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Intrinsically thermochromic fluorans†

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A Suzuki coupling strategy has been employed to access a series of novel fluorans substituted with a phenolic moiety. These fluorans display good thermochromism in methyl stearate and obviate the need for traditional complex formulations containing acidic colour developers.

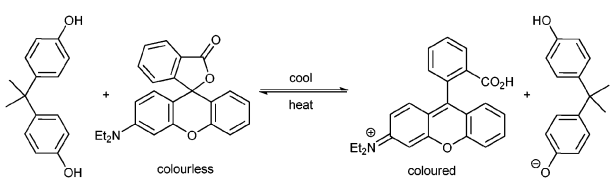
The last few years have seen a resurgence in interest in organic dye systems with a particular emphasis directed towards dyes designed for solar cells,[1] sensors and probes for a variety of analytes,[2] optical microscopy and nanoscopy[3] and photochromic systems[4] amongst other technological applications.[5] Dyes derived from the xanthene system[6] feature prominently amongst these examples and additionally in electrochromic displays.[7] Thermochromic formulations containing spiro[isobenzofuran-1(3*H*),9′(9*H*)xanthen]-3-ones, more commonly referred to as fluorans, have attracted significant commercial interest for image recording.[8,9] In order for fluorans to exhibit a thermochromic response, a formulation incorporating the fluoran (colour former) and a Brønsted acid (colour developer) in an inert relatively low melting matrix *e.g.* methyl stearate, is required.[9] The reversible colour generation results from temperature dependent association and proton transfer between the acidic developer and the fluoran; at low temperature the fluoran is in close association with the acidic developer and intense colour is observed as a consequence of cationic dye generation through lactone ring-opening. However, upon warming the wax above its melting temperature, the association between these partners is diminished and a colourless solution results (Scheme 1).[9,10]

We now communicate our preliminary observations on the value of transition metal-coupling chemistry for the derivatisation of readily accessible bromo-substituted fluorans, and through such a coupling process, incorporate a phenolic unit which obviates the requirement for complex formulation preparation involving the use of bisphenol A; the latter, in polymer formulations, has recently been associated with undesirable environmental health issues.[11] Of interest to this study are the recent reports concerning the palladium-catalysed arylation of a 9-trifloxyxanthene with a triaryl boroxin as the key step in the synthesis of a series of rosamines (9-arylxanthenes)[12] and the related arylation[13] and borylation[14] of fluorescein monotriflate in the design of new sensor systems.

Three bromo-substituted fluorans **1–3** were employed as substrates in order to investigate the coupling process and any subsequent intrinsic thermochromic behaviour. The isomeric diethylamino substituted bromobenzo[*a*]fluorans **1** and **2** were obtained in moderate yield from the acid-catalysed condensation between the ketoacid **4a** and either 6-bromo-2-naphthol or 7-bromo-2-naphthol,[15] respectively. The methoxy substituted bromobenzo[*a*]fluoran **3** resulted from a similar sequence from 6-bromo-2-naphthol and a mixture of the ketoacids **4b** : **4c** (~2 : 1) derived from the Friedel–Crafts benzoylation of 1,3-dimethoxybenzene with $AlCl_3$ (Scheme 2). The new fluorans **1–3** displayed the expected ^1H and ^{13}C NMR signals.[16]

The synthesis of biaryls employing the Suzuki coupling reaction is a versatile and routinely employed reaction in organic synthesis.[17] Heating a toluene ethanol solution of **1** with 3-hydroxybenzene boronic acid in the presence of 3 mol% $Pd(PPh_3)_4$ and K_2CO_3 gave, after aqueous work-up and column chromatography, two new fluorans 9′-diethylamino-3′-(3-hydroxyphenyl)benzo[*a*]fluoran **5a** (69%)[18] and the debrominated derivative **6a** (15%) (Scheme 3); the latter structure was verified by independent synthesis. The moderate yield of **5a** was somewhat disappointing in view of the relatively high conversion indicated by TLC analysis of the reaction mixture. It is likely that the moderate isolated yield of pure **5a** is in part attributed to a combination of the poor resolution between the two new products and the chromatographic purification process which results in some ring-opening of the fluorans on the chromatography silica.

The structure of **5a** was unequivocally established by X-ray crystallography (Fig. 1).[19] The pale maroon crystal was obtained by the slow solvent diffusion technique from $MeOH/CH_2Cl_2$ and crystallised in the triclinic space group $P\bar{1}$. The asymmetric unit



Scheme 1 Typical thermochromic equilibrium for a fluoran.

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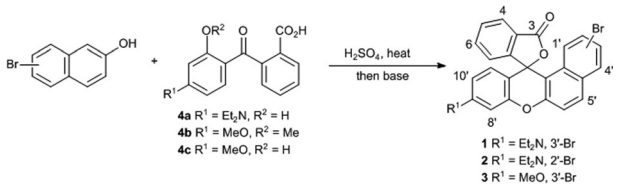
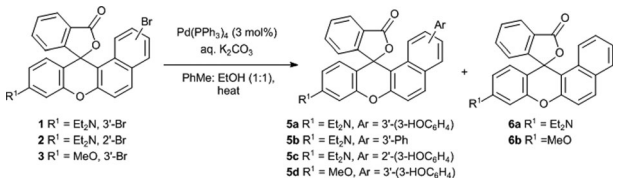
† Electronic supplementary information (ESI) available: Selected spectroscopic data for new compounds and crystallographic data for compound **5a** are provided. CCDC 845168. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/c1cc15854f



Scheme 2 Synthesis of bromofluorans **1–3**.



Scheme 3 Synthesis of hydroxyphenyl substituted fluorans **5**.

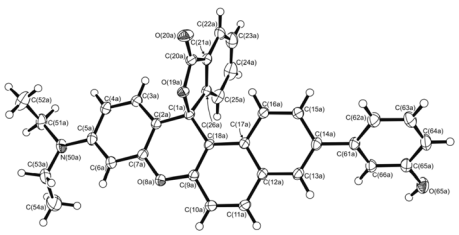


Fig. 1 X-ray crystal structure of **5a** with thermal ellipsoids scaled at the 50% probability level.

contained two molecules, labelled A and B, that displayed slightly different conformations. The bond lengths and angles of **5a** were comparable to those of related simple fluorans.[20]

Interestingly, the unit cell indicates intermolecular H–bonding between the phenolic moiety and the lactone C═O (Fig. 2), and is perhaps suggestive of an extremely low concentration of ring-opened fluoran molecules and whilst these could not be detected they may account for the pale maroon colour of the crystal. The intermolecular H-bonding of **5a** generates infinite linear chains with alternating A and B molecules (Fig. 2).

The chains run parallel to [−1, 1, 1] *i.e.* parallel to the body-diagonal of the unit cell that intercepts points 1, 0, 0 and 0, 1, 1. In each chain, hydrogen bonds are alternating intermolecular O65A–H65A···O20B and O65B–H65B···O20A bonds with the following geometry (Å, °) (Table 1).

Repeating the coupling protocol with **1** and benzene boronic acid gave **5b** (36%). The alternate bromobenzo[*a*]fluorans **2** and **3** gave **5c** and **5d**, respectively in 58% yield upon a similar coupling reaction with 3-hydroxybenzene boronic acid (Scheme 3). The formation of by-products **6a** (9% from **2**) and **6b** (14% from **3**)

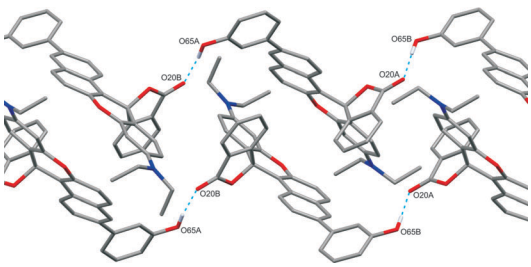


Fig. 2 Stick view of compound **5a** showing the hydrogen-bonded chains of alternating A and B molecules.

Table 1 Bond lengths and angles for intermolecular H-bonds between donor (D) and acceptor (A) groups for chains of **5a**

D–H···*A*	*D*–H	H···*A*	D···A	*D*–H···*A*
O65A–H65A···O20B[a]	0.84	1.95	2.7823(15)	170.4
O65B–H65B···O20A[b]	0.84	1.92	2.7507(14)	172.0

Symmetry codes:[a] $-x+2, -y+1, -z+1$; [b] $-x+1, -y+2, -z+2$.

was noted and clean separation by chromatography could not be accomplished thus accounting for only moderate yields of the pure isolated products. The debromination of aromatic bromides in Pd-catalysed reactions is a relatively common problem.[21]

The evaluation of a typical fluoran colour former relies upon examination of a formulation of the fluoran in methyl stearate containing bisphenol A and monitoring the colour of the mixture above and below the melting point of methyl stearate.[9] In the present work bisphenol A was not required because of the intrinsic developer unit. Thus with the exception of **5d**, which was too insoluble in hot methyl stearate, the remaining substituted fluorans **5a–c** were dissolved in hot (160 °C) methyl stearate and filtered through glass wool. The foregoing colourless solutions were then cooled to ambient temperature during which time **5a** and **5c** developed an intense maroon colour as a consequence of ring-opening of the fluoran unit presumably through intermolecular association between the phenolic moieties and the spirolactone units.[10] The colour change of **5a** in methyl stearate as a thin film sandwiched between two microscope slides is clearly indicated (Fig. 3) and also in a formulated ink screen printed label (Fig. 4).[22]

The difference in reflectance of **5a** in methyl stearate at low and high temperature is shown by the reflectance spectra (Fig. 5). Furthermore, cycling the temperature of the printed label above and below the range ~27–34 °C resulted in switching between the colourless and coloured states and further confirmed the reversibility of the thermochromic process. These observations are comparable to the performance of current formulated thermochromic inks.[23] It is noteworthy that the solution of **5b**, which does not contain a phenolic residue, remained colourless throughout the temperature cycling experiments, but upon addition of bisphenol A displayed a typical thermochromic response with the reversible development of a maroon shade (Fig. 6) with comparable spectroscopic features to those noted for **5a**.

The union of a phenolic moiety to benzofluoran by a Suzuki coupling methodology provides a very simple and moderately efficient approach to the design of new intrinsically thermochromic fluorans from readily available bromofluorans. Prototype formulations incorporating these new hydroxyphenyl substituted benzofluorans demonstrate reversible and intense colour development without the requirement for acidic colour developers such as bisphenol A. These preliminary results

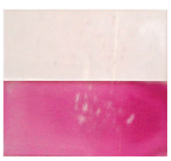


Fig. 3 Compound **5a** in methyl stearate (lower cold, upper warm).

Fig. 4 Screen printed label containing **5a** (LHS cold, RHS warm).

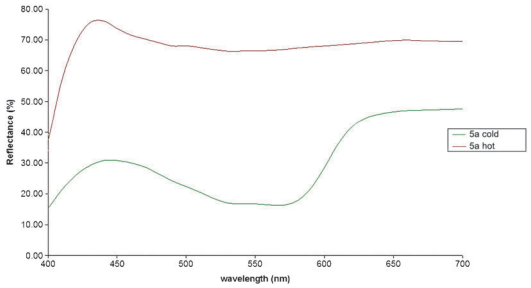


Fig. 5 Reflectance spectra of **5a** in methyl stearate at 20 °C and 50 °C.

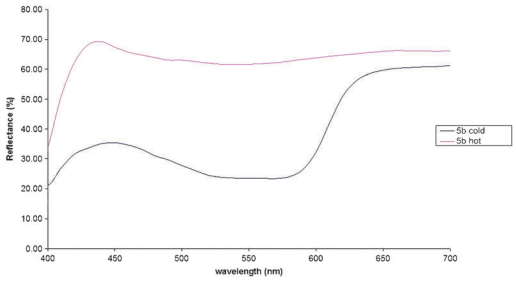


Fig. 6 Reflectance spectra of **5b** in methyl stearate containing bisphenol A at 20 °C and 50 °C.

should open up access to new more environmentally friendly thermochromic image recording systems. Our studies concerning the extension of this strategy involving more varied substituted fluorans to enable a full colour gamut to be accessed are ongoing.

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18 Experimental methods for the coupling reactions leading to **5a–d** are provided in the supplementary information.

19 Crystal data for **5a** crystallised from $MeOH/CH_2Cl_2$ by solvent vapour diffusion: $C_{34}H_{27}NO_4$, M = 513.57, triclinic, space group $P\bar{1}$, a = 13.1397(13) Å, α = 72.535(5)°, b = 14.8298(14) Å, β = 69.311(5)°, c = 16.2973(15) Å, γ = 68.257(5)°, volume = 2706.7(4) Å^3, ρ_c = 1.26 Mg m^{-3}, T = 150 K, Z = 4, reflections measured 81 602, independent reflections 17 792 R(int) = 0.0381, R_1 = 0.0719 ($I > 2\sigma(I)$), wR_2 (all data) = 0.1344. Full data are provided in the supplementary information (see also CCDC 845168).

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22 Details of the microencapsulation process and subsequent ink formulation are provided in the electronic supplementary information†.

23 See electronic supplementary information for hysteresis data for a comparison of a formulation of **5a** with that of a commercial fluoran.

