrals were used with good results. Other parameters used were based on those reported previously,[12] and gave satisfactory agreement between theory and experiment, predicting relative trends very well.

For the various alkyl substituted derivatives in series **2** and **3**, the effects of the alkyl groups could be reproduced closely by relatively minor empirical parameterisation of the π-equivalent and π-excessive ring nitrogen atoms and of the carbon atom bearing the alkyl group. These changes in the ionisation potentials and electron affinities from the normal heterocyclic values[12] compensated empirically for the +I effect of the alkyl groups, and also for the solvent polarity effects. The values used, in electron volts, were as follows: VSIP (EA) –N: 18.5 (9.0); –N=: 14.0 (2.0); –C–: 10.16 (0.03); [normal values for imidazole and pyrazole for non-polar solvents: 21.0 (10.0), 16.0 (2.5), 11.16 (0.03), respectively].[12] Thus excellent correlation between theoretical and experimental λ_{max} values was obtained (Fig. 1a and 1b).

*Diimidazopiperazinediones (**2**)*

Because of the generally low solubility properties of these derivatives, UV/visible absorption spectra were measured in dimethylformamide. Absorption maxima, molar absorption coefficients and half-bandwidths are summarised in Table 1. The results of the PPP calculations are compared with the experimental data in Table 1. It can be seen that the correlation between predicted and observed λ_{max} values is excellent, most predicted values falling within about 5 nm of the observed value and the largest discrepancy being 10 nm. Correlation between calculated oscillator strengths and experimental ϵ_{max} values is far less satisfactory, however, particularly with the shorter wavelength absorbing materials.

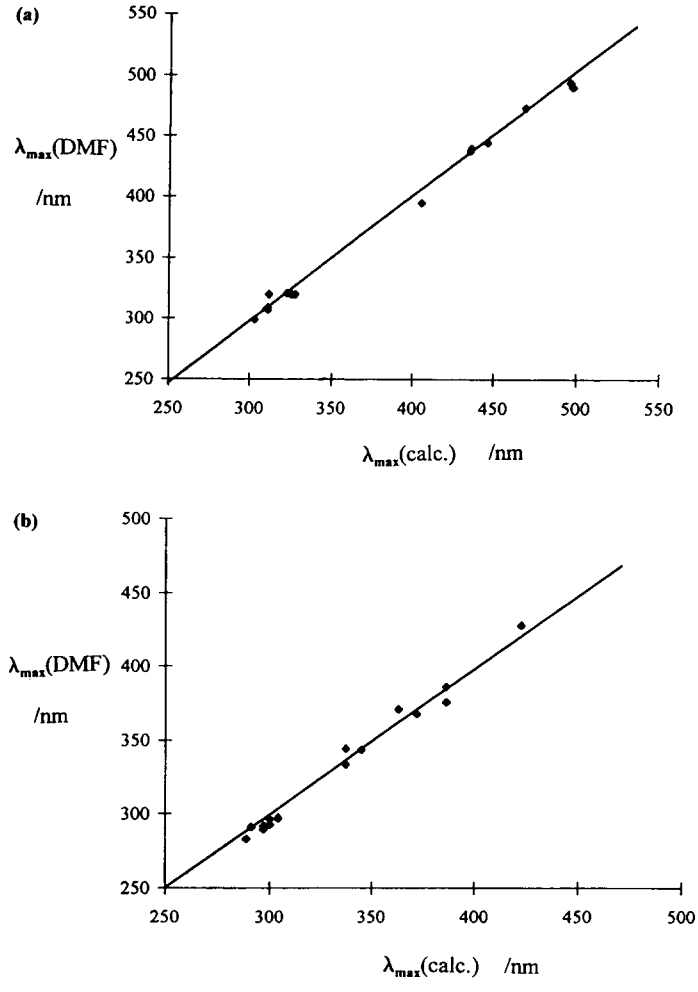


Fig. 1. Correlation between PPP-calculated and observed λ_{max} values (solvent DMF) for (a) diimidazopiperazinediones **2** and (b) dipyrazolopiperazinediones **3**.

The MO calculations show that the longest wavelength transition of the diimidazopiperazinedione system can be well approximated to the HOMO → LUMO transition, and electron density changes for the parent chromophore **2a** indicate that this transition involves a large degree of electron density migration from the ring bridgehead positions onto the carbonyl groups. Changes at peripheral ring positions are smaller, and cannot be used reliably to predict the effects of substituents. However, it is evident that positions 1 and 6 (see numbering scheme in structure **2**) show a significant decrease in electron density for the HOMO → LUMO transition, implying

TABLE 1
Experimental and Calculated Electronic Absorption Spectral Data for **2** and **3**[a]

Dye	λ_{max}/nm	ϵ_{max}/l mol^{-1}cm^{-1}	$\Delta\lambda_{1/2}$[b]/nm	λ_{max} (calc.)/nm	**f** (calc.)[c]
2a	299	8700	54	303	0.79
2b	320	11 800	80	328	0.77
2c	308	–[d]	–[d]	310	0.85
2d	309	–[d]	–[d]	311	0.85
2e	320	–[d]	37	312	0.80
2f	307	–[d]	64	311	0.85
2g	321	12 300	39	325	0.91
2h	395	16 400	47	405	0.90
2i	320	11 300	61	326	0.86
2j	438	33 200	60	435	1.43
2k	440	43 600	61	436	1.41
2l	445	34 400	72	445	1,27
2m	474	30 400	95	468	1.27
2n	495	31 000	118	496	1.17
2o	491	36 500	105	497	0.86
3a	283	–[d]	–[d]	289	0.92
3b	297	13 400	58	304	0.89
3c	298	15 800	59	304	0.89
3d	293	14 400	70	300	0.95
3e	428	9700	67	422	1.05
3f	297	14 800	65	300	0.95
3g	291	–[d]	60	291	0.95
3h	292	–[d]	62	297	1.00
3i	290	10 500	65	297	1.00
3j	334	–[d]	–[d]	337	0.80
3k	350, 336	15 700; 17 000	57	345	0.85
3l	356, 336	12 900; 13 500	55	345	0.85
3m	344	11 600	49	337	1.05
3n	371	13 700	57	363	0.80
3o	368	18 300	58	372	0.96
3p	376	16 100	75	386	1.21
3q	386	17 800	81	386	1.24

[a] Solvent DMF; [b] half-bandwidth; [c] oscillator strength; [d] too unstable in DMF for accurate measurement.

that attachment of electron-donating groups at these positions would be most effective for producing a bathochromic shift. This was confirmed by consideration of 1,6-diamino derivative (**2h**) which absorbs at 395 nm and is yellow in colour. The amino groups thus produce a bathochromic shift of 96 nm.

According to the electron density changes for the HOMO → LUMO transition for the unsubstituted system, positions 3 and 8 undergo a small increase in electron density and one might expect electron-donating groups

in these positions to exert a hypsochromic effect. However, this simple picture is invalid, and MO calculations for 3,8-bis-donor (+M) derivatives indicate that large bathochromic shifts are to be expected. This effect can be clearly seen with the 3,8-diarylamino dyes (**2l–n**) which show a progressive bathochromic shift as the electron donating strength of the aryl residue is enhanced by substitution. Thus λ_{max} values for the 4-methoxy (**2l**), 4-amino (**2m**) and 4-*NN*-diethylamino (**2n**) derivatives are 445, 474 and 495 nm, respectively. It is interesting that further substitution of the system to give a triarylamino derivative does not give an additional bathochromic shift and may even cause a small hypsochromic shift (compare **2n** and **2o** which have λ_{max} values of 495 and 491 nm, respectively).

It is interesting to compare the light absorption properties of **2** with those of the 9,10-anthraquinone dyes, which they superficially resemble. The parent system **2a** has λ_{max} 299 nm in DMF, which is significantly more hypsochromic than anthraquinone (λ_{max} (π-π^* band) 326 nm in DMF). The 1,6-diamino-diimidazopiperazinedione (**2h**) has λ_{max} = 395 nm in DMF and 1,5-diaminoanthraquinone (the most appropriate isomer for comparison purposes) has λ_{max} = 490 nm. The bathochromic shifts induced by the amino groups are thus 96 nm and 164 nm, respectively, showing the greater sensitivity of the anthraquinone system towards electron donating groups and indicating the potentially more limited colour range that can be provided by 1,6-donor substituents in system **2**. However, the molar absorption coefficients of **2h** and 1,5-diaminoanthraquinone are 16400 and 12000 l mol^{-1} cm^{-1}, respectively, suggesting that the former system has a distinct colour strength advantage over the anthraquinone dyes. The 3,8-bis-(4′-MeO-phenylamino)-1,6-dibromo derivative **2l** shows a red shift of 146 nm relative to the unsubstituted chromophore **2a**. In the case of anthraquinone, introduction of two *p*-methoxyphenylamino groups into positions 1,5 results in a bathochromic shift of about 220 nm. Although the additional bromine atoms in **2l** preclude an exact comparison, their effect is likely to be small and so it can be concluded that for both the 1,6- and 3,8-bis-donor substitution patterns, the bathochromic shift of the diimidazopiperazinedione chromophore is significantly smaller than that achievable with corresponding disubstitution of the 9,10-anthraquinone chromophore. It is notable that the 3,8-bis-arylamino derivatives (**2l–n**), like the 1,6-diamino compound **2h**, have higher absorption intensities than corresponding anthraquinone dyes, and the values compare closely with those of azo dyes. Thus **2l–n** have ϵ_{max} values around 30000–34000 l $mol^{-1}cm^{-1}$, whereas 1,5-diarylaminoanthraquinones have values near 12000 l $mol^{-1}cm^{-1}$. The widely used 1,4-diarylaminoanthraquinones have values of only *ca* 16000 l $mol^{-1}cm^{-1}$.

A further potential colour advantage of the diimidazopiperazinediones is their relatively narrow bandwidths, suggesting that they could provide bright

colours. Thus half-bandwidths of the coloured derivatives of **2** range from 47 nm to 118 nm, most values being below 100 nm. In contrast, azo and anthraquinone dyes generally have values in excess of 100 nm (e.g. 1,4-bis-*p*-toluidinoanthraquinone, 120 nm).

*Dipyrazolopiperazinediones (**3**)*

Table 1 lists the light absorption characteristics in DMF for the various derivatives (**3**). For comparison the PPP-MO calculated λ_{max} values and oscillator strengths are also listed. An excellent correlation between the observed and calculated λ_{max} values was observed (Fig. 1b), with a maximum discrepancy of 10 nm. As with the previous series, calculated oscillator strengths do not correlate well with observed ϵ_{max} values, but some of the general trends are predicted.

The parent unsubstituted chromophore **3a** has $\lambda_{max} = 283$ nm, somewhat hypsochromic relative to the imidazole analogue **2a**. Consideration of the π-electron density changes for the HOMO $\rightarrow$ LUMO transition shows that there is a high degree of electron density migration from positions 3 and 8 to the carbonyl groups, and a small amount of donation from the 2,7-positions. In general agreement with the former prediction it can be seen that substitution at the 3,8-positions of the 2,7-dimethyl derivative **3b** with amino groups results in a large bathochromic shift from 297 nm to 428 nm ($\Delta\lambda$ 131 nm), which is much larger than that found for **2h** (96 nm), but not as large as that observed between anthraquinone and 1,5-diaminoanthraquinone (164 nm).

Although the 2,7-diamino derivative was not synthesised, MO theory predicted a λ_{max} value of 365 nm for the 2,7-diamino-3,8-dimethyl derivative, confirming that maximum bathochromic shifts are to be expected for 3,8- rather than 2,7-diamino -substitution.

PPP-MO theory did predict that aryl substituents in the 2,7-positions should enhance the absorption intensity, and this was confirmed with derivatives **3m–q**, where ϵ_{max} values up to *ca* 18 000 l mol^{-1}cm^{-1} were observed. However, the dipyrazolopiperazinedione system is not intrinsically as intense as the analogous diimidazo system (**2**), and in that respect is probably more comparable with the anthraquinone chromophore.

CONCLUSIONS

The diimidazopiperazinedione derivatives (**2**) absorb generally at short wavelengths and in the absence of strong electron-donating groups are colourless materials (λ_{max} *ca* 300–320 nm). Electron donating substituents cause a bathochromic shift of the first absorption band, and the 1,6- and

3,8-diamino derivatives are strongly coloured molecules, particularly the 3,8-diarylamino compounds. The system is not as bathochromic as the 9,10-anthraquinone system, and colours outside the yellow to red range would be difficult to achieve. However, the colour strength of such dyes would be 2–3 times higher than comparable anthraquinones, and this, combined with narrower bandwidths, could be advantageous. The dipyrazolo-piperazinediones (**3**) appear to have a dependence of bathochromic shift on electron-donating groups intermediate between the diimidazo analogues and the anthraquinones, but this potential advantage is offset by the low colour strength of the system. Thus absorption coefficients are of the same order of magnitude as for the anthraquinone dyes. It is doubtful if the two systems **2** and **3** should be regarded as cross-conjugated chromophores with the special light absorption characteristics often associated with such systems, and they seem to be more closely related to the anthraquinone dyes.

ACKNOWLEDGEMENTS

The authors are indebted to the S.E.R.C. Mass Spectrometry Service Centre, Swansea, for the provision of mass spectrometry services.

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